Introduction

WasmEdge is a lightweight, high-performance, and extensible WebAssembly runtime for cloud native, edge, and decentralized applications. It powers serverless apps, embedded functions, microservices, smart contracts, and IoT devices. WasmEdge is currently a CNCF (Cloud Native Computing Foundation) Sandbox project.

The WasmEdge Runtime provides a well-defined execution sandbox for its contained WebAssembly bytecode program. The runtime offers isolation and protection for operating system resources (e.g., file system, sockets, environment variables, processes) and memory space. The most important use case for WasmEdge is to safely execute user-defined or community-contributed code as plug-ins in a software product (e.g., SaaS, software-defined vehicles, edge nodes, or even blockchain nodes). It enables third-party developers, vendors, suppliers, and community members to extend and customize the software product.

This book will guide the users and developers to work with WasmEdge and show the commonly use cases.

- WasmEdge Quick Start
- Introduce the WasmEdge use cases
- WasmEdge Features
- Create WebAssembly program from your programming languages
- How to use the WasmEdge Library and the WasmEdge command line tools (CLI)
- How to develop a plug-in for WasmEdge

If you find some issues or have any advisement, welcome to contribute to WasmEdge!

Quick Start

In this chapter, we introduce how to install and run the WASM quickly with WasmEdge runtime.

- Install and uninstall WasmEdge on your platforms
- How to use WasmEdge Docker images
- Execute WASM with WasmEdge CLI
- Run WASM in Ahead-of-time (AOT) compiled mode

WasmEdge Installation And Uninstallation

Quick Install

The easiest way to install WasmEdge is to run the following command. Your system should have `git` and `curl` as prerequisites.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
```

For `Windows 10`, you could use Windows Package Manager Client (aka `winget.exe`) to install WasmEdge with a single command in your terminal.

```
winget install wasmedge
```

If you would like to install WasmEdge with its Tensorflow and image processing extensions, please run the following command. It will attempt to install WasmEdge with the `tensorflow` and `image` extensions on your system.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e all
```

Run the following command to make the installed binary available in the current session.

```
source $HOME/.wasmedge/env
```

That's it! You can now use WasmEdge from the CLI, or launch it from an application. To update WasmEdge to a new release, just re-run the above command to write over the old files.

Trouble Shooting

Some users, especially in China, reported that they had encountered the Connection refused error when trying to download the `install.sh` from the `githubusercontent.com`.

Please make sure your network connection can access the `github.com` and `githubusercontent.com` via VPN.

```
# The error message
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
curl: (7) Failed to connect to raw.githubusercontent.com port 443: Connection
refused
```

Install for All Users

By default, WasmEdge is installed in the `$HOME/.wasmedge` directory. You can install it into a system directory, such as `/usr/local` to make it available to all users. To specify an install directory, you can run the `install.sh` script with the `-p` flag. You will need to run the following commands as the `root` user or `sudo` since they write into system directories.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -p /usr/local
```

Or, with all extensions:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e all -p /usr/local
```

Install the Specific Version of WasmEdge

The WasmEdge installer script will install the latest official release by default. You could install the specific version of WasmEdge, including pre-releases or old releases by passing the `-v` argument to the installer script. Here is an example.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e all -v 0.11.2
```

If you are interested in the latest builds from the `HEAD` of the `master` branch, which is basically WasmEdge's nightly builds, you can download the release package directly from our Github Action's CI artifact. Here is an example.

What's Installed

After installation, you have the following directories and files. Here we assume that you installed into the `$HOME/.wasmedge` directory. You could also change it to `/usr/local` if you did a system-wide install. If you used `winget` to install WasmEdge, the files are located at `C:\Program Files\WasmEdge`.

- The `$HOME/.wasmedge/bin` directory contains the WasmEdge Runtime CLI executable files. You can copy and move them around on your file system.
  - The `wasmedge` tool is the standard WasmEdge runtime. You can use it from the CLI.
    - Execute a WASM file: `wasmedge --dir .:. app.wasm`
  - The `wasmedgec` tool is the ahead-of-time (AOT) compiler to compile a `.wasm` file into a native `.so` file (or `.dylib` on MacOS, `.dll` on Windows, or `.wasm` as the universal WASM format on all platforms). The `wasmedge` can then execute the output file.
    - Compile a WASM file into a AOT-compiled WASM: `wasmedgec app.wasm app.so`
    - Execute the WASM in AOT mode: `wasmedge --dir .:. app.so`
  - The `wasmedge-tensorflow`, `wasmedge-tensorflow-lite` tools are runtimes that support the WasmEdge tensorflow extension.
- The `$HOME/.wasmedge/lib` directory contains WasmEdge shared libraries, as well as dependency libraries. They are useful for WasmEdge SDKs to launch WasmEdge programs and functions from host applications.
- The `$HOME/.wasmedge/include` directory contains the WasmEdge header files. They are useful for WasmEdge SDKs.

Uninstall

To uninstall WasmEdge, you can run the following command.

```
bash <(curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master
/utils/uninstall.sh)
```

If the `wasmedge` binary is not in `PATH` and it wasn't installed in the default `$HOME/.wasmedge` folder, then you must provide the installation path.

```
bash <(curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master
/utils/uninstall.sh) -p /path/to/parent/folder
```

If you wish to uninstall uninteractively, you can pass in the `--quick` or `-q` flag.

```
bash <(curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master
/utils/uninstall.sh) -q
```

> If a parent folder of the `wasmedge` binary contains `.wasmedge`, the folder will be considered for removal. For example, the script removes the default `$HOME/.wasmedge` folder altogether.

If you used `winget` to install WasmEdge, run the following command.

```
`winget` uninstall wasmedge
```

Install WasmEdge for Node.js

WasmEdge can run WebAssembly functions emebedded in Node.js applications. To install the WasmEdge module in your Node.js environment is easy. Just use the `npm` tool.

```
npm install -g wasmedge-core # Append --unsafe-perm if permission denied
```

To install WasmEdge with Tensorflow and other extensions.

```
npm install -g wasmedge-extensions # Append --unsafe-perm if permission denied
```

The Second State Functions is a WasmEdge-based FaaS service build on Node.js.

Using WasmEdge in Docker

WasmEdge DockerSlim

The `wasmedge/slim:{version}` Docker images provide a slim WasmEdge images built with DockerSlim every releases.

- Image `wasmedge/slim-runtime:{version}` includes only WasmEdge runtime with `wasmedge` command.
- Image `wasmedge/slim:{version}` includes the following command line utilities:
  - `wasmedge`
  - `wasmedgec`
- Image `wasmedge/slim-tf:{version}` includes the following command line utilities:
  - `wasmedge`
  - `wasmedgec`
  - `wasmedge-tensorflow-lite`
  - `wasmedge-tensorflow`
  - `show-tflite-tensor`
- The working directory of the release docker image is `/app`.

Examples

Use `wasmedgec` and `wasmedge` (link):

```
$ docker pull wasmedge/slim:0.11.2

$ docker run -it --rm -v $PWD:/app wasmedge/slim:0.11.2 wasmedgec hello.wasm
hello.aot.wasm
[2022-07-07 08:15:49.154] [info] compile start
[2022-07-07 08:15:49.163] [info] verify start
[2022-07-07 08:15:49.169] [info] optimize start
[2022-07-07 08:15:49.808] [info] codegen start
[2022-07-07 08:15:50.419] [info] output start
[2022-07-07 08:15:50.421] [info] compile done
[2022-07-07 08:15:50.422] [info] output start

$ docker run -it --rm -v $PWD:/app wasmedge/slim:0.11.2 wasmedge hello.aot.wasm
world
hello
world
```

Use `wasmedge-tensorflow-lite` (link):

```
$ docker pull wasmedge/slim-tf:0.11.2
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/aiy_food_V1_labelmap.txt
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/food.jpg
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/lite-
model_aiy_vision_classifier_food_V1_1.tflite
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/main.js

$ docker run -it --rm -v $PWD:/app wasmedge/slim-tf:0.11.2 wasmedge-tensorflow-
lite --dir .:. qjs_tf.wasm main.js
label:
Hot dog
confidence:
0.8941176470588236
```

Docker Images for Building WasmEdge

WasmEdge supports a wide range of Linux distributions dated back to 2014. The official release contains statically linked binaries and libraries for older Linux systems. The table below shows build targets in WasmEdge's official release packages.

Developers can use the `docker pull wasmedge/wasmedge:{tag_name}` command to pull the docker image for WasmEdge building.

tag name	arch	based operating system	LLVM version	ENVs
`latest`	x86_64	Ubuntu 20.04 LTS	12.0.0	CC=clang, CXX=clang++
`ubuntu-build-gcc`	x86_64	Ubuntu 20.04 LTS	12.0.0	CC=gcc, CXX=g++

tag name	arch	based operating system	LLVM version	ENVs
`ubuntu-build-clang`	x86_64	Ubuntu 20.04 LTS	12.0.0	CC=clang, CXX=clang++
`ubuntu2004_x86_64`	x86_64	Ubuntu 20.04 LTS	10.0.0	CC=gcc, CXX=g++
`ubuntu2104_armv7l`	armhf	Ubuntu 21.04	12.0.0	CC=gcc, CXX=g++
`manylinux2014_x86_64`	x86_64	CentOS 7, 7.9.2009	12.0.0	CC=gcc, CXX=g++
`manylinux2014_aarch64`	aarch64	CentOS 7, 7.9.2009	12.0.0	CC=gcc, CXX=g++

Running WASM with WasmEdge CLI

After installing WasmEdge or starting the WasmEdge app dev Docker container, there are several ways to run WebAssembly programs.

`wasmedge` CLI

The `wasmedge` binary is a command line interface (CLI) program that runs WebAssembly programs.

- If the WebAssembly program contains a `main()` function, `wasmedge` would execute it as a standalone program in the command mode.
- If the WebAssembly program contains one or more exported public functions, `wasmedge` could invoke individual functions in the reactor mode.

By default, the `wasmedge` will execute WebAssembly programs in interpreter mode, and execute the AOT-compiled `.so`, `.dylib`, `.dll`, or `.wasm` (universal output format) in AOT mode. If you want to accelerate the WASM execution, we recommend to compile the WebAssembly with the AOT compiler first.

Users can run the `wasmedge -h` for realizing the command line options quickly, or refer to the detailed `wasmedge` CLI options here.

Call A WebAssembly Function Written in WAT

We created the hand-written fibonacci.wat and used the wat2wasm tool to convert it into the fibonacci.wasm WebAssembly program. It exported a `fib()` function which takes a single `i32` integer as the input parameter. We can execute `wasmedge` in reactor mode to invoke the exported function.

You can run:

```
wasmedge --reactor fibonacci.wasm fib 10
```

The output will be:

```
89
```

Call A WebAssembly Function Compiled From Rust

The add.wasm WebAssembly program contains an exported `add()` function, which is compiled from Rust. Checkout its Rust source code project here. We can execute `wasmedge` in reactor mode to invoke the `add()` function with two `i32` integer input parameters.

You can run:

```
wasmedge --reactor add.wasm add 2 2
```

The output will be:

```
4
```

Execute A Standalone WebAssembly Program: Hello world

The hello.wasm WebAssembly program contains a `main()` function. Checkout its Rust source code project here. It prints out `hello` followed by the command line arguments.

You can run:

```
wasmedge hello.wasm second state
```

The output will be:

```
hello
second
state
```

`wasmedgec` CLI

The `wasmedgec` binary is a CLI program to compile WebAssembly into native machine code (i.e., the AOT compiler). For the pure WebAssembly, the `wasmedge` tool will execute the WASM in interpreter mode. After compiling with the AOT compiler, the `wasmedge` tool can execute the WASM in AOT mode which is much faster.

The options and flags for the `wasmedgec` are as follows.

1. Input Wasm file(`/path/to/input/wasm/file`).

2. Output file name(`/path/to/output/file`).
    - By default, it will generate the universal Wasm binary format.
    - Users can still generate native binary only by specifying the `.so` , `.dylib` , or `.dll` extensions.

Users can run the `wasmedgec -h` for realizing the command line options quickly, or refer to the detailed `wasmedgec` CLI options here.

```
# This is slow in interpreter mode.
wasmedge app.wasm

# AOT compilation.
wasmedgec app.wasm app_aot.wasm

# This is now MUCH faster in AOT mode.
wasmedge app_aot.wasm
```

Execution in AOT Mode

The `wasmedge` command line tool will execute the original WASM files in interpreter mode. For the much better performance, we recommend users to compile the WASM with the `wasmedgec` AOT compiler to execute the WASM in AOT mode. There are 2 output formats of the AOT compiler:

Output Format: Universal WASM

By default, the `wasmedgec` AOT compiler tool could wrap the AOT-compiled native binary into a custom section in the origin WASM file. We call this the universal WASM binary format.

This AOT-compiled WASM file is compatible with any WebAssembly runtime. However, when this WASM file is executed by the WasmEdge runtime, WasmEdge will extract the native binary from the custom section and execute it in AOT mode.

Note: On MacOS platforms, the universal WASM format will `bus error` in execution. It's because the `wasmedgec` tool optimizes the WASM in `O2` level by default. We are trying to fix this issue. For working around, please use the shared library output format instead.

```
wasmedgec app.wasm app_aot.wasm
wasmedge app_aot.wasm
```

Output Format: Shared Library

Users can assign the shared library extension for the output files (`.so` on Linux, `.dylib` on MacOS, and `.dll` on Windows) to generate the shared library output format output.

This AOT-compiled WASM file is only for WasmEdge use, and cannot be used by other WebAssembly runtimes.

```
wasmedgec app.wasm app_aot.so
wasmedge app_aot.so
```

WasmEdge Features

WasmEdge is one of the fastest WebAssembly runtimes on the market (based on `LLVM AOT`).

- A Lightweight Design for High-performance Serverless Computing, published on IEEE Software, Jan 2021. https://arxiv.org/abs/2010.07115
- Performance Analysis for Arm vs. x86 CPUs in the Cloud, published on infoQ.com, Jan 2021. https://www.infoq.com/articles/arm-vs-x86-cloud-performance/
- WasmEdge is the fastest WebAssembly Runtime in Suborbital Reactr test suite, Dec 2021

Besides, WasmEdge supports various WebAssembly proposals and WASI proposals, as well as several non-standard extensions, which indicates that WasmEdge is an extensionable WebAssembly runtime. In this chapter, we'll introduce the key features of WasmEdge.

- Supported WASM and WASI proposals
- WasmEdge proprietary extensions
- Running WasmEdge on various platforms
- Integrability of WasmEdge on programming languages or frameworks
- Compare with other containers

Supported WASM And WASI Proposals

WebAssembly proposals

WasmEdge supports the following WebAssembly proposals. Those proposals are likely to become official WebAssembly specifications in the future.

Proposal	WasmEdge CLI flag	WasmEdge C API enumeration
Import/Export of Mutable Globals	`--disable-import-export-mut-globals`	`WasmEdge_Proposal_ImportExportMutGlobals`
Non-trapping float-to-int conversions	`--disable-non-trap-float-to-int`	`WasmEdge_Proposal_NonTrapFloatToIntConversions`
Sign-extension operators	`--disable-sign-extension-operators`	`WasmEdge_Proposal_SignExtensionOperators`
Multi-value	`--disable-multi-value`	`WasmEdge_Proposal_MultiValue`
Reference Types	`--disable-reference-types`	`WasmEdge_Proposal_ReferenceTypes`
Bulk memory operations	`--disable-bulk-memory`	`WasmEdge_Proposal_BulkMemoryOperations`
Fixed-width SIMD	`--disable-simd`	`WasmEdge_Proposal_SIMD`

Proposal	WasmEdge CLI flag	WasmEdge C API enumeration
Tail call	`--enable-tail-call`	`WasmEdge_Proposal_TailCall`
Multiple memories	`--enable-multi-memory`	`WasmEdge_Proposal_MultiMemories`
Extended Constant Expressions	`--enable-extended-const`	`WasmEdge_Proposal_ExtendedConst`
Threads	`--enable-threads`	`WasmEdge_Proposal_Threads`

The following proposals is under development and may be supported in the future:

- Component Model
- Exception handling
- Garbage collection
- WebAssembly C and C++ API

WASI proposals

WasmEdge implements the following WASI proposals.

Proposal	Platforms
Sockets	`x86_64 Linux` , `aarch64 Linux` (since `0.10.0`)
Crypto	`x86_64 Linux` , `aarch64 Linux` (since `0.10.1`)
Machine Learning (wasi-nn)	`x86_64 Linux` , OpenVINO (since `0.10.1`), PyTorch (since `0.11.1`), and TensorFlow-Lite (since `0.11.2`) backends
proxy-wasm	`x86_64 Linux (Interpreter only)` (since `0.8.2`)

The following proposals is under development and may be supported in the future:

- TensorFlow backend of `WASI-NN`

WasmEdge Proprietary Extensions

A key differentiator of WasmEdge from other WebAssembly runtimes is its support for non-standard extensions. The WebAssembly System Interface (WASI) provides a mechanism for developers to extend WebAssembly efficiently and securely. The WasmEdge team created the following WASI-like extensions based on real-world customer demands.

- Tensorflow. Developers can write Tensorflow inference functions using a simple Rust API, and then run the function securely and at native speed inside WasmEdge.
- Image processing. WasmEdge uses native libraries to manipulate images for computer vision tasks.
- KV Storage. The WasmEdge storage interface allows WebAssembly programs to read and write a key value store.
- Network sockets. WasmEdge applications can access the network sockets for TCP and HTTP connections.
- Command interface. WasmEdge enables webassembly functions execute native commands in the host operating system. It supports passing arguments, environment variables, `STDIN` / `STDOUT` pipes, and security policies for host access.
- Ethereum. The WasmEdge Ewasm extension supports Ethereum smart contracts compiled to WebAssembly. It is a leading implementation for Ethereum flavored WebAssembly (Ewasm).
- Substrate. The Pallet allows WasmEdge to act as an Ethereum smart contract execution engine on any Substrate based blockchains.

Extension Supported Platforms

Extension	Description	`x86_64` `Linux`	`aarch64` `Linux`	`arm64` `Android`	
WasmEdge-Image	Image host function extension with shared library.	since `0.9.0`	since `0.9.1`	since `0.9.1`	si `0`
WasmEdge-Tensorflow	TensorFlow host function extension with shared	TensorFlow and TensorFlow-Lite since `0.9.0`	TensorFlow-Lite since `0.9.1`	TensorFlow-Lite since `0.9.1`	Te ar Te Li `0`

Extension	Description	x86_64 Linux	aarch64 Linux	arm64 Android	
	library.				
WasmEdge-Tensorflow-Tools	WasmEdge CLI tools with TensorFlow and image extension.	since `0.9.0`	since `0.9.1`	since `0.9.1`	si `0`

WasmEdge Integrations

WasmEdge is a "serverless" runtime for cloud native and edge computing applications. It allows developers safely embed third-party or "native" functions into a host application or a distributed computing framework.

Embed WasmEdge Into A Host Application

A major use case of WasmEdge is to start a VM instance from a host application. Depending on your host application's programming language, you can use WasmEdge SDKs to start and invoke WasmEdge functions.

- Embed WasmEdge functions into a `C`-based application using the WasmEdge C API. Checkout the quick start guide.
- Embed WasmEdge functions into a `Go` application using the WasmEdge Go API. Here is a tutorial and are some examples!
- Embed WasmEdge functions into a `Rust` application using the WasmEdge Rust crate.
- Embed WasmEdge functions into a `Node.js` application using the `NAPI`. Here is a tutorial.
- Embed WasmEdge functions into any application by spawning a new process. See examples for Vercel Serverless Functions and AWS Lambda.

However, the WebAssembly spec only supports very limited data types as input parameters and return values for the WebAssembly bytecode functions. In order to pass complex data types, such as a string of an array, as call arguments into WebAssembly compiled from Rust, you should use the `bindgen` solution provided by the `wasmedge-bindgen`. We currently support the `wasmedge-bindgen` in the Rust and in Go.

Use WasmEdge As A Docker-Like Container

WasmEdge provides an OCI compliant interface. You can use container tools, such as CRI-O, Docker Hub, and Kubernetes, to orchestrate and manage WasmEdge runtimes.

- Manage WasmEdge with CRI-O and Docker Hub.

Call Native Host Functions From WasmEdge

A key feature of WasmEdge is its extensibility. WasmEdge APIs allow developers to register "host functions" from the host programming languages into a WasmEdge instance, and then invoke these functions from the WebAssembly program.

- The WasmEdge C API supports the C host functions.
- The WasmEdge Go API supports the Go host functions.
- The WasmEdge Rust API supports the Rust host functions.

Here is an example of a JavaScript program in WasmEdge calling a C-based host function in the underlying OS.

The host functions break the Wasm sandbox to access the underly OS or hardware. But the sandbox breaking is done with explicit permission from the system's operator.

Supported Platforms

WasmEdge supports a wide range of operating systems and hardware platforms. It allows WebAssembly applications to be truly portable across platforms. It runs not only on Linux-like systems, but also on microkernels such as the `seL4` real-time system.

WasmEdge now supports:

- Linux (`x86_64` and `aarch64`)
- MacOS (`x86_64` and `M1`)
- Windows
- Android
- seL4
- OpenWrt
- OpenHarmony
- Raspberry Pi

Comparison

What's the relationship between WebAssembly and Docker?

Check out our infographic WebAssembly vs. Docker. WebAssembly runs side by side with Docker in cloud native and edge native applications.

What's the difference for Native clients (NaCl), Application runtimes, and WebAssembly?

We created a handy table for the comparison.

	NaCl	Application runtimes (eg Node & Python)	Docker-like container	WebAssembly
Performance	Great	Poor	OK	Great
Resource footprint	Great	Poor	Poor	Great
Isolation	Poor	OK	OK	Great
Safety	Poor	OK	OK	Great
Portability	Poor	Great	OK	Great
Security	Poor	OK	OK	Great
Language and framework choice	N/A	N/A	Great	OK
Ease of use	OK	Great	Great	OK
Manageability	Poor	Poor	Great	Great

What's the difference between WebAssembly and eBPF?

`eBPF` is the bytecode format for a Linux kernel space VM that is suitable for network or security related tasks. WebAssembly is the bytecode format for a user space VM that is suited for business applications. See details here.

WasmEdge Use Cases

Featuring AOT compiler optimization, WasmEdge is one of the fastest WebAssembly runtimes on the market today. Therefore WasmEdge is widely used in edge computing, automotive, Jamstack, serverless, SaaS, service mesh, and even blockchain applications.

- Modern web apps feature rich UIs that are rendered in the browser and/or on the edge cloud. WasmEdge works with popular web UI frameworks, such as React, Vue, Yew, and Percy, to support isomorphic server-side rendering (SSR) functions on edge servers. It could also support server-side rendering of Unity3D animations and AI-generated interactive videos for web applications on the edge cloud.
- WasmEdge provides a lightweight, secure and high-performance runtime for microservices. It is fully compatible with application service frameworks such as Dapr, and service orchestrators like Kubernetes. WasmEdge microservices can run on edge servers, and have access to distributed cache, to support both stateless and stateful business logic functions for modern web apps. Also related: Serverless function-as-a-service in public clouds.
- Serverless SaaS (Software-as-a-Service) functions enables users to extend and customize their SaaS experience without operating their own API callback servers. The serverless functions can be embedded into the SaaS or reside on edge servers next to the SaaS servers. Developers simply upload functions to respond to SaaS events or to connect SaaS APIs.
- Smart device apps could embed WasmEdge as a middleware runtime to render interactive content on the UI, connect to native device drivers, and access specialized hardware features (i.e, the GPU for AI inference). The benefits of the WasmEdge runtime over native-compiled machine code include security, safety, portability, manageability, and developer productivity. WasmEdge runs on Android, OpenHarmony, and seL4 RTOS devices.
- WasmEdge could support high performance DSLs (Domain Specific Languages) or act as a cloud-native JavaScript runtime by embedding a JS execution engine or interpreter.
- Developers can leverage container tools such as Kubernetes, Docker and CRI-O to deploy, manage, and run lightweight WebAssembly applications.
- WasmEdge applications can be plugged into existing application frameworks or platforms.

If you have any great ideas on WasmEdge, don't hesitate to open a GitHub issue to discuss together.

Server Side Rendering Modern Web UI

Traditional web applications follows the client-server model. In the past era of application servers, the entire UI is dynamically generated from the server. The browser is simply a thin client that displays the rendered web pages at real time. However, as the browser becomes more capable and sophisticated, the client can now take on more workload to improve application UX, performance, and security.

That gives rise to the era of Jamstack. There is now a clear separation between frontend and backend services. The frontend is a static web site (HTML + JavaScript + WebAssembly) generated from UI frameworks such as React.js, Vue.js, Yew or Percy, and the backend consists of microservices. Yet, as Jamstack gains popularity, the diversity of clients (both browsers and apps) makes it very difficult to achieve great performance across all use cases.

The solution is server-side rendering (SSR). That is to have edge servers run the "client side" UI code (ie the React generated JavaScript OR Percy generated WebAssembly), and send back the rendered HTML DOM objects to the browser. In this case, the edge server must execute the exact same code (i.e. JavaScript and WebAssembly) as the browser to render the UI. That is called isomorphic Jamstack applications. The WasmEdge runtime provides a lightweight, high performance, OCI complaint, and polyglot container to run all kinds of SSR functions on edge servers.

- React JS SSR function
- Vue JS SSR function (coming soon)
- Yew Rust compiled to WebAssembly SSR function (coming soon)
- Percy Rust compiled to WebAssembly SSR function

We also exploring ways to render more complex UI and interactions on WasmEdge-based edge servers, and then stream the rendered results to the client application. Potential examples include

- Render Unity3D animations on the edge server (based on WebAssembly rendering of Unity3D)
- Render interactive video (generated from AI) on the edge server

Of course, the edge cloud could grow well beyond SSR for UI components. It could also host high-performance microservices for business logic and serverless functions. Read on to the next chapter.

Microservices

The edge cloud can run application logic microservices very close to the client device.

- The microservices could be stateless computational tasks, such as AI inference and stream data analysis, which offload computation from the client.
- The microservices could also interact with data cache services that sync with backend databases.

The edge cloud has advantages such as low latency, high security, and high performance. Operationally, WasmEdge can be embedded into cloud-native infrastructure via its SDKs in C, Go and Rust. It is also an OCI compliant runtime that can be directly managed by container tools as a lightweight and high-performance alternative to Linux containers. The following application frameworks have been tested to work with WasmEdge-based microservices.

Dapr (Distributed Application Runtime)

- Tutorial
- Code template

Service mesh (work in progress)

- Linkerd
- MOSN
- Envoy

Orchestration and management

- Kubernetes
- KubeEdge
- SuperEdge
- OpenYurt

Serverless Function-As-A-Service in Public Clouds

WasmEdge works with existing serverless or Jamstack platforms to provide a high-performance, portable and secure runtime for functions. It offers significant benefits even when it runs inside Docker or microVMs on those platforms.

AWS Lambda

- Tutorial
- Code template

Tencent Serverless Functions

- Tutorial in Chinese
- Code template

Vercel Serverless Functions

- Tutorial
- Code template

Netlify Functions

- Tutorial
- Code template

Second State Functions

- Tutorials

Serverless Software-As-A-Service Functions

WasmEdge can support customized SaaS extensions or applications using serverless functions instead of traditional network APIs. That dramatically improves SaaS users' and developers' productivity.

- WasmEdge could be embedded into SaaS products to execute user-defined functions. In this scenario, the WasmEdge function API replaces the SaaS web API. The embedded WasmEdge functions are much faster, safer, and easier to use than RPC functions over the web.
- Edge servers could provide WasmEdge-based containers to interact with existing SaaS or PaaS APIs without requiring the user to run his own servers (eg callback servers). The serverless API services can be co-located in the same networks as the SaaS to provide optimal performance and security.

The examples below showcase how WasmEdge-based serverless functions connect together SaaS APIs from different services, and process data flows across those SaaS APIs according each user's business logic.

Slack

- Build a serverless chatbot for Slack

Lark

It is also known as 飞书 aka the Chinese Slack. It is created by Byte Dance, the parent company of Tiktok.

- Build a serverless chatbot for Lark

WasmEdge On Smart Devices

Smart device apps could embed WasmEdge as a middleware runtime to render interactive content on the UI, connect to native device drivers, and access specialized hardware features (i.e, the GPU for AI inference). The benefits of the WasmEdge runtime over native-compiled machine code include security, safety, portability, manageability, OTA upgradability, and developer productivity. WasmEdge runs on the following device OSes.

- Android
- OpenHarmony
- Raspberry Pi
- The seL4 RTOS

With WasmEdge on both the device and the edge server, we can support isomorphic Server-Side Rendering (SSR) and microservices for rich-client mobile applications that is both portable and upgradable.

JavaScript or Domain Specific Language Runtime

In order for WebAssembly to be widely adopted by developers as a runtime, it must support "easy" languages like JavaScript. Or, better yet, through its advanced compiler toolchain, WasmEdge could support high performance DSLs (Domain Specific Languages), which are low code solutions designed for specific tasks.

JavaScript

WasmEdge can act as a cloud-native JavaScript runtime by embedding a JS execution engine or interpreter. It is faster and lighter than running a JS engine inside Docker. WasmEdge supports JS APIs to access native extension libraries such as network sockets, tensorflow, and user-defined shared libraries. It also allows embedding JS into other high-performance languages (eg, Rust) or using Rust / C to implement JS functions.

- Tutorials
  - Run JavaScript
  - Embed JavaScript in Rust
  - Create JavaScript API using Rust functions
  - Call C native shared library functions from JavaScript
- Examples
- WasmEdge's embedded QuickJS engine

DSL for image classification

The image classification DSL is a YAML format that allows the user to specify a tensorflow model and its parameters. WasmEdge takes an image as the input of the DSL and outputs the detected item name / label.

- Example: Run a YAML to detect food items in an image

DSL for chatbots

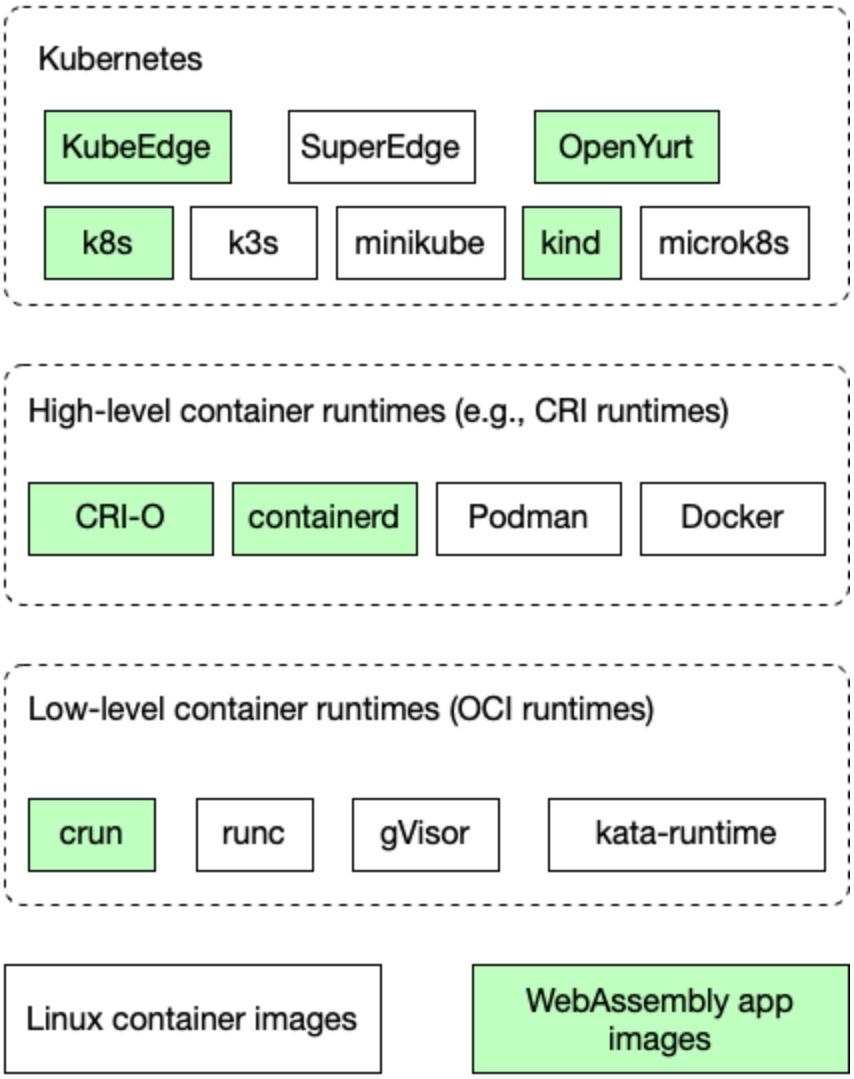
A chatbot DSL function takes an input string and responds with a reply string. The DSL specifies the internal state transitions of the chatbot, as well as AI models for language understanding. This work is in progress.

WasmEdge in Kubernetes

Developers can leverage container tools such as Kubernetes, Docker and CRI-O to deploy, manage, and run lightweight WebAssembly applications. In this chapter, we will demonstrate how Kubernetes ecosystem tools work with WasmEdge WebAssembly applications.

Compared with Linux containers, WebAssembly could be 100x faster at startup, have a much smaller memory and disk footprint, and have a better-defined safety sandbox. However, the trade-off is that WebAssembly requires its own language SDKs, and compiler toolchains, making it a more constrained developer environment than Linux containers. WebAssembly is increasingly used in Edge Computing scenarios where it is difficult to deploy Linux containers or when the application performance is vital.

One of the great advantages of Linux application containers is the rich ecosystem of tools. The good news is that you can use the exact same tools to manage WebAssembly applications, enabling Linux containers and WebAssembly apps to run side-by-side in the same system.



The container ecosystem

The contents of this chapter are organized by the approaches for integrating WasmEdge into container toolchains.

- The slimmed Linux container tailored for WasmEdge offers the easiest option (but with performance trade-offs) to integrate WasmEdge applications into any container tooling system.
- The most important integration approach is to replace the underlying OCI runtime of the toolchain stack with a WasmEdge-enabled `crun` runtime.
  - Quick start provides simple and scripted tutorials to run WasmEdge-based applications as container images in Kubernetes.
  - Demo apps discusses the two demo WasmEdge applications we will run in Kubernetes clusters. Those applications are compiled from Rust source code, packaged as OCI images, and uploaded to Docker Hub.
  - Container runtimes covers how to configure low level container runtimes, such as crun, to load and run WebAssembly OCI images.

    - CRI runtimes covers how to configure and use high level container runtimes, such as CRI-O and containerd, to load and run WebAssembly OCI images on top of low level container runtimes.
    - Kubernetes covers how to configure and use Kubernetes and Kubernetes variations, such as KubeEdge and SuperEdge, to load and run WebAssembly OCI images on top of CRI runtimes.
- If you cannot replace the OCI runtime in your toolchain with WasmEdge-enabled `crun`, you can use a containerd shim to start and run a WasmEdge application without any intrusive change.

The goal is to load and run WebAssembly OCI images side by side with Linux OCI images (e.g., today's Docker containers) across the entire Kubernetes stack.

Quick start

We have created Ubuntu-based scripts for you to quickly get started with the following combination of runtimes in a standard Kubernetes setup.

CRI (high level) runtime	OCI (low level) runtime	
CRI-O	crun + WasmEdge	Script
containerd	crun + WasmEdge	Script

CRI-O and crun

You can use the CRI-O install.sh script to install CRI-O and `crun` on Ubuntu 20.04.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/crio/install.sh | bash
```

Next, install Kubernetes using the following script.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/kubernetes_crio/install.sh | bash
```

The simple_wasi_application.sh script shows how to pull a WebAssembly application from Docker Hub, and then run it as a containerized application in Kubernetes.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/kubernetes_crio/simple_wasi_application.sh | bash
```

You should see results from the WebAssembly program printed in the console log. Here is an example.

containerd and crun

You can use the containerd install.sh script to install `containerd` and `crun` on Ubuntu 20.04.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/containerd/install.sh | bash
```

Next, install Kubernetes using the following script.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/kubernetes_containerd/install.sh | bash
```

The simple_wasi_application.sh script shows how to pull a WebAssembly application from Docker Hub, and then run it as a containerized application in Kubernetes.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-examples/main/kubernetes_containerd/simple_wasi_application.sh | bash
```

You should see results from the WebAssembly program printed in the console log. Here is an example.

Read on to the rest of this chapter to learn how exactly those runtimes are configured.

Demo apps

In this chapter, we will cover two demo apps. We will build them from Rust source code, build OCI images around them, and then publish the images to Docker Hub.

If you have not done so, please

- Install Rust
- Register for Docker Hub

Next, explore the examples

- A simple WASI example
- A HTTP server example

Since we have already built and published those demo apps on Docker Hub, you could also just go straight to the container runtime sections to use these images.

A simple WebAssembly example

In this article, I will show you how to build a container image for a WebAssembly application. It can then be started and managed by Kubernetes ecosystem tools, such as CRI-O, Docker, crun, and Kubernetes.

Prerequisites

> If you simply want a wasm bytecode file to test as a container image, you can skip the building process and just download the wasm file here.

If you have not done so already, follow these simple instructions to install Rust.

Download example code

```
git clone https://github.com/second-state/wasm-learning
cd wasm-learning/cli/wasi
```

Build the WASM bytecode

```
rustup target add wasm32-wasi
cargo build --target wasm32-wasi --release
```

The wasm bytecode application is in the `target/wasm32-wasi/release/wasi_example_main.wasm` file. You can now publish and use it as a container image.

Apply executable permission on the Wasm bytecode

```
chmod +x target/wasm32-wasi/release/wasi_example_main.wasm
```

Create Dockerfile

Create a file called `Dockerfile` in the `target/wasm32-wasi/release/` folder with the following content:

```
FROM scratch
ADD wasi_example_main.wasm /
CMD ["/wasi_example_main.wasm"]
```

Create container image with annotations

Please note that adding self-defined annotation is still a new feature in buildah.

The `crun` container runtime can start the above WebAssembly-based container image. But it requires the `module.wasm.image/variant=compat-smart` annotation on the container image to indicate that it is a WebAssembly application without a guest OS. You can find the details in Official crun repo.

To add `module.wasm.image/variant=compat-smart` annotation in the container image, you will need the latest buildah. Currently, Docker does not support this feature. Please follow the install instructions of buildah to build the latest buildah binary.

Build and install the latest buildah on Ubuntu

On Ubuntu zesty and xenial, use these commands to prepare for buildah.

```
sudo apt-get -y install software-properties-common

export OS="xUbuntu_20.04"
sudo bash -c "echo \"deb https://download.opensuse.org/repositories/devel:
/kubic:/libcontainers:/stable/$OS/ /\" > /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable.list"
sudo bash -c "curl -L https://download.opensuse.org/repositories/devel:/kubic:
/libcontainers:/stable/$OS/Release.key | apt-key add -"

sudo add-apt-repository -y ppa:alexlarsson/flatpak
sudo apt-get -y -qq update
sudo apt-get -y install bats git libapparmor-dev libdevmapper-dev libglib2.0-
dev libgpgme-dev libseccomp-dev libselinux1-dev skopeo-containers go-md2man
containers-common
sudo apt-get -y install golang-1.16 make
```

Then, follow these steps to build and install buildah on Ubuntu.

```
mkdir -p ~/buildah
cd ~/buildah
export GOPATH=`pwd`
git clone https://github.com/containers/buildah ./src/github.com/containers
/buildah
cd ./src/github.com/containers/buildah
PATH=/usr/lib/go-1.16/bin:$PATH make
cp bin/buildah /usr/bin/buildah
buildah --help
```

Create and publish a container image with buildah

In the `target/wasm32-wasi/release/` folder, do the following.

```
$ sudo buildah build --annotation "module.wasm.image/variant=compat-smart" -t
wasm-wasi-example .
# make sure docker is install and running
# systemctl status docker
# to make sure regular user can use docker
# sudo usermod -aG docker $USER
# newgrp docker

# You may need to use docker login to create the `~/.docker/config.json` for
auth.
$ sudo buildah push --authfile ~/.docker/config.json wasm-wasi-example
docker://docker.io/wasmedge/example-wasi:latest
```

That's it! Now you can try to run it in CRI-O or Kubernetes!

HTTP server example

Let's build a container image for a WebAssembly HTTP service. The HTTP service application is developed in Rust using the WasmEdge networking socket API. Kubernetes could manage the wasm application lifecycle with CRI-O, Docker and Containerd.

Prerequisites

This is a Rust example, which require you to install Rust and WasmEdge before you can Compile and Run the http service.

Download example code

```
mkdir http_server
cd http_server
wget -q https://raw.githubusercontent.com/second-state/wasmedge_wasi_socket
/main/examples/http_server/Cargo.toml
mkdir src
cd src
wget -q https://raw.githubusercontent.com/second-state/wasmedge_wasi_socket
/main/examples/http_server/src/main.rs
cd ../
```

Build the WASM bytecode

```
rustup target add wasm32-wasi
cargo build --target wasm32-wasi --release
```

The wasm bytecode application is now should be located in the `./target/wasm32-wasi/release/http_server.wasm` You can now test run it with wasmedge and then publish it as a container image.

Apply executable permission on the Wasm bytecode

```
chmod +x ./target/wasm32-wasi/release/http_server.wasm
```

Running the http_server application bytecode with wasmedge

When you run the bytecode with wasmedge and see the result as the following, you are ready to package the bytecode into the container.

```
$ wasmedge ./target/wasm32-wasi/release/http_server.wasm
new connection at 1234
```

You can test the server from another terminal window.

```
$ curl -X POST http://127.0.0.1:1234 -d 'name=WasmEdge'
echo: name=WasmEdge
```

Create Dockerfile

Create a file called `Dockerfile` in the `target/wasm32-wasi/release/` folder with the following content:

```
FROM scratch
ADD http_server.wasm /
CMD ["/http_server.wasm"]
```

Create container image with annotations

Please note that adding self-defined annotation is still a new feature in buildah.

The `crun` container runtime can start the above WebAssembly-based container image. But it requires the `module.wasm.image/variant=compat-smart` annotation on the container image to indicate that it is a WebAssembly application without a guest OS. You can find the details in Official crun repo.

To add `module.wasm.image/variant=compat-smart` annotation in the container image, you will need the latest buildah. Currently, Docker does not support this feature. Please follow the install instructions of buildah to build the latest buildah binary.

Build and install the latest buildah on Ubuntu

On Ubuntu zesty and xenial, use these commands to prepare for buildah.

```
sudo apt-get -y install software-properties-common

export OS="xUbuntu_20.04"
sudo bash -c "echo \"deb https://download.opensuse.org/repositories/devel:
/kubic:/libcontainers:/stable/$OS/ /\" > /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable.list"
sudo bash -c "curl -L https://download.opensuse.org/repositories/devel:/kubic:
/libcontainers:/stable/$OS/Release.key | apt-key add -"

sudo add-apt-repository -y ppa:alexlarsson/flatpak
sudo apt-get -y -qq update

sudo apt-get -y install bats git libapparmor-dev libdevmapper-dev libglib2.0-
dev libgpgme-dev libseccomp-dev libselinux1-dev skopeo-containers go-md2man
containers-common
sudo apt-get -y install golang-1.16 make
```

Then, follow these steps to build and install buildah on Ubuntu.

```
mkdir -p ~/buildah
cd ~/buildah
export GOPATH=`pwd`
git clone https://github.com/containers/buildah ./src/github.com/containers
/buildah
cd ./src/github.com/containers/buildah
PATH=/usr/lib/go-1.16/bin:$PATH make
cp bin/buildah /usr/bin/buildah
buildah --help
```

Create and publish a container image with buildah

In the `target/wasm32-wasi/release/` folder, do the following.

```
sudo buildah build --annotation "module.wasm.image/variant=compat-smart" -t
http_server .

#
# make sure docker is install and running
# systemctl status docker
# to make sure regular user can use docker
# sudo usermod -aG docker $USER#
# newgrp docker

# You may need to use docker login to create the `~/.docker/config.json` for
auth.
#
# docker login

sudo buildah push --authfile ~/.docker/config.json http_server
docker://docker.io/wasmedge/example-wasi-http:latest
```

That's it! Now you can try to run it in CRI-O or Kubernetes!

Container runtimes

The container image can be started by any OCI-compliant container runtime, such as

- crun: a high performance and lightweight container runtime written in C
- runc: a widely used container runtime written in Go
- youki: a OCI-compatible container runtime implementation written in Rust

crun

The crun project has WasmEdge support baked in. For now, the easiest approach is just built it yourself from source. First, let's make sure that `crun` dependencies are installed on your Ubuntu 20.04. For other Linux distributions, please see here.

```
sudo apt update
sudo apt install -y make git gcc build-essential pkgconf libtool \
    libsystemd-dev libprotobuf-c-dev libcap-dev libseccomp-dev libyajl-dev \
    go-md2man libtool autoconf python3 automake
```

Next, configure, build, and install a `crun` binary with WasmEdge support.

```
git clone https://github.com/containers/crun
cd crun
./autogen.sh
./configure --with-wasmedge
make
sudo make install
```

runc

Coming soon, or you can help out

youki

Coming soon, or you can help out

CRI runtimes

The high-level container runtime, such as CRI-O and containerd, pulls container images from registries (e.g., Docker Hub), manages them on disk, and launches a lower-level runtime to run container processes. From this chapter, you can check out specific tutorials for CRI-O and containerd.

- CRI-O
- containerd

CRI-O

Quick start

The GitHub repo contains scripts and Github Actions for running our example apps on CRI-O.

- Simple WebAssembly example Quick start | Github Actions
- HTTP service example Quick start | Github Actions

In the sections below, we will explain the steps in the quick start scripts.

Install CRI-O

Use the following commands to install CRI-O on your system.

```
export OS="xUbuntu_20.04"
export VERSION="1.21"
apt update
apt install -y libseccomp2 || sudo apt update -y libseccomp2
echo "deb https://download.opensuse.org/repositories/devel:/kubic:
/libcontainers:/stable/$OS/ /" > /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable.list
echo "deb https://download.opensuse.org/repositories/devel:/kubic:
/libcontainers:/stable:/cri-o:/$VERSION/$OS/ /" > /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable:cri-o:$VERSION.list

curl -L https://download.opensuse.org/repositories
/devel:kubic:libcontainers:stable:cri-o:$VERSION/$OS/Release.key | apt-key add
-
curl -L https://download.opensuse.org/repositories/devel:/kubic:/libcontainers:
/stable/$OS/Release.key | apt-key add -

apt-get update
apt-get install criu libyajl2
apt-get install cri-o cri-o-runc cri-tools containernetworking-plugins
systemctl start crio
```

Configure CRI-O to use crun

CRI-O uses the `runc` runtime by default and we need to configure it to use `crun` instead. That is done by adding to two configuration files.

> Make sure that you have built and installed the `crun` binary with WasmEdge support before starting the following steps.

First, create a `/etc/crio/crio.conf` file and add the following lines as its content. It tells CRI-O to use `crun` by default.

```
[crio.runtime]
default_runtime = "crun"
```

The `crun` runtime is in turn defined in the `/etc/crio/crio.conf.d/01-crio-runc.conf` file.

```
[crio.runtime.runtimes.runc]
runtime_path = "/usr/lib/cri-o-runc/sbin/runc"
runtime_type = "oci"
runtime_root = "/run/runc"
# The above is the original content

# Add our crunw runtime here
[crio.runtime.runtimes.crun]
runtime_path = "/usr/bin/crun"
runtime_type = "oci"
runtime_root = "/run/crun"
```

Next, restart CRI-O to apply the configuration changes.

```
systemctl restart crio
```

Run a simple WebAssembly app

Now, we can run a simple WebAssembly program using CRI-O. A separate article explains how to compile, package, and publish the WebAssembly program as a container image to Docker hub. In this section, we will start off pulling this WebAssembly-based container image from Docker hub using CRI-O tools.

```
sudo crictl pull docker.io/hydai/wasm-wasi-example:with-wasm-annotation
```

Next, we need to create two simple configuration files that specifies how CRI-O should run this WebAssembly image in a sandbox. We already have those two files container_wasi.json and sandbox_config.json. You can just download them to your local directory as follows.

```
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/crio/sandbox_config.json
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/crio/container_wasi.json
```

Now you can use CRI-O to create a pod and a container using the specified configurations.

```
# Create the POD. Output will be different from example.
$ sudo crictl runp sandbox_config.json
7992e75df00cc1cf4bff8bff660718139e3ad973c7180baceb9c84d074b516a4
# Set a helper variable for later use.
$ POD_ID=7992e75df00cc1cf4bff8bff660718139e3ad973c7180baceb9c84d074b516a4

# Create the container instance. Output will be different from example.
$ sudo crictl create $POD_ID container_wasi.json sandbox_config.json
# Set a helper variable for later use.
CONTAINER_ID=1d056e4a8a168f0c76af122d42c98510670255b16242e81f8e8bce8bd3a4476f
```

Starting the container would execute the WebAssembly program. You can see the output in the console.

```
# List the container, the state should be `Created`
$ sudo crictl ps -a
CONTAINER           IMAGE                                              CREATED
STATE               NAME                       ATTEMPT             POD ID
1d056e4a8a168       wasmedge/example-wasi:latest                       About a
minute ago   Created             podsandbox1-wasm-wasi   0
7992e75df00cc

# Start the container
$ sudo crictl start $CONTAINER_ID

# Check the container status again.
# If the container is not finishing its job, you will see the Running state
# Because this example is very tiny. You may see Exited at this moment.
$ sudo crictl ps -a
CONTAINER           IMAGE                                              CREATED
STATE               NAME                       ATTEMPT             POD ID
1d056e4a8a168       wasmedge/example-wasi:latest                       About a
minute ago   Running             podsandbox1-wasm-wasi   0
7992e75df00cc

# When the container is finished. You can see the state becomes Exited.
$ sudo crictl ps -a
CONTAINER           IMAGE                                              CREATED
STATE               NAME                       ATTEMPT             POD ID
1d056e4a8a168       wasmedge/example-wasi:latest                       About a
minute ago   Exited              podsandbox1-wasm-wasi   0
7992e75df00cc

# Check the container's logs. It should show outputs from the WebAssembly
programs
$ sudo crictl logs $CONTAINER_ID

Test 1: Print Random Number
Random number: 960251471

Test 2: Print Random Bytes
Random bytes: [50, 222, 62, 128, 120, 26, 64, 42, 210, 137, 176, 90, 60, 24,
183, 56, 150, 35, 209, 211, 141, 146, 2, 61, 215, 167, 194, 1, 15, 44, 156, 27,
179, 23, 241, 138, 71, 32, 173, 159, 180, 21, 198, 197, 247, 80, 35, 75, 245,
31, 6, 246, 23, 54, 9, 192, 3, 103, 72, 186, 39, 182, 248, 80, 146, 70, 244,
28, 166, 197, 17, 42, 109, 245, 83, 35, 106, 130, 233, 143, 90, 78, 155, 29,
230, 34, 58, 49, 234, 230, 145, 119, 83, 44, 111, 57, 164, 82, 120, 183, 194,
201, 133, 106, 3, 73, 164, 155, 224, 218, 73, 31, 54, 28, 124, 2, 38, 253, 114,
222, 217, 202, 59, 138, 155, 71, 178, 113]

Test 3: Call an echo function
Printed from wasi: This is from a main function
This is from a main function

Test 4: Print Environment Variables
The env vars are as follows.
```

```
PATH: /usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin
TERM: xterm
HOSTNAME: crictl_host
PATH: /usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin
The args are as follows.
/var/lib/containers/storage/overlay
/006e7cf16e82dc7052994232c436991f429109edea14a8437e74f601b5ee1e83/merged
/wasi_example_main.wasm
50000000

Test 5: Create a file `/tmp.txt` with content `This is in a file`

Test 6: Read the content from the previous file
File content is This is in a file

Test 7: Delete the previous file
```

Next, you can try to run the app in Kubernetes!

Run a HTTP server app

Finally, we can run a simple WebAssembly-based HTTP micro-service in CRI-O. A separate article explains how to compile, package, and publish the WebAssembly program as a container image to Docker hub. In this section, we will start off pulling this WebAssembly-based container image from Docker hub using CRI-O tools.

```
sudo crictl pull docker.io/avengermojo/http_server:with-wasm-annotation
```

Next, we need to create two simple configuration files that specifies how CRI-O should run this WebAssembly image in a sandbox. We already have those two files container_http_server.json and sandbox_config.json. You can just download them to your local directory as follows.

> The `sandbox_config.json` file is the same for the simple WASI example and the HTTP server example. The other `container_*.json` file is application specific as it contains the application's Docker Hub URL.

```
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/crio/sandbox_config.json
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/crio/http_server/container_http_server.json
```

Now you can use CRI-O to create a pod and a container using the specified configurations.

```
# Create the POD. Output will be different from example.
$ sudo crictl runp sandbox_config.json
7992e75df00cc1cf4bff8bff660718139e3ad973c7180baceb9c84d074b516a4
# Set a helper variable for later use.
$ POD_ID=7992e75df00cc1cf4bff8bff660718139e3ad973c7180baceb9c84d074b516a4

# Create the container instance. Output will be different from example.
$ sudo crictl create $POD_ID container_http_server.json sandbox_config.json
# Set a helper variable for later use.
CONTAINER_ID=1d056e4a8a168f0c76af122d42c98510670255b16242e81f8e8bce8bd3a4476f
```

Starting the container would execute the WebAssembly program. You can see the output in the console.

```
# Start the container
$ sudo crictl start $CONTAINER_ID

# Check the container status. It should be Running.
# If not, wait a few seconds and check again
$ sudo crictl ps -a
CONTAINER           IMAGE                                              CREATED
STATE               NAME                ATTEMPT             POD ID
4eeddf8613691       wasmedge/example-wasi-http:latest                  Less than a
second ago   Running             http_server         0
1d84f30e7012e

# Check the container's logs to see the HTTP server is listening at port 1234
$ sudo crictl logs $CONTAINER_ID
new connection at 1234

# Get the IP address assigned to the container
$ sudo crictl inspect $CONTAINER_ID | grep IP.0 | cut -d: -f 2 | cut -d'"' -f 2
10.85.0.2

# Test the HTTP service at that IP address
$ curl -d "name=WasmEdge" -X POST http://10.85.0.2:1234
echo: name=WasmEdge
```

Next, you can try to run it in Kubernetes!

containerd

Quick start

The GitHub repo contains scripts and Github Actions for running our example apps on containerd.

- Simple WebAssembly example Quick start | Github Actions
- HTTP service example Quick start | Github Actions

In the sections below, we will explain the steps in the quick start scripts.

Install containerd

Use the following commands to install containerd on your system.

```
export VERSION="1.5.7"
echo -e "Version: $VERSION"
echo -e "Installing libseccomp2 ..."
sudo apt install -y libseccomp2
echo -e "Installing wget"
sudo apt install -y wget

wget https://github.com/containerd/containerd/releases/download/v${VERSION}
/cri-containerd-cni-${VERSION}-linux-amd64.tar.gz
wget https://github.com/containerd/containerd/releases/download/v${VERSION}
/cri-containerd-cni-${VERSION}-linux-amd64.tar.gz.sha256sum
sha256sum --check cri-containerd-cni-${VERSION}-linux-amd64.tar.gz.sha256sum

sudo tar --no-overwrite-dir -C / -xzf cri-containerd-cni-${VERSION}-linux-
amd64.tar.gz
sudo systemctl daemon-reload
```

Configure containerd to use `crun` as the underlying OCI runtime. It makes changes to the `/etc/containerd/config.toml` file.

```
sudo mkdir -p /etc/containerd/
sudo bash -c "containerd config default > /etc/containerd/config.toml"
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/containerd/containerd_config.diff
sudo patch -d/ -p0 < containerd_config.diff
```

Start the containerd service.

```
sudo systemctl start containerd
```

Next, make sure that you have built and installed the `crun` binary with WasmEdge support before running the following examples.

Run a simple WebAssembly app

Now, we can run a simple WebAssembly program using containerd. A separate article explains how to compile, package, and publish the WebAssembly program as a container image to Docker hub. In this section, we will start off pulling this WebAssembly-based container image from Docker hub using containerd tools.

```
sudo ctr i pull docker.io/wasmedge/example-wasi:latest
```

Now, you can run the example in just one line with ctr (the containerd cli).

```
sudo ctr run --rm --runc-binary crun --runtime io.containerd.runc.v2 --label
module.wasm.image/variant=compat-smart docker.io/wasmedge/example-wasi:latest
wasm-example /wasi_example_main.wasm 50000000
```

Starting the container would execute the WebAssembly program. You can see the output in the console.

```
Creating POD ...
Random number: -1678124602
Random bytes: [12, 222, 246, 184, 139, 182, 97, 3, 74, 155, 107, 243, 20, 164,
175, 250, 60, 9, 98, 25, 244, 92, 224, 233, 221, 196, 112, 97, 151, 155, 19,
204, 54, 136, 171, 93, 204, 129, 177, 163, 187, 52, 33, 32, 63, 104, 128, 20,
204, 60, 40, 183, 236, 220, 130, 41, 74, 181, 103, 178, 43, 231, 92, 211, 219,
47, 223, 137, 70, 70, 132, 96, 208, 126, 142, 0, 133, 166, 112, 63, 126, 164,
122, 49, 94, 80, 26, 110, 124, 114, 108, 90, 62, 250, 195, 19, 189, 203, 175,
189, 236, 112, 203, 230, 104, 130, 150, 39, 113, 240, 17, 252, 115, 42, 12,
185, 62, 145, 161, 3, 37, 161, 195, 138, 232, 39, 235, 222]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
```

Next, you can try to run it in Kubernetes!

Run a HTTP server app

Finally, we can run a simple WebAssembly-based HTTP micro-service in containerd. A separate article explains how to compile, package, and publish the WebAssembly program as a container image to Docker hub. In this section, we will start off pulling this WebAssembly-based container image from Docker hub using containerd tools.

```
sudo ctr i pull docker.io/wasmedge/example-wasi-http:latest
```

Now, you can run the example in just one line with ctr (the containerd cli). Notice that we are running the container with `--net-host` so that the HTTP server inside the WasmEdge container is accessible from the outside shell.

```
sudo ctr run --rm --net-host --runc-binary crun --runtime io.containerd.runc.v2
--label module.wasm.image/variant=compat-smart docker.io/wasmedge/example-wasi-
http:latest http-server-example /http_server.wasm
```

Starting the container would execute the WebAssembly program. You can see the output in the console.

```
new connection at 1234

# Test the HTTP service at that IP address
curl -d "name=WasmEdge" -X POST http://127.0.0.1:1234
echo: name=WasmEdge
```

Next, you can try to run it in Kubernetes!

Kubernetes

Most high-level container runtimes implement Kubernetes' CRI (Container Runtime Interface) spec so that they can be managed by Kubernetes tools. That means you can use Kubernetes tools to manage the WebAssembly app image in pods and namespaces. Check out specific instructions for different flavors of Kubernetes setup in this chapter.

- Kubernetes + CRI-O
- Kubernetes + containerd
- KinD
- KubeEdge
- SuperEdge
- OpenYurt
- Knative

Kubernetes + CRI-O

Quick start

The GitHub repo contains scripts and Github Actions for running our example apps on Kubernetes + CRI-O.

- Simple WebAssembly example Quick start | Github Actions
- WebAssembly-based HTTP service Quick start | Github Actions

In the rest of this section, we will explain the steps in detail. We will assume that you have already installed and configured CRI-O to work with WasmEdge container images.

Install and start Kubernetes

Run the following commands from a terminal window. It sets up Kubernetes for local development.

```
# Install go
$ wget https://golang.org/dl/go1.17.1.linux-amd64.tar.gz
$ sudo rm -rf /usr/local/go
sudo tar -C /usr/local -xzf go1.17.1.linux-amd64.tar.gz
source /home/${USER}/.profile

# Clone k8s
git clone https://github.com/kubernetes/kubernetes.git
cd kubernetes
git checkout v1.22.2

# Install etcd with hack script in k8s
sudo CGROUP_DRIVER=systemd CONTAINER_RUNTIME=remote
CONTAINER_RUNTIME_ENDPOINT='unix:///var/run/crio/crio.sock' ./hack/install-
etcd.sh
export PATH="/home/${USER}/kubernetes/third_party/etcd:${PATH}"
sudo cp third_party/etcd/etcd* /usr/local/bin/

# After run the above command, you can find the following files: /usr/local
/bin/etcd  /usr/local/bin/etcdctl  /usr/local/bin/etcdutl

# Build and run k8s with CRI-O
sudo apt-get install -y build-essential
sudo CGROUP_DRIVER=systemd CONTAINER_RUNTIME=remote
CONTAINER_RUNTIME_ENDPOINT='unix:///var/run/crio/crio.sock' ./hack/local-up-
cluster.sh

... ...
Local Kubernetes cluster is running. Press Ctrl-C to shut it down.
```

Do NOT close your terminal window. Kubernetes is running!

Run WebAssembly container images in Kubernetes

Finally, we can run WebAssembly programs in Kubernetes as containers in pods. In this section, we will start from **another terminal window** and start using the cluster.

```
export KUBERNETES_PROVIDER=local

sudo cluster/kubectl.sh config set-cluster local
--server=https://localhost:6443 --certificate-authority=/var/run/kubernetes
/server-ca.crt
sudo cluster/kubectl.sh config set-credentials myself --client-key=/var
/run/kubernetes/client-admin.key --client-certificate=/var/run/kubernetes
/client-admin.crt
sudo cluster/kubectl.sh config set-context local --cluster=local --user=myself
sudo cluster/kubectl.sh config use-context local
sudo cluster/kubectl.sh
```

Let's check the status to make sure that the cluster is running.

```
$ sudo cluster/kubectl.sh cluster-info

# Expected output
Cluster "local" set.
User "myself" set.
Context "local" created.
Switched to context "local".
Kubernetes control plane is running at https://localhost:6443
CoreDNS is running at https://localhost:6443/api/v1/namespaces/kube-system
/services/kube-dns:dns/proxy

To further debug and diagnose cluster problems, use 'kubectl cluster-info
dump'.
```

A simple WebAssembly app

A separate article explains how to compile, package, and publish a simple WebAssembly WASI program as a container image to Docker hub. Run the WebAssembly-based image from Docker Hub in the Kubernetes cluster as follows.

```
sudo cluster/kubectl.sh run -it --rm --restart=Never wasi-demo
--image=wasmedge/example-wasi:latest
--annotations="module.wasm.image/variant=compat-smart" /wasi_example_main.wasm
50000000
```

The output from the containerized application is printed into the console.

```
Random number: 401583443
Random bytes: [192, 226, 162, 92, 129, 17, 186, 164, 239, 84, 98, 255, 209, 79,
51, 227, 103, 83, 253, 31, 78, 239, 33, 218, 68, 208, 91, 56, 37, 200, 32, 12,
106, 101, 241, 78, 161, 16, 240, 158, 42, 24, 29, 121, 78, 19, 157, 185, 32,
162, 95, 214, 175, 46, 170, 100, 212, 33, 27, 190, 139, 121, 121, 222, 230,
125, 251, 21, 210, 246, 215, 127, 176, 224, 38, 184, 201, 74, 76, 133, 233,
129, 48, 239, 106, 164, 190, 29, 118, 71, 79, 203, 92, 71, 68, 96, 33, 240,
228, 62, 45, 196, 149, 21, 23, 143, 169, 163, 136, 206, 214, 244, 26, 194, 25,
101, 8, 236, 247, 5, 164, 117, 40, 220, 52, 217, 92, 179]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
pod "wasi-demo-2" deleted
```

A WebAssembly-based HTTP service

A separate article explains how to compile, package, and publish a simple WebAssembly HTTP service application as a container image to Docker hub. Since the HTTP service container requires networking support provided by Kubernetes, we will use a k8s-http_server.yaml file to specify its exact configuration.

```
apiVersion: v1
kind: Pod
metadata:
  name: http-server
  namespace: default
  annotations:
    module.wasm.image/variant: compat-smart
spec:
  hostNetwork: true
  containers:
  - name: http-server
    image: wasmedge/example-wasi-http:latest
    command: [ "/http_server.wasm" ]
    ports:
    - containerPort: 1234
      protocol: TCP
    livenessProbe:
      tcpSocket:
        port: 1234
      initialDelaySeconds: 3
      periodSeconds: 30
```

Run the WebAssembly-based image from Docker Hub using the above `k8s-http_server.yaml` file in the Kubernetes cluster as follows.

```
sudo ./kubernetes/cluster/kubectl.sh apply -f k8s-http_server.yaml
```

Use the following command to see the running container applications and their IP addresses. Since we are using `hostNetwork` in the yaml configuration, the HTTP server image is running on the local network with IP address `127.0.0.1`.

```
$ sudo cluster/kubectl.sh get pod --all-namespaces -o wide

NAMESPACE     NAME                          READY   STATUS              RESTARTS
AGE   IP           NODE        NOMINATED NODE   READINESS GATES
default       http-server                   1/1     Running             1 (26s ago)
60s     127.0.0.1   127.0.0.1   <none>           <none>
```

Now, you can use the `curl` command to access the HTTP service.

```
$ curl -d "name=WasmEdge" -X POST http://127.0.0.1:1234
echo: name=WasmEdge
```

That's it!

Kubernetes + containerd

Quick start

The GitHub repo contains scripts and Github Actions for running our example apps on Kubernetes + containerd.

- Simple WebAssembly example Quick start | Github Actions
- WebAssembly-based HTTP service Quick start | Github Actions

In the rest of this section, we will explain the steps in detail. We will assume that you have already installed and configured containerd to work with WasmEdge container images.

Install and start Kubernetes

Run the following commands from a terminal window. It sets up Kubernetes for local development.

```
# Install go
$ wget https://golang.org/dl/go1.17.1.linux-amd64.tar.gz
$ sudo rm -rf /usr/local/go
$ sudo tar -C /usr/local -xzf go1.17.1.linux-amd64.tar.gz
$ source /home/${USER}/.profile

# Clone k8s
$ git clone https://github.com/kubernetes/kubernetes.git
$ cd kubernetes
$ git checkout v1.22.2

# Install etcd with hack script in k8s
$ sudo CGROUP_DRIVER=systemd CONTAINER_RUNTIME=remote
CONTAINER_RUNTIME_ENDPOINT='unix:///var/run/crio/crio.sock' ./hack/install-
etcd.sh
$ export PATH="/home/${USER}/kubernetes/third_party/etcd:${PATH}"
$ sudo cp third_party/etcd/etcd* /usr/local/bin/

# After run the above command, you can find the following files: /usr/local
/bin/etcd  /usr/local/bin/etcdctl  /usr/local/bin/etcdutl

# Build and run k8s with containerd
$ sudo apt-get install -y build-essential
$ sudo CGROUP_DRIVER=systemd CONTAINER_RUNTIME=remote
CONTAINER_RUNTIME_ENDPOINT='unix:///var/run/crio/crio.sock' ./hack/local-up-
cluster.sh

... ...
Local Kubernetes cluster is running. Press Ctrl-C to shut it down.
```

Do NOT close your terminal window. Kubernetes is running!

Run WebAssembly container images in Kubernetes

Finally, we can run WebAssembly programs in Kubernetes as containers in pods. In this section, we will start from **another terminal window** and start using the cluster.

```
export KUBERNETES_PROVIDER=local

sudo cluster/kubectl.sh config set-cluster local
--server=https://localhost:6443 --certificate-authority=/var/run/kubernetes
/server-ca.crt
sudo cluster/kubectl.sh config set-credentials myself --client-key=/var
/run/kubernetes/client-admin.key --client-certificate=/var/run/kubernetes
/client-admin.crt
sudo cluster/kubectl.sh config set-context local --cluster=local --user=myself
sudo cluster/kubectl.sh config use-context local
sudo cluster/kubectl.sh
```

Let's check the status to make sure that the cluster is running.

```
$ sudo cluster/kubectl.sh cluster-info

# Expected output
Cluster "local" set.
User "myself" set.
Context "local" created.
Switched to context "local".
Kubernetes control plane is running at https://localhost:6443
CoreDNS is running at https://localhost:6443/api/v1/namespaces/kube-system
/services/kube-dns:dns/proxy

To further debug and diagnose cluster problems, use 'kubectl cluster-info
dump'.
```

A simple WebAssembly app

A separate article explains how to compile, package, and publish a simple WebAssembly WASI program as a container image to Docker hub. Run the WebAssembly-based image from Docker Hub in the Kubernetes cluster as follows.

```
sudo cluster/kubectl.sh run -it --rm --restart=Never wasi-demo
--image=wasmedge/example-wasi:latest
--annotations="module.wasm.image/variant=compat-smart"
--overrides='{"kind":"Pod", "apiVersion":"v1", "spec": {"hostNetwork": true}}'
/wasi_example_main.wasm 50000000
```

The output from the containerized application is printed into the console.

```
Random number: 401583443
Random bytes: [192, 226, 162, 92, 129, 17, 186, 164, 239, 84, 98, 255, 209, 79,
51, 227, 103, 83, 253, 31, 78, 239, 33, 218, 68, 208, 91, 56, 37, 200, 32, 12,
106, 101, 241, 78, 161, 16, 240, 158, 42, 24, 29, 121, 78, 19, 157, 185, 32,
162, 95, 214, 175, 46, 170, 100, 212, 33, 27, 190, 139, 121, 121, 222, 230,
125, 251, 21, 210, 246, 215, 127, 176, 224, 38, 184, 201, 74, 76, 133, 233,
129, 48, 239, 106, 164, 190, 29, 118, 71, 79, 203, 92, 71, 68, 96, 33, 240,
228, 62, 45, 196, 149, 21, 23, 143, 169, 163, 136, 206, 214, 244, 26, 194, 25,
101, 8, 236, 247, 5, 164, 117, 40, 220, 52, 217, 92, 179]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
pod "wasi-demo-2" deleted
```

A WebAssembly-based HTTP service

A separate article explains how to compile, package, and publish a simple WebAssembly HTTP service application as a container image to Docker hub. Run the WebAssembly-based image from Docker Hub in the Kubernetes cluster as follows.

```
sudo cluster/kubectl.sh run --restart=Never http-server
--image=wasmedge/example-wasi-http:latest
--annotations="module.wasm.image/variant=compat-smart"
--overrides='{"kind":"Pod", "apiVersion":"v1", "spec": {"hostNetwork": true}}'
```

Since we are using `hostNetwork` in the `kubectl run` command, the HTTP server image is running on the local network with IP address `127.0.0.1`. Now, you can use the `curl` command to access the HTTP service.

```
$ curl -d "name=WasmEdge" -X POST http://127.0.0.1:1234
echo: name=WasmEdge
```

That's it!

Kubernetes in Docker (KinD)

KinD is a Kubernetes distribution that runs inside Docker and is well suited for local development or integration testing. It runs containerd as CRI and runc as OCI Runtime.

Quick start

As prerequisite we need to install KinD first. To do that the quick start guide and the release page can be used to install the latest version of the KinD CLI.

If KinD is installed we can directly start with the example from here:

```
# Create a "WASM in KinD" Cluster
kind create cluster --image ghcr.io/liquid-reply/kind-crun-wasm:v1.23.0
# Run the example
kubectl run -it --rm --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest --annotations="module.wasm.image/variant=compat-smart"
/wasi_example_main.wasm 50000000
```

In the rest of this section, we will explain how to create a KinD node image with wasmedge support.

Build crun

KinD uses the `kindest/node` image for the control plane and worker nodes. The image contains containerd as CRI and runc as OCI Runtime. To enable WasmEdge support we replace `runc` with `crun`.

For the node image we only need the crun binary and not the entire build toolchain. Therefore we use a multistage dockerfile where we create crun in the first step and only copy the crun binary to the node image.

```
FROM ubuntu:21.10 AS builder
WORKDIR /data
RUN DEBIAN_FRONTEND=noninteractive apt update \
    && DEBIAN_FRONTEND=noninteractive apt install -y curl make git gcc build-
essential pkgconf libtool libsystemd-dev libprotobuf-c-dev libcap-dev
libseccomp-dev libyajl-dev go-md2man libtool autoconf python3 automake \
    && curl https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -p /usr/local \
    && git clone --single-branch --branch feat/handler_per_container
https://github.com/liquid-reply/crun \
    && cd crun \
    && ./autogen.sh \
    && ./configure --with-wasmedge --enable-embedded-yajl\
    && make

...
```

Now we have a fresh `crun` binary with wasmedge enabled under `/data/crun/crun` that we can copy from this container in the next step.

Replace crun and configure containerd

Both runc and crun implement the OCI runtime spec and they have the same CLI parameters. Therefore we can just replace the runc binary with our crun-wasmedge binary we created before.

Since crun is using some shared libraries we need to install libyajl, wasmedge and criu to make our crun work.

Now we already have a KinD that uses crun instead of runc. Now we just need two config changes. The first one in the `/etc/containerd/config.toml` where we add the `pod_annotations` that can be passed to the runtime:

```
[plugins."io.containerd.grpc.v1.cri".containerd.runtimes.runc]
  pod_annotations = ["*.wasm.*", "wasm.*", "module.wasm.image/*",
"*.module.wasm.image", "module.wasm.image/variant.*"]
```

And the second one to the `/etc/containerd/cri-base.json` where we remove a hook that causes some issues.

The resulting dockerfile looks as follows:

```
...

FROM kindest/node:v1.23.0

COPY config.toml /etc/containerd/config.toml
COPY --from=builder /data/crun/crun /usr/local/sbin/runc
COPY --from=builder /usr/local/lib/libwasmedge.so /usr/local/lib/libwasmedge.so

RUN echo "Installing Packages ..." \
    && bash -c 'cat <<< $(jq "del(.hooks.createContainer)" /etc/containerd/cri-
base.json) > /etc/containerd/cri-base.json' \
    && ldconfig
```

Build and test

Finally we can build a new `node-wasmedge` image. To test it, we create a kind cluster from that image and run the simple app example.

```
docker build -t node-wasmedge .
kind create cluster --image node-wasmedge
# Now you can run the example to validate your cluster
kubectl run -it --rm --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest --annotations="module.wasm.image/variant=compat-smart"
/wasi_example_main.wasm 50000000
```

Create a crun demo for KubeEdge

1. Setup Cloud Side (KubeEdge Master Node)

Install Go

```
$ wget https://golang.org/dl/go1.17.3.linux-amd64.tar.gz
$ tar xzvf go1.17.3.linux-amd64.tar.gz

$ export PATH=/home/${user}/go/bin:$PATH
$ go version
go version go1.17.3 linux/amd64
```

Install CRI-O

Please see CRI-O Installation Instructions.

```
# Create the .conf file to load the modules at bootup
cat <<EOF | sudo tee /etc/modules-load.d/crio.conf
overlay
br_netfilter
EOF

sudo modprobe overlay
sudo modprobe br_netfilter

# Set up required sysctl params, these persist across reboots.
cat <<EOF | sudo tee /etc/sysctl.d/99-kubernetes-cri.conf
net.bridge.bridge-nf-call-iptables  = 1
net.ipv4.ip_forward                 = 1
net.bridge.bridge-nf-call-ip6tables = 1
EOF

sudo sysctl --system
export OS="xUbuntu_20.04"
export VERSION="1.21"
cat <<EOF | sudo tee /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable.list
deb https://download.opensuse.org/repositories/devel:/kubic:/libcontainers:
/stable/$OS/ /
EOF
cat <<EOF | sudo tee /etc/apt/sources.list.d
/devel:kubic:libcontainers:stable:cri-o:$VERSION.list
deb http://download.opensuse.org/repositories/devel:/kubic:/libcontainers:
/stable:/cri-o:/$VERSION/$OS/ /
EOF

curl -L https://download.opensuse.org/repositories/devel:/kubic:/libcontainers:
/stable/$OS/Release.key | sudo apt-key --keyring /etc/apt/trusted.gpg.d
/libcontainers.gpg add -
curl -L https://download.opensuse.org/repositories
/devel:kubic:libcontainers:stable:cri-o:$VERSION/$OS/Release.key | sudo apt-key
--keyring /etc/apt/trusted.gpg.d/libcontainers-cri-o.gpg add -

sudo apt-get update
sudo apt-get install cri-o cri-o-runc

sudo systemctl daemon-reload
sudo systemctl enable crio --now
sudo systemctl status cri-o
```

output:

```
$ sudo systemctl status cri-o
● crio.service - Container Runtime Interface for OCI (CRI-O)
     Loaded: loaded (/lib/systemd/system/crio.service; enabled; vendor preset:
enabled)
     Active: active (running) since Mon 2021-12-06 13:46:29 UTC; 16h ago
       Docs: https://github.com/cri-o/cri-o
   Main PID: 6868 (crio)
      Tasks: 14
     Memory: 133.2M
     CGroup: /system.slice/crio.service
             └─6868 /usr/bin/crio

Dec 07 06:04:13 master crio[6868]: time="2021-12-07 06:04:13.694226800Z"
level=info msg="Checking image status: k8s.gcr.io/pause:3.4.1" id=1dbb722e-
f031-410c-9f45-5d4b5760163e name=/runtime.v1alpha2.ImageServic>
Dec 07 06:04:13 master crio[6868]: time="2021-12-07 06:04:13.695739507Z"
level=info msg="Image status: &{0xc00047fdc0 map[]}" id=1dbb722e-f031-410c-
9f45-5d4b5760163e name=/runtime.v1alpha2.ImageService/ImageSta>
Dec 07 06:09:13 master crio[6868]: time="2021-12-07 06:09:13.698823984Z"
level=info msg="Checking image status: k8s.gcr.io/pause:3.4.1" id=661b754b-
48a4-401b-a03f-7f7a553c7eb6 name=/runtime.v1alpha2.ImageServic>
Dec 07 06:09:13 master crio[6868]: time="2021-12-07 06:09:13.703259157Z"
level=info msg="Image status: &{0xc0004d98f0 map[]}" id=661b754b-48a4-401b-
a03f-7f7a553c7eb6 name=/runtime.v1alpha2.ImageService/ImageSta>
Dec 07 06:14:13 master crio[6868]: time="2021-12-07 06:14:13.707778419Z"
level=info msg="Checking image status: k8s.gcr.io/pause:3.4.1"
id=8c7e4d36-871a-452e-ab55-707053604077 name=/runtime.v1alpha2.ImageServic>
Dec 07 06:14:13 master crio[6868]: time="2021-12-07 06:14:13.709379469Z"
level=info msg="Image status: &{0xc000035030 map[]}" id=8c7e4d36-871a-452e-
ab55-707053604077 name=/runtime.v1alpha2.ImageService/ImageSta>
Dec 07 06:19:13 master crio[6868]: time="2021-12-07 06:19:13.713158978Z"
level=info msg="Checking image status: k8s.gcr.io/pause:3.4.1" id=827b6315-
f145-4f76-b8da-31653d5892a2 name=/runtime.v1alpha2.ImageServic>
Dec 07 06:19:13 master crio[6868]: time="2021-12-07 06:19:13.714030148Z"
level=info msg="Image status: &{0xc000162bd0 map[]}" id=827b6315-f145-4f76-
b8da-31653d5892a2 name=/runtime.v1alpha2.ImageService/ImageSta>
Dec 07 06:24:13 master crio[6868]: time="2021-12-07 06:24:13.716746612Z"
level=info msg="Checking image status: k8s.gcr.io/pause:3.4.1"
id=1d53a917-4d98-4723-9ea8-a2951a472cff name=/runtime.v1alpha2.ImageServic>
Dec 07 06:24:13 master crio[6868]: time="2021-12-07 06:24:13.717381882Z"
level=info msg="Image status: &{0xc00042ce00 map[]}"
id=1d53a917-4d98-4723-9ea8-a2951a472cff name=/runtime.v1alpha2.ImageService
/ImageSta>
```

Install and Creating a cluster with kubeadm for K8s

Please see Creating a cluster with kubeadm.

Install K8s

```
sudo apt-get update
sudo apt-get install -y apt-transport-https curl
echo "deb [signed-by=/usr/share/keyrings/kubernetes-archive-keyring.gpg]
https://apt.kubernetes.io/ kubernetes-xenial main" | sudo tee /etc/apt
/sources.list.d/kubernetes.list

sudo apt update
K_VER="1.21.0-00"
sudo apt install -y kubelet=${K_VER} kubectl=${K_VER} kubeadm=${K_VER}
sudo apt-mark hold kubelet kubeadm kubectl
```

Create a cluster with kubeadm

```
#kubernetes scheduler requires this setting to be done.
$ sudo swapoff -a
$ sudo vim /etc/fstab
mark contain swapfile of row

$ cat /etc/cni/net.d/100-crio-bridge.conf
{
    "cniVersion": "0.3.1",
    "name": "crio",
    "type": "bridge",
    "bridge": "cni0",
    "isGateway": true,
    "ipMasq": true,
    "hairpinMode": true,
    "ipam": {
        "type": "host-local",
        "routes": [
            { "dst": "0.0.0.0/0" },
            { "dst": "1100:200::1/24" }
        ],
        "ranges": [
            [{ "subnet": "10.85.0.0/16" }],
            [{ "subnet": "1100:200::/24" }]
        ]
    }
}
$ export CIDR=10.85.0.0/16
$ sudo kubeadm init --apiserver-advertise-address=192.168.122.160 --pod-
network-cidr=$CIDR --cri-socket=/var/run/crio/crio.sock

$ mkdir -p $HOME/.kube
$ sudo cp -i /etc/kubernetes/admin.conf $HOME/.kube/config
$ sudo chown $(id -u):$(id -g) $HOME/.kube/config
```

output:

```
Your Kubernetes control-plane has initialized successfully!

To start using your cluster, you need to run the following as a regular user:

  mkdir -p $HOME/.kube
  sudo cp -i /etc/kubernetes/admin.conf $HOME/.kube/config
  sudo chown $(id -u):$(id -g) $HOME/.kube/config

You should now deploy a Pod network to the cluster.
Run "kubectl apply -f [podnetwork].yaml" with one of the options listed at:
  /docs/concepts/cluster-administration/addons/

You can now join any number of machines by running the following on each node
as root:

  kubeadm join <control-plane-host>:<control-plane-port> --token <token>
--discovery-token-ca-cert-hash sha256:<hash>
```

To make kubectl work for your non-root user, run these commands, which are also part of the kubeadm init output:

```
mkdir -p $HOME/.kube
sudo cp -i /etc/kubernetes/admin.conf $HOME/.kube/config
sudo chown $(id -u):$(id -g) $HOME/.kube/config
```

Setup KubeEdge Master Node

Please see Deploying using Keadm.

IMPORTANT NOTE:

1. At least one of kubeconfig or master must be configured correctly, so that it can be used to verify the version and other info of the k8s cluster.
2. Please make sure edge node can connect cloud node using local IP of cloud node, or you need to specify public IP of cloud node with --advertise-address flag.
3. --advertise-address(only work since 1.3 release) is the address exposed by the cloud side (will be added to the SANs of the CloudCore certificate), the default value is the local IP.

```
wget https://github.com/kubeedge/kubeedge/releases/download/v1.8.0/keadm-
v1.8.0-linux-amd64.tar.gz
tar xzvf keadm-v1.8.0-linux-amd64.tar.gz
cd keadm-v1.8.0-linux-amd64/keadm/
sudo ./keadm init --advertise-address=192.168.122.160 --kube-config=/home
/${user}/.kube/config
```

output:

```
Kubernetes version verification passed, KubeEdge installation will start...
...
KubeEdge cloudcore is running, For logs visit:  /var/log/kubeedge/cloudcore.log
```

2. Setup Edge Side (KubeEdge Worker Node)

You can use the CRI-O install.sh script to install CRI-O and `crun` on Ubuntu 20.04.

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/crio/install.sh | bash
```

Install Go on Edge Side

```
$ wget https://golang.org/dl/go1.17.3.linux-amd64.tar.gz
$ tar xzvf go1.17.3.linux-amd64.tar.gz

$ export PATH=/home/${user}/go/bin:$PATH
$ go version
go version go1.17.3 linux/amd64
```

Get Token From Cloud Side

Run keadm gettoken in cloud side will return the token, which will be used when joining edge nodes.

```
$ sudo ./keadm gettoken --kube-config=/home/${user}/.kube/config
27a37ef16159f7d3be8fae95d588b79b3adaaf92727b72659eb89758c66ffda2.eyJhbGciOiJIUz
I1NiIsInR5cCI6IkpXVCJ9.eyJleHAiOjE1OTAyMTYwNzd9.JBj8LLYWXwbbvHKffJBpPd5CyxqapRQ
YDIXtFZErgYE
```

Download Kubeedge and join edge nodes

Please see Setting different container runtime with CRI and Deploying using Keadm.

```
$ wget https://github.com/kubeedge/kubeedge/releases/download/v1.8.0/keadm-
v1.8.0-linux-amd64.tar.gz
$ tar xzvf keadm-v1.8.0-linux-amd64.tar.gz
$ cd keadm-v1.8.0-linux-amd64/keadm/

$ sudo ./keadm join \
--cloudcore-ipport=192.168.122.160:10000 \
--edgenode-name=edge \
--token=b4550d45b773c0480446277eed1358dcd8a02a0c214646a8082d775f9c447d81.eyJhbG
ciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJleHAiOjE2Mzg4ODUzNzd9.A9WOYJFrgL2swVGnydpb4gM
ojyvyoNPCXaA4rXGowqU \
--remote-runtime-endpoint=unix:///var/run/crio/crio.sock \
--runtimetype=remote \
--cgroupdriver=systemd
```

Output:

```
Host has mosquit+ already installed and running. Hence skipping the
installation steps !!!
...
KubeEdge edgecore is running, For logs visit:  /var/log/kubeedge/edgecore.log
```

Get Edge Node Status From Cloud Side

Output:

```
kubectl get node
NAME       STATUS    ROLES                  AGE   VERSION
edge       Ready     agent,edge             10s   v1.19.3-kubeedge-v1.8.2
master     Ready     control-plane,master   68m   v1.21.0
```

3. Enable kubectl logs Feature

Before metrics-server deployed, kubectl logs feature must be activated, please see here.

4. Run a simple WebAssembly app

We can run the WebAssembly-based image from Docker Hub in the Kubernetes cluster.

Cloud Side

```
$ kubectl run -it --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest --annotations="module.wasm.image/variant=compat-smart"
/wasi_example_main.wasm 50000000

Random number: -1694733782
Random bytes: [6, 226, 176, 126, 136, 114, 90, 2, 216, 17, 241, 217, 143, 189,
123, 197, 17, 60, 49, 37, 71, 69, 67, 108, 66, 39, 105, 9, 6, 72, 232, 238,
102, 5, 148, 243, 249, 183, 52, 228, 54, 176, 63, 249, 216, 217, 46, 74, 88,
204, 130, 191, 182, 19, 118, 193, 77, 35, 189, 6, 139, 68, 163, 214, 231, 100,
138, 246, 185, 47, 37, 49, 3, 7, 176, 97, 68, 124, 20, 235, 145, 166, 142, 159,
114, 163, 186, 46, 161, 144, 191, 211, 69, 19, 179, 241, 8, 207, 8, 112, 80,
170, 33, 51, 251, 33, 105, 0, 178, 175, 129, 225, 112, 126, 102, 219, 106, 77,
242, 104, 198, 238, 193, 247, 23, 47, 22, 29]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
```

The WebAssembly app of pod successfully deploy to edge node.

```
$ kubectl describe pod wasi-demo

Name:         wasi-demo
Namespace:    default
Priority:     0
Node:         edge/192.168.122.229
Start Time:   Mon, 06 Dec 2021 15:45:34 +0000
Labels:       run=wasi-demo
Annotations:  module.wasm.image/variant: compat-smart
Status:       Succeeded
IP:
IPs:          <none>
Containers:
  wasi-demo:
    Container ID:  cri-
o://1ae4d0d7f671050331a17e9b61b5436bf97ad35ad0358bef043ab820aed81069
    Image:         wasmedge/example-wasi:latest
    Image ID:      docker.io/wasmedge/example-
wasi@sha256:525aab8d6ae8a317fd3e83cdac14b7883b92321c7bec72a545edf276bb2100d6
    Port:          <none>
    Host Port:     <none>
    Args:
      /wasi_example_main.wasm
      50000000
    State:          Terminated
      Reason:       Completed
      Exit Code:    0
      Started:      Mon, 06 Dec 2021 15:45:33 +0000
      Finished:     Mon, 06 Dec 2021 15:45:33 +0000
    Ready:          False
    Restart Count:  0
    Environment:    <none>
    Mounts:
      /var/run/secrets/kubernetes.io/serviceaccount from kube-api-access-bhszr
(ro)
Conditions:
  Type           Status
  Initialized    True
  Ready          False
  PodScheduled   True
Volumes:
  kube-api-access-bhszr:
    Type:                     Projected (a volume that contains injected data
from multiple sources)
    TokenExpirationSeconds:  3607
    ConfigMapName:           kube-root-ca.crt
    ConfigMapOptional:       <nil>
    DownwardAPI:             true
QoS Class:                   BestEffort
Node-Selectors:              <none>
Tolerations:                 node.kubernetes.io/not-ready:NoExecute op=Exists
for 300s
```

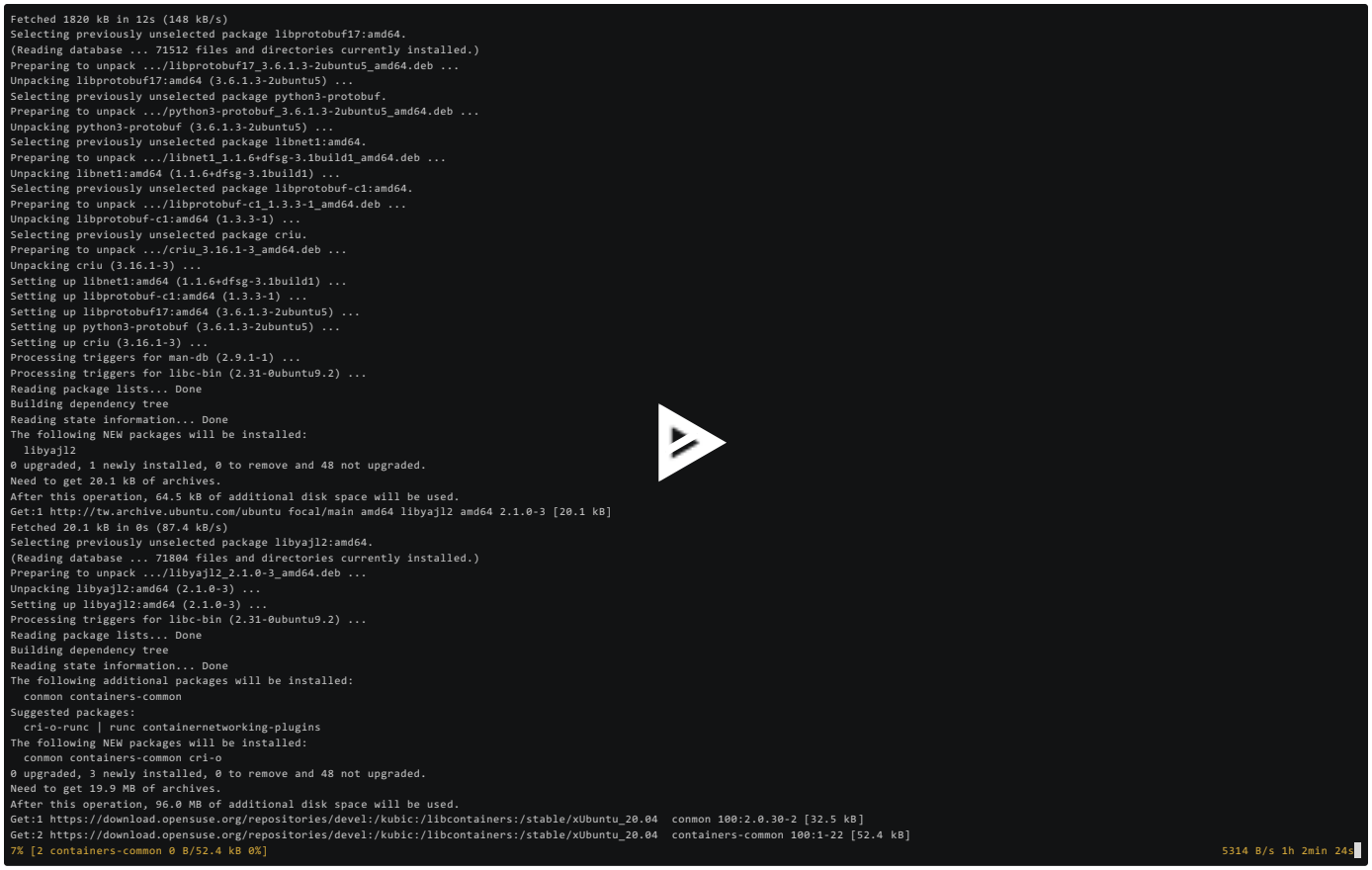
```
                            node.kubernetes.io/unreachable:NoExecute op=Exists
for 300s
Events:
  Type    Reason     Age   From               Message
  ----    ------     ----  ----               -------
```

Edge Side

```
$ sudo crictl ps -a
CONTAINER           IMAGE
CREATED             STATE               NAME                ATTEMPT
POD ID
1ae4d0d7f6710
0423b8eb71e312b8aaa09a0f0b6976381ff567d5b1e5729bf9b9aa87bff1c9f3
16 minutes ago      Exited              wasi-demo           0
2bc2ac0c32eda
1e6c7cb6bc731       k8s.gcr.io/kube-
proxy@sha256:2a25285ff19f9b4025c8e54dac42bb3cd9aceadc361f2570489b8d723cb77135
18 minutes ago      Running             kube-proxy          0
8b7e7388ad866
```

That's it.

5. Demo Run Screen Recording


Fetched 1820 kB in 12s (148 kB/s)
Selecting previously unselected package libprotobuf17:amd64.
(Reading database ... 71512 files and directories currently installed.)
Preparing to unpack .../libprotobuf17_3.6.1.3-2ubuntu5_amd64.deb ...
Unpacking libprotobuf17:amd64 (3.6.1.3-2ubuntu5) ...
Selecting previously unselected package python3-protobuf.
Preparing to unpack .../python3-protobuf_3.6.1.3-2ubuntu5_amd64.deb ...
Unpacking python3-protobuf (3.6.1.3-2ubuntu5) ...
Selecting previously unselected package libnet1:amd64.
Preparing to unpack .../libnet1_1.1.6+dfsg-3.1build1_amd64.deb ...
Unpacking libnet1:amd64 (1.1.6+dfsg-3.1build1) ...
Selecting previously unselected package libprotobuf-c1:amd64.
Preparing to unpack .../libprotobuf-c1_1.3.3-1_amd64.deb ...
Unpacking libprotobuf-c1:amd64 (1.3.3-1) ...
Selecting previously unselected package criu.
Preparing to unpack .../criu_3.16.1-3_amd64.deb ...
Unpacking criu (3.16.1-3) ...
Setting up libnet1:amd64 (1.1.6+dfsg-3.1build1) ...
Setting up libprotobuf-c1:amd64 (1.3.3-1) ...
Setting up libprotobuf17:amd64 (3.6.1.3-2ubuntu5) ...
Setting up python3-protobuf (3.6.1.3-2ubuntu5) ...
Setting up criu (3.16.1-3) ...
Processing triggers for man-db (2.9.1-1) ...
Processing triggers for libc-bin (2.31-0ubuntu9.2) ...
Reading package lists... Done
Building dependency tree
Reading state information... Done
The following NEW packages will be installed:
libyajl2
0 upgraded, 1 newly installed, 0 to remove and 48 not upgraded.
Need to get 20.1 kB of archives.
After this operation, 64.5 kB of additional disk space will be used.
Get:1 http://tw.archive.ubuntu.com/ubuntu focal/main amd64 libyajl2 amd64 2.1.0-3 [20.1 kB]
Fetched 20.1 kB in 0s (87.4 kB/s)
Selecting previously unselected package libyajl2:amd64.
(Reading database ... 71804 files and directories currently installed.)
Preparing to unpack .../libyajl2_2.1.0-3_amd64.deb ...
Unpacking libyajl2:amd64 (2.1.0-3) ...
Setting up libyajl2:amd64 (2.1.0-3) ...
Processing triggers for libc-bin (2.31-0ubuntu9.2) ...
Reading package lists... Done
Building dependency tree
Reading state information... Done
The following additional packages will be installed:
conmon containers-common
Suggested packages:
cri-o-runc | runc containernetworking-plugins
The following NEW packages will be installed:
conmon containers-common cri-o
0 upgraded, 3 newly installed, 0 to remove and 48 not upgraded.
Need to get 19.9 MB of archives.
After this operation, 96.0 MB of additional disk space will be used.
Get:1 https://download.opensuse.org/repositories/devel:/kubic:/libcontainers:/stable/xUbuntu_20.04 conmon 100:2.0.30-2 [32.5 kB]
Get:2 https://download.opensuse.org/repositories/devel:/kubic:/libcontainers:/stable/xUbuntu_20.04 containers-common 100:1-22 [52.4 kB]
7% [2 containers-common 0 B/52.4 kB 0%]
5314 B/s 1h 2min 24s

SuperEdge

Install Superedge

One-click install of edge Kubernetes cluster

- Download the installation package

Choose installation package according to your installation node CPU architecture [amd64, arm64]

```
arch=amd64 version=v0.6.0 && rm -rf edgeadm-linux-* && wget https://superedge-
1253687700.cos.ap-guangzhou.myqcloud.com/$version/$arch/edgeadm-linux-
containerd-$arch-$version.tgz && tar -xzvf edgeadm-linux-* && cd edgeadm-
linux-$arch-$version && ./edgeadm
```

- Install edge Kubernetes master node with containerd runtime

```
./edgeadm init --kubernetes-version=1.18.2 --image-repository
superedge.tencentcloudcr.com/superedge --service-cidr=10.96.0.0/12 --pod-
network-cidr=192.168.0.0/16 --install-pkg-path ./kube-linux-*.tar.gz
--apiserver-cert-extra-sans=<Master Public IP> --apiserver-advertise-address=
<Master Intranet IP> --enable-edge=true --runtime=containerd
```

- Join edge node with containerd runtime

```
./edgeadm join <Master Public/Intranet IP Or Domain>:Port --token xxxx
--discovery-token-ca-cert-hash sha256:xxxxxxxxxx --install-pkg-path <edgeadm
kube-* install package address path> --enable-edge=true --runtime=containerd
```

See the detailed processOne-click install of edge Kubernetes cluster

Other installation, deployment, and administration, see our **Tutorial**.

Install WasmEdge

Use the simple install script to install WasmEdge on your edge node.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
```

Build And install Crun with WasmEdge

The crun project has WasmEdge support baked in. For now, the easiest approach is just to build it yourself from source. First, let's make sure that crun dependencies are installed on your Ubuntu 20.04. For other Linux distributions, please see here.

```
sudo apt update
sudo apt install -y make git gcc build-essential pkgconf libtool \
    libsystemd-dev libprotobuf-c-dev libcap-dev libseccomp-dev libyajl-dev \
    go-md2man libtool autoconf python3 automake
```

Next, configure, build, and install a crun binary with WasmEdge support.

```
git clone https://github.com/containers/crun
cd crun
./autogen.sh
./configure --with-wasmedge
make
sudo make install
```

Reconfigure containerd with crun runtime

Superedge containerd node has default config, we should modify the configuration file(/etc /containerd/config.toml) according to the following steps.

Firstly, we generate `config.toml.diff` diff file and patch it.

```
cat > config.toml.diff << EOF
--- /etc/containerd/config.toml 2022-02-14 15:05:40.061562127 +0800
+++ /etc/containerd/config.toml.crun    2022-02-14 15:03:35.846052853 +0800
@@ -24,17 +24,23 @@
   max_concurrent_downloads = 10

   [plugins.cri.containerd]
-        default_runtime_name = "runc"
-    [plugins.cri.containerd.runtimes.runc]
+        default_runtime_name = "crun"
+    [plugins.cri.containerd.runtimes.crun]
       runtime_type = "io.containerd.runc.v2"
-      pod_annotations = []
+      pod_annotations = ["*.wasm.*", "wasm.*", "module.wasm.image/*",
"*.module.wasm.image", "module.wasm.image/variant.*"]
       container_annotations = []
       privileged_without_host_devices = false
-      [plugins.cri.containerd.runtimes.runc.options]
-        BinaryName = "runc"
+      [plugins.cri.containerd.runtimes.crun.options]
+        BinaryName = "crun"
   # cni
   [plugins.cri.cni]
     bin_dir = "/opt/cni/bin"
     conf_dir = "/etc/cni/net.d"
     conf_template = ""

+  [plugins."io.containerd.runtime.v1.linux"]
+    no_shim = false
+    runtime = "crun"
+    runtime_root = ""
+    shim = "containerd-shim"
+    shim_debug = false
EOF


sudo patch -d/ -p0 < config.toml.diff
sudo systemctl restart containerd
```

Create Wasmedge application in Superedge

We can run a wasm image which has been pushed to dockerhub. If you want to learn how to compile, package, and publish the WebAssembly program as a container image to Docker hub, please refer to here.

```
cat > wasmedge-app.yaml << EOF
apiVersion: v1
kind: Pod
metadata:
  annotations:
    module.wasm.image/variant: compat-smart
  labels:
    run: wasi-demo
  name: wasi-demo
spec:
  containers:
  - args:
    - /wasi_example_main.wasm
    - "50000000"
    image: wasmedge/example-wasi:latest
    imagePullPolicy: IfNotPresent
    name: wasi-demo
  hostNetwork: true
  restartPolicy: Never
EOF

kubectl create -f wasmedge-app.yaml
```

The output will show by executing `kubectl logs wasi-demo` command.

```
Random number: -1643170076
Random bytes: [15, 223, 242, 238, 69, 114, 217, 106, 80, 214, 44, 225, 20, 182,
2, 189, 226, 184, 97, 40, 154, 6, 56, 202, 45, 89, 184, 80, 5, 89, 73, 222,
143, 132, 17, 79, 145, 64, 33, 17, 250, 102, 91, 94, 26, 200, 28, 161, 46, 93,
123, 36, 100, 167, 43, 159, 82, 112, 255, 165, 37, 232, 17, 139, 97, 14, 28,
169, 225, 156, 147, 22, 174, 148, 209, 57, 82, 213, 19, 215, 11, 18, 32, 217,
188, 142, 54, 127, 237, 237, 230, 137, 86, 162, 185, 66, 88, 95, 226, 53, 174,
76, 226, 25, 151, 186, 156, 16, 62, 63, 230, 148, 133, 102, 33, 138, 20, 83,
31, 60, 246, 90, 167, 189, 103, 238, 106, 51]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
```

OpenYurt + containerd + crun

In this article, we will introduce how to run a WasmEdge simple demo app with Containerd over OpenYurt.

Set up an OpenYurt Cluster

Here, we introduce two ways to set up an OpenYurt Cluster. The first one is to set up an OpenYurt Cluster from scratch, use `yurtctl convert` to realize a K8s Cluster conversion to an OpenYurt Cluster. The second one is to use the ability of OpenYurt Experience Center, which is easy to achieve an OpenYurt Cluster.

Prerequisite

	OS/kernel	Private IP/Public IP
Master	Ubuntu 20.04.3 LTS/5.4.0-91-generic	192.168.3.169/120.55.126.18
Node	Ubuntu 20.04.3 LTS/5.4.0-91-generic	192.168.3.170/121.43.113.152

It should be noted that some steps may differ slightly depending on the operating system differences. Please refer to the installation of OpenYurt and crun.

We use `yurtctl convert` to convert a K8s Cluster to OpenYurt Cluster, so we should set up a K8s Cluster. If you use `yurtctl init/join` to set up an OpenYurt Cluster, you can skip this step which introduces the process of installing K8s.

Find the difference between `yurtctl convert/revert` and `yurtctl init/join`, you can refer to the following two articles.

how use `Yurtctl init/join`

Conversion between OpenYurt and Kubernetes: `yurtctl convert/revert`

- Close the swap space of the master and node firstly.

```
sudo swapoff -a
//verify
free -m
```

- Configure the file /etc/hosts of two nodes as the following.

```
192.168.3.169  oy-master
120.55.126.18  oy-master
92.168.3.170   oy-node
121.43.113.152 oy-node
```

- Load the br_netfilter Kernel module and modify the Kernel parameter.

```
//load the module
sudo modprobe br_netfilter
//verify
lsmod | grep br_netfilter
// create k8s.conf
cat <<EOF | sudo tee /etc/sysctl.d/k8s.conf
net.bridge.bridge-nf-call-ip6tables = 1
net.bridge.bridge-nf-call-iptables = 1
EOF
sudo sysctl --system
```

- Setup the value of rp-filter (adjusting the value of two parameters in `/etc/sysctl.d/10-network-security.conf` from 2 to 1 and setting up the value of /proc/sys/net/ipv4/ip_forward to 1)

```
sudo vi /etc/sysctl.d/10-network-security.conf
echo 1 > /proc/sys/net/ipv4/ip_forward
sudo sysctl --system
```

Install containerd and modify the default configure of containerd

Use the following commands to install containerd on your edge node which will run a WasmEdge simple demo.

```
export VERSION="1.5.7"
echo -e "Version: $VERSION"
echo -e "Installing libseccomp2 ..."
sudo apt install -y libseccomp2
echo -e "Installing wget"
sudo apt install -y wget

wget https://github.com/containerd/containerd/releases/download/v${VERSION}
/cri-containerd-cni-${VERSION}-linux-amd64.tar.gz
wget https://github.com/containerd/containerd/releases/download/v${VERSION}
/cri-containerd-cni-${VERSION}-linux-amd64.tar.gz.sha256sum
sha256sum --check cri-containerd-cni-${VERSION}-linux-amd64.tar.gz.sha256sum

sudo tar --no-overwrite-dir -C / -xzf cri-containerd-cni-${VERSION}-linux-
amd64.tar.gz
sudo systemctl daemon-reload
```

As the crun project support WasmEdge as default, we just need to configure the containerd configuration for runc. So we need to modify the runc parameters in /etc/containerd /config.toml to curn and add pod_annotation.

```
sudo mkdir -p /etc/containerd/
sudo bash -c "containerd config default > /etc/containerd/config.toml"
wget https://raw.githubusercontent.com/second-state/wasmedge-containers-
examples/main/containerd/containerd_config.diff
sudo patch -d/ -p0 < containerd_config.diff
```

After that, restart containerd to make the configuration take effect.

```
systemctl start containerd
```

Install WasmEdge

Use the simple install script to install WasmEdge on your edge node.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
```

Build and install crun

We need a crun binary that supports WasmEdge on the edge node. For now, the most straightforward approach is to build it yourself from the source. First, let's ensure that crun dependencies are installed on your Ubuntu 20.04. For other Linux distributions, please see here.

- Dependencies are required for the build

```
sudo apt update
sudo apt install -y make git gcc build-essential pkgconf libtool \
  libsystemd-dev libprotobuf-c-dev libcap-dev libseccomp-dev libyajl-dev \
  go-md2man libtool autoconf python3 automake
```

- Configure, build, and install a crun binary with WasmEdge support.

```
git clone https://github.com/containers/crun
cd crun
./autogen.sh
./configure --with-wasmedge
make
sudo make install
```

From scratch set up an OpenYurt Cluster

In this demo, we will use two machines to set up an OpenYurt Cluster. One simulated cloud node is called Master, the other one simulated edge node is called Node. These two nodes form the simplest OpenYurt Cluster, where OpenYurt components run on.

Set up a K8s Cluster

Kubernetes version 1.18.9

```
$ sudo apt-get update && sudo apt-get install -y ca-certificates curl software-
properties-common apt-transport-https
// add K8s source
$ curl -s https://mirrors.aliyun.com/kubernetes/apt/doc/apt-key.gpg | sudo apt-
key add -
$ sudo tee /etc/apt/sources.list.d/kubernetes.list <<EOF
$ deb https://mirrors.aliyun.com/kubernetes/apt/ kubernetes-xenial main
// install K8s components 1.18.9
$ sudo apt-get update && sudo apt-get install -y kubelet=1.18.9-00
kubeadm=1.18.9-00 kubectl=1.18.9-00
// Initialize the master node
$ sudo kubeadm init --pod-network-cidr 172.16.0.0/16 \
--apiserver-advertise-address=192.168.3.167 \
--image-repository registry.cn-hangzhou.aliyuncs.com/google_containers
// join the work node
$ kubeadm join 192.168.3.167:6443 --token 3zefbt.99e6denc1cxpk9fg \
   --discovery-token-ca-cert-hash
sha256:8077d4e7dd6eee64a999d56866ae4336073ed5ffc3f23281d757276b08b9b195
```

Install yurtctl

Use the following command line to install yurtctl. The yurtctl CLI tool helps install/uninstall OpenYurt and also convert a standard Kubernetes cluster to an OpenYurt cluster.

```
git clone https://github.com/openyurtio/openyurt.git
cd openyurt
make build WHAT=cmd/yurtctl
```

Install OpenYurt components

OpenYurt includes several components. YurtHub is the traffic proxy between the components on the node and Kube-apiserver. The YurtHub on the edge will cache the data returned from the cloud. Yurt controller supplements the upstream node controller to support edge computing requirements. TunnelServer connects with the TunnelAgent daemon running in each edge node via a reverse proxy to establish secure network access between the cloud site control plane and the edge nodes that are connected to the intranet. For more detailed information, you could refer to the OpenYurt docs.

```
yurtctl convert --deploy-yurttunnel --cloud-nodes oy-master --provider kubeadm\
--yurt-controller-manager-image="openyurt/yurt-controller-manager:v0.5.0"\
--yurt-tunnel-agent-image="openyurt/yurt-tunnel-agent:v0.5.0"\
--yurt-tunnel-server-image="openyurt/yurt-tunnel-server:v0.5.0"\
--node-servant-image="openyurt/node-servant:latest"\
--yurthub-image="openyurt/yurthub:v0.5.0"
```

We need to change the `openyurt/node-server-version` to latest here: `--node-servant-image="openyurt/node-servant:latest"`

Actually, OpenYurt components 0.6.0 version is recommended to be installed and proved to be a success to run a WasmEdge demo. How to install OpenYurt:0.6.0, you can see this

Use OpenYurt Experience Center to quickly set up an OpenYurt Cluster

An easier way to set up an OpenYurt Cluster is to use the OpenYurt Experience Center. All you need to do is to sign up for an account for testing, and then you will get an OpenYurt cluster. Next, you could just use `yurtctl join` command line to join an edge node. See more OpenYurt Experience Center details here.

Run a simple WebAssembly app

Next, let's run a WebAssembly program through the OpenYurt cluster as a container in the pod. This section will start off pulling this WebAssembly-based container image from Docker hub. If you want to learn how to compile, package, and publish the WebAssembly program as a container image to Docker hub, please refer to WasmEdge Book.

One thing is to note that because the kubectl run (version 1.18.9) missed annotations parameters, we need to adjust the command line here. If you are using OpenYurt Experience Center with OpenYurt 0.6.0 and Kubernetes 1.20.11 by default, please refer to the Kubernetes sections in the WasmEdge book to run the wasm app.

```
// kubectl 1.18.9
$ sudo kubectl run -it --rm --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest  --overrides='{"kind":"Pod","metadata":{"annotations":
{"module.wasm.image/variant":"compat-smart"}} , "apiVersion":"v1", "spec":
{"hostNetwork": true}}' /wasi_example_main.wasm 50000000

// kubectl 1.20.11
$ sudo kubectl run -it --rm --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest --annotations="module.wasm.image/variant=compat-smart"
--overrides='{"kind":"Pod", "apiVersion":"v1", "spec": {"hostNetwork": true}}'
/wasi_example_main.wasm 50000000
```

The output from the containerized application is printed into the console. It is the same for all Kubernetes versions.

```
Random number: 1123434661
Random bytes: [25, 169, 202, 211, 22, 29, 128, 133, 168, 185, 114, 161, 48,
154, 56, 54, 99, 5, 229, 161, 225, 47, 85, 133, 90, 61, 156, 86, 3, 14, 10, 69,
185, 225, 226, 181, 141, 67, 44, 121, 157, 98, 247, 148, 201, 248, 236, 190,
217, 245, 131, 68, 124, 28, 193, 143, 215, 32, 184, 50, 71, 92, 148, 35, 180,
112, 125, 12, 152, 111, 32, 30, 86, 15, 107, 225, 39, 30, 178, 215, 182, 113,
216, 137, 98, 189, 72, 68, 107, 246, 108, 210, 148, 191, 28, 40, 233, 200, 222,
132, 247, 207, 239, 32, 79, 238, 18, 62, 67, 114, 186, 6, 212, 215, 31, 13, 53,
138, 97, 169, 28, 183, 235, 221, 218, 81, 84, 235]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
pod "wasi-demo" deleted
```

You can now check out the pod status through the Kubernetes command line.

```
crictl ps -a
```

You can see the events from scheduling to running the WebAssembly workload in the log.

```
CONTAINER           IMAGE               CREATED             STATE
NAME                 ATTEMPT             POD ID
0c176ed65599a       0423b8eb71e31       8 seconds ago       Exited
wasi-demo
```

Knative

Knative is a platform-agnostic solution for running serverless deployments.

Quick start

You can refer to Kubernetes + containerd to build a kubernetes cluster. However, as the default runtime is replaced from runc to crun in this document, it is not suitable for existing k8s cluster.

Here we setup crun as a runtimeClass in kubernetes cluster, rather than replace the default runtime. Then deploy Knative serving service and run a WASM serverless service.

Compile crun

Please refer to the document crun

```
# Install dependencies
$ sudo apt update
$ sudo apt install -y make git gcc build-essential pkgconf libtool \
    libsystemd-dev libprotobuf-c-dev libcap-dev libseccomp-dev libyajl-dev \
    go-md2man libtool autoconf python3 automake

# Compile crun
$ git clone https://github.com/containers/crun
$ cd crun
$ ./autogen.sh
$ ./configure --with-wasmedge
$ make
$ sudo make install
```

Install and setup Containerd

To make things easy, we use apt to install containerd. Here is the document for ubuntu Once you have installed the containerd, edit the configuration /etc/containerd/config.toml

```
$ cat /etc/containerd/config.toml

# comment this line to make cri wokrs
# disabled_plugins = ["cri"]

# add the following section to setup crun runtime, make sure the BinaryName
equal to your crun binary path
[plugins]
  [plugins.cri]
    [plugins.cri.containerd]
      [plugins.cri.containerd.runtimes]
...
        [plugins.cri.containerd.runtimes.crun]
           runtime_type = "io.containerd.runc.v2"
           pod_annotations = ["*.wasm.*", "wasm.*", "module.wasm.image/*",
"*.module.wasm.image", "module.wasm.image/variant.*"]
           privileged_without_host_devices = false
           [plugins.cri.containerd.runtimes.crun.options]
             BinaryName = "/usr/local/bin/crun"
...

# restart containerd service
$ sudo systemctl restart containerd

# check if crun works
$ ctr image pull docker.io/wasmedge/example-wasi:latest
$ ctr run --rm --runc-binary crun --runtime io.containerd.runc.v2 --label
module.wasm.image/variant=compat-smart docker.io/wasmedge/example-wasi:latest
wasm-example /wasi_example_main.wasm 50000000
Creating POD ...
Random number: -1678124602
Random bytes: [12, 222, 246, 184, 139, 182, 97, 3, 74, 155, 107, 243, 20, 164,
175, 250, 60, 9, 98, 25, 244, 92, 224, 233, 221, 196, 112, 97, 151, 155, 19,
204, 54, 136, 171, 93, 204, 129, 177, 163, 187, 52, 33, 32, 63, 104, 128, 20,
204, 60, 40, 183, 236, 220, 130, 41, 74, 181, 103, 178, 43, 231, 92, 211, 219,
47, 223, 137, 70, 70, 132, 96, 208, 126, 142, 0, 133, 166, 112, 63, 126, 164,
122, 49, 94, 80, 26, 110, 124, 114, 108, 90, 62, 250, 195, 19, 189, 203, 175,
189, 236, 112, 203, 230, 104, 130, 150, 39, 113, 240, 17, 252, 115, 42, 12,
185, 62, 145, 161, 3, 37, 161, 195, 138, 232, 39, 235, 222]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
```

Creating a cluster with kubeadm

Referring to the tree documents Installing kubeadm, Creating a cluster with kubeadm and Install flannel cni, to create a kubernetes cluster.

```
# install kubeadm
$ sudo apt-get update
$ sudo apt-get install -y apt-transport-https ca-certificates curl
$ sudo curl -fsSLo /usr/share/keyrings/kubernetes-archive-keyring.gpg
https://packages.cloud.google.com/apt/doc/apt-key.gpg
$ echo "deb [signed-by=/usr/share/keyrings/kubernetes-archive-keyring.gpg]
https://apt.kubernetes.io/ kubernetes-xenial main" | sudo tee /etc/apt
/sources.list.d/kubernetes.list
$ sudo apt-get update
$ sudo apt-get install -y kubelet kubeadm kubectl
$ sudo apt-mark hold kubelet kubeadm kubectl

# create kubernetes cluster
$ swapoff -a
$ kubeadm init --pod-network-cidr=10.244.0.0/16 --cri-socket unix:///var
/run/containerd/containerd.sock

# install cni
$ kubectl apply -f https://raw.githubusercontent.com/flannel-io/flannel/master
/Documentation/kube-flannel.yml

# untaint master node
$ kubectl taint nodes --all node-role.kubernetes.io/control-plane-
$ export KUBECONFIG=/etc/kubernetes/admin.conf

# add crun runtimeClass
$ cat > runtime.yaml <<EOF
apiVersion: node.k8s.io/v1
kind: RuntimeClass
metadata:
  name: crun
handler: crun
EOF
$ kubectl apply runtime.yaml

# Verify if configuration works
$ kubectl run -it --rm --restart=Never wasi-demo --image=wasmedge/example-
wasi:latest --annotations="module.wasm.image/variant=compat-smart"
--overrides='{"kind":"Pod", "apiVersion":"v1", "spec": {"hostNetwork": true,
"runtimeClassName": "crun"}}' /wasi_example_main.wasm 50000000
Random number: 1534679888
Random bytes: [88, 170, 82, 181, 231, 47, 31, 34, 195, 243, 134, 247, 211, 145,
28, 30, 162, 127, 234, 208, 213, 192, 205, 141, 83, 161, 121, 206, 214, 163,
196, 141, 158, 96, 137, 151, 49, 172, 88, 234, 195, 137, 44, 152, 7, 130, 41,
33, 85, 144, 197, 25, 104, 236, 201, 91, 210, 17, 59, 248, 80, 164, 19, 10, 46,
116, 182, 111, 112, 239, 140, 16, 6, 249, 89, 176, 55, 6, 41, 62, 236, 132, 72,
70, 170, 7, 248, 176, 209, 218, 214, 160, 110, 93, 232, 175, 124, 199, 33, 144,
2, 147, 219, 236, 255, 95, 47, 15, 95, 192, 239, 63, 157, 103, 250, 200, 85,
237, 44, 119, 98, 211, 163, 26, 157, 248, 24, 0]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
```

```
The args are as follows.
/wasi_example_main.wasm
50000000
File content is This is in a file
pod "wasi-demo" deleted
```

Setting up Knative Serving

Referring to Installing Knative Serving using YAML files, install the knative serving service.

```
# install the Knative Serving component
$ kubectl apply -f https://github.com/knative/serving/releases/download
/knative-v1.7.2/serving-crds.yaml
$ kubectl apply -f https://github.com/knative/serving/releases/download
/knative-v1.7.2/serving-core.yaml

# install a networking layer
$ kubectl apply -f https://github.com/knative/net-kourier/releases/download
/knative-v1.7.0/kourier.yaml
$ kubectl patch configmap/config-network \
  --namespace knative-serving \
  --type merge \
  --patch '{"data":{"ingress-class":"kourier.ingress.networking.knative.dev"}}'
$ kubectl --namespace kourier-system get service kourier

# verify the installation
$ kubectl get pods -n knative-serving

# open runtimeClass feature gate in Knative
$ kubectl patch configmap/config-features -n knative-serving --type merge
--patch '{"data":{"kubernetes.podspec-runtimeclassname":"enabled"}}'
```

WASM cases in Knative Serving

Now we can try to run a WASM serverless service.

```
# apply the serverless service configuration
# we need setup annotations, runtimeClassName and ports.
$ cat > http-wasm-serverless.yaml <<EOF
apiVersion: serving.knative.dev/v1
kind: Service
metadata:
  name: http-wasm
  namespace: default
spec:
  template:
    metadata:
      annotations:
        module.wasm.image/variant: compat-smart
    spec:
      runtimeClassName: crun
      timeoutSeconds: 1
      containers:
      - name: http-server
        image: docker.io/wasmedge/example-wasi-http:latest
        ports:
        - containerPort: 1234
          protocol: TCP
        livenessProbe:
          tcpSocket:
            port: 1234
EOF

$ kubectl apply http-wasm-serverless.yaml

# wait for a while, check if the serverless service available
$ kubectl get ksvc http-wasm
NAME          URL                                          LATESTCREATED
LATESTREADY         READY   REASON
http-wasm     http://http-wasm.default.knative.example.com     http-wasm-00001
http-wasm-00001     True

# try to call the service
# As we do not setup DNS, so we can only call the service via Kourier, Knative
Serving ingress port.
# get Kourier port which is 31997 in following example
$ kubectl --namespace kourier-system get service kourier
NAME      TYPE           CLUSTER-IP      EXTERNAL-IP       PORT(S)
AGE
kourier   LoadBalancer   10.105.58.134
80:31997/TCP,443:31019/TCP   53d
$ curl -H "Host: http-wasm.default.knative.example.com" -d "name=WasmEdge" -X
POST http://localhost:31997

# check the new start pod
$ kubectl get pods
NAME                                          READY   STATUS    RESTARTS   AGE
http-wasm-00001-deployment-748bdc7cf-96l4r     2/2     Running   0          19s
```

Running WasmEdge apps with the Docker CLI

The Docker CLI is a very popular developer tool. However, it is not easy to replace Docker's underlying OCI runtime (`runc`) with the WasmEdge-enabled `crun` . In this section, we will discuss two ways to run WasmEdge applications in Docker.

- Wrap WasmEdge in a slim Linux container
- Use containerd shim

Use the slim Linux container

An easy way to run WebAssembly applications in the Docker ecosystem is to simply embed the WebAssembly bytecode file in a Linux container image. Specifically, we trim down the Linux OS inside the container to the point where it is just enough to support the `wasmedge` runtime. This approach has many advantages.

- It works seamlessly with any tool in the Docker or container ecosystem since the WebAssembly application is wrapped in a regular container.
- The memory footprint of the entire image of Linux OS and WasmEdge can be reduced to as low as 4MB.
- The attack surface of the slimmed Linux OS is dramatically reduced from a regular Linux OS.
- The overall application security is managed by the WebAssembly sandbox. The risk for software supply chain attack is greatly reduced since the WebAssembly sandbox only has access to explicitly declared capabilities.
- The above three advantages are amplified if the application is complex. For example, a WasmEdge AI inference application would NOT require a Python install. A WasmEdge node.js application would NOT require a Node.js and v8 install.

However, this approach still requires starting up a Linux container. The containerized Linux OS, however slim, still takes 80% of the total image size. There is still a lot of room for optimization. The performance and security of this approach would not be as great as running WebAssembly applications directly in crun or in a containerd shim.

Run a simple WebAssembly app

We can run a simple WebAssembly program using Docker. An slim Linux image with WasmEdge installed is only 4MB as opposed to 30MB for a general Linux image for native compiled applications. The Linux + WasmEdge image is similar to a unikernel OS image. It minimizes the footprint, performance overhead, and potential attack surface for WebAssembly applications.

The sample application is here. First, create a `Dockerfile` based on our release image. Include the wasm application file in the new image, and run the `wasmedge` command at start up.

```
FROM wasmedge/slim-runtime:0.10.1
ADD wasi_example_main.wasm /
CMD ["wasmedge", "--dir", ".:/", "/wasi_example_main.wasm"]
```

Run the WebAssembly application in Docker CLI as follows.

```
$ docker build -t wasmedge/myapp -f Dockerfile ./
... ...
Successfully tagged wasmedge/myapp:latest

$ docker run --rm wasmedge/myapp
Random number: -807910034
Random bytes: [113, 123, 78, 85, 63, 124, 68, 66, 151, 71, 91, 249, 242, 160,
164, 133, 35, 209, 106, 143, 202, 87, 147, 87, 236, 49, 238, 165, 125, 175,
172, 114, 136, 205, 200, 176, 30, 122, 149, 21, 39, 58, 221, 102, 165, 179,
124, 13, 60, 166, 188, 127, 83, 95, 145, 0, 25, 209, 226, 190, 10, 184, 139,
191, 243, 149, 197, 85, 186, 160, 162, 156, 181, 74, 255, 99, 203, 161, 108,
153, 90, 155, 247, 183, 106, 79, 48, 255, 172, 17, 193, 36, 245, 195, 170, 202,
119, 238, 104, 254, 214, 227, 149, 20, 8, 147, 105, 227, 114, 146, 246, 153,
251, 139, 130, 1, 219, 56, 228, 154, 146, 203, 205, 56, 27, 115, 79, 254]
Printed from wasi: This is from a main function
This is from a main function
The env vars are as follows.
The args are as follows.
wasi_example_main.wasm
File content is This is in a file
```

Run a HTTP server app

We can run a simple WebAssembly-based HTTP micro-service using the Docker CLI. The sample application is here. Follow instructions to compile and build the `http_server.wasm` file.

Create a `Dockerfile` based on our release image. Include the `http_server.wasm` application file in the new image, and run the `wasmedge` command at start up.

```
FROM wasmedge/slim-runtime:0.10.1
ADD http_server.wasm /
CMD ["wasmedge", "--dir", ".:/", "/http_server.wasm"]
```

Run the WebAssembly server application in Docker CLI as follows. Notice that we map the server port from the container to the host.

```
$ docker build -t wasmedge/myapp -f Dockerfile ./
... ...
Successfully tagged wasmedge/myapp:latest

$ docker run --rm -p 1234:1234 wasmedge/myapp
new connection at 1234
```

You can now access the server from another terminal.

```
$ curl -X POST http://127.0.0.1:1234 -d "name=WasmEdge"
echo: name=WasmEdge
```

Run a lightweight Node.js server

With WasmEdge QuickJS support for the Node.js API, we can run a lightweight and secure node.js server from Docker CLI. The slim Linux + WasmEdge + Node.js support image size is less than 15MB as opposed to over 350MB for a standard Node.js image. You will need to do the following.

- Download the WasmEdge QuickJS runtime here. You will have the `wasmedge_quickjs.wasm` file.
- Download the modules directory from the WasmEdge QuickJS repo.
- Create a JavaScript file for the server. Below is an example `http_echo.js` file you can use.

```
import { createServer, request, fetch } from 'http';

createServer((req, resp) => {
  req.on('data', (body) => {
    resp.write('echo:')
    resp.end(body)
  })
}).listen(8001, () => {
  print('listen 8001 ...\n');
})
```

Add those files to the Docker image and run the JavaScript file at startup.

```
FROM wasmedge/slim-runtime:0.10.1
ADD wasmedge_quickjs.wasm /
ADD http_echo.js /
ADD modules /modules
CMD ["wasmedge", "--dir", ".:/", "/wasmedge_quickjs.wasm", "http_echo.js"]
```

Start the server from Docker CLI.

```
$ docker build -t wasmedge/myapp -f Dockerfile ./
... ...
Successfully tagged wasmedge/myapp:latest

$ docker run --rm -p 8001:8001 wasmedge/myapp
listen 8001 ...
```

You can now access the server from another terminal.

```
$ curl -X POST http://127.0.0.1:8001 -d "WasmEdge"
echo:WasmEdge
```

Run a lightweight Tensorflow inference application

A unique and powerful feature of the WasmEdge runtime is its support for AI frameworks. In this example, we will show you how to run an image recognition service from Docker CLI. The sample application is here. First, create a `Dockerfile` based on our `tensorflow` release image. Include the wasm application file in the new image, and run the `wasmedge-tensorflow-lite` command at start up.

The Dockerfile is as follows. The whole package is 115MB. It is less than 1/4 of a typically Linux + Python + Tensorflow setup.

```
FROM wasmedge/slim-tf:0.10.1
ADD wasmedge_hyper_server_tflite.wasm /
CMD ["wasmedge-tensorflow-lite", "--dir", ".:/",
"/wasmedge_hyper_server_tflite.wasm"]
```

Start the server from Docker CLI.

```
$ docker build -t wasmedge/myapp -f Dockerfile ./
... ...
Successfully tagged wasmedge/myapp:latest

$ docker run --rm -p 3000:3000 wasmedge/myapp
listen 3000 ...
```

You can now access the server from another terminal.

```
$ curl http://localhost:3000/classify -X POST --data-binary "@grace_hopper.jpg"
military uniform is detected with 206/255 confidence
```

Use the containerd shim

As we discussed, wrapping WebAssembly inside a Docker Linux container results in performance and security penalties. However, we cannot easily replace the OCI runtime (`runc`) in the Docker toolchain as well. In this chapter, we will discuss another approach to start and run WebAssembly bytecode applications directly from the Docker CLI.

Coming soon

App Frameworks and Platforms

WasmEdge applications can be plugged into existing application frameworks or platforms. WasmEdge provides a safe and efficient extension mechanism for those frameworks.

In this chapter, we will introduce several such frameworks and platforms.

- Service mesh and frameworks support WasmEdge to run as containers for microservices. We will cover distributed application framework Dapr, service mesh MOSN, and event mesh Apache EventMesh.
- Application frameworks support WasmEdge as an embedded function or plug-in runtime. We will cover streaming data framework YoMo and Go function schedulder / framework Reactr.
- Serverless platforms allows WasmEdge programs to run as serverless functions in their infrastructure. We will cover AWS Lambda, Tencent Serverless Cloud Functions, Vercel Serverless Functions, Netlify Functions, and Second State Functions.

Service mesh and distributed runtimes

WasmEdge could be a lightweight runtime for sidecar microservices and the API proxy as the Docker alternative.

Sidecar microservices

For sidecar frameworks that support multiple application runtimes, we could simply embed WasmEdge applications into the sidecar through its C, Go, Rust, or Node.js SDKs. In addition, WasmEdge applications could be managed directly by container tools and act as sidecar microservices.

- Dapr showcases how to run WasmEdge microservices as Dapr sidecars.
- Apache EventMesh showcases how to run WasmEdge microservices as Apache EventMesh sidecars

Extension for the API proxy

The API proxy is another crucial component in the service mesh. It manages and directs API requests to sidecars in a manner that keeps the system scalable. Developers need to script those proxies to route traffic according to changing infrastructure and ops requirements. Seeing widespread demand for using WebAssembly instead of the LUA scripting language, the community came together and created the proxy-wasm spec. It defines the host interface that WebAssembly runtimes must support to plug into the proxy. WasmEdge supports proxy-wasm now.

- MOSN shows how to use WasmEdge as extensions for MOSN.
- wasm-nginx-module shows how to use WasmEdge run Go/Rust code in OpenResty.

If you have some great ideas on WasmEdge and microservices, feel free to create an issue or PR on the WasmEdge GitHub repo!

Dapr

In this article, I will demonstrate how to use WasmEdge as a sidecar application runtime for Dapr. There are two ways to do this:

- **Standalone WasmEdge** is the **recommended approach** is to write a microservice using Rust or JavaScript, and run it in WasmEdge. The WasmEdge application serves web requests and communicates with the sidecar via sockets using the Dapr API. In this case, we can run WasmEdge as a managed container in k8s.
- Alternatively, Embedded WasmEdge is to create a simple microservice in Rust or Go to listen for web requests and communicate with the Dapr sidecar. It passes the request data to a WasmEdge runtime for processing. The business logic of the microservice is a WebAssembly function created and deployed by an application developer.

> While the first approach (running the entire microservice in WasmEdge) is much preferred, we are still working on a fully fledged Dapr SDKs for WasmEdge. You can track their progress in GitHub issues -- Rust and JavaScript.

Quick start

First you need to install Dapr and WasmEdge. Go and Rust are optional for the standalone WasmEdge approach. However, they are required for the demo app since it showcases both standalone and embedded WasmEdge approaches.

Fork or clone the demo application from Github. You can use this repo as your own application template.

```
git clone https://github.com/second-state/dapr-wasm
```

The demo has 4 Dapr sidecar applications. The web-port project provides a public web service for a static HTML page. This is the application's UI. From the static HTML page, the user can select a microservice to turn an input image into grayscale. All 3 microsoervices below perform the same function. They are just implemented using different approaches.

- **Standalone WasmEdge approach:** The image-api-wasi-socket-rs project provides a standalone WasmEdge sidecar microservice that takes the input image and returns the grayscale image. The microservice is written in Rust and compiled into WebAssembly bytecode to run in WasmEdge.

- Embedded WasmEdge approach #1: The image-api-rs project provides a simple Rust-based microservice. It embeds a WasmEdge function to turn an input image into a grayscale image.
- Embedded WasmEdge approach #2: The image-api-go project provides a simple Go-based microservice. It embeds a WasmEdge function to turn an input image into a grayscale image.

You can follow the instructions in the README to start the sidecar services. Here are commands to build the WebAssembly functions and start the sidecar services. The first set of commands deploy the static web page service and the standalone WasmEdge service written in Rust. It forms a complete application to turn an input image into grayscale.

```
# Build and start the static HTML web page service for the UI and router for
sending the uploaded image to the grayscale microservice
cd web-port
go build
./run_web.sh
cd ../

# Build the standalone image grayscale web service for WasmEdge
cd image-api-wasi-socket-rs
cargo build  --target wasm32-wasi
cd ../

# Run the microservice as a Dapr sidecar app
cd image-api-wasi-socket-rs
./run_api_wasi_socket_rs.sh
cd ../
```

The second set of commands create the alternative microservices for the embedded WasmEdge function.

```
# Build the grayscale WebAssembly functions, and deploy them to the sidecar
projects
cd functions/grayscale
./build.sh
cd ../../

# Build and start the Rust-based microservice for embedding the grayscale
WasmEdge function
cd image-api-rs
cargo build --release
./run_api_rs.sh
cd ../

# Build and start the Go-based microservice for embedding the grayscale
WasmEdge function
cd image-api-go
go build
./run_api_go.sh
cd ../
```

Finally, you should be able to see the web UI in your browser.

Recommended: The standalone WasmEdge microservice in Rust

The standalone WasmEdge microservice starts a non-blocking TCP server inside WasmEdge. The TCP server passes incoming requests to `handle_client()`, which passes HTTP requests to `handle_http()`, which calls `grayscale()` to process the image data in the request.

```
fn main() -> std::io::Result<()> {
    let port = std::env::var("PORT").unwrap_or(9005.to_string());
    println!("new connection at {}", port);
    let listener = TcpListener::bind(format!("127.0.0.1:{}", port))?;
    loop {
        let _ = handle_client(listener.accept()?.0);
    }
}

fn handle_client(mut stream: TcpStream) -> std::io::Result<()> {
  ... ...
}

fn handle_http(req: Request<Vec<u8>>) -> bytecodec::Result<Response<String>> {
  ... ...
}

fn grayscale(image: &[u8]) -> Vec<u8> {
    let detected = image::guess_format(&image);
    let mut buf = vec![];
    if detected.is_err() {
        return buf;
    }

    let image_format_detected = detected.unwrap();
    let img = image::load_from_memory(&image).unwrap();
    let filtered = img.grayscale();
    match image_format_detected {
        ImageFormat::Gif => {
            filtered.write_to(&mut buf, ImageOutputFormat::Gif).unwrap();
        }
        _ => {
            filtered.write_to(&mut buf, ImageOutputFormat::Png).unwrap();
        }
    };
    return buf;
}
```

Work in progress: It will soon interact with the Dapr sidecar through the WasmEdge Dapr SDK in Rust.

Now, you can build the microservice. It is a simple matter of compiling from Rust to WebAssembly.

```
cd image-api-wasi-socket-rs
cargo build  --target wasm32-wasi
```

Deploy the WasmEdge microservice in Dapr as follows.

```
dapr run --app-id image-api-wasi-socket-rs \
         --app-protocol http \
         --app-port 9005 \
         --dapr-http-port 3503 \
         --components-path ../config \
         --log-level debug \
         wasmedge ./target/wasm32-wasi/debug/image-api-wasi-socket-rs.wasm
```

Alternative: The embedded WasmEdge microservices

The embedded WasmEdge approach requires us to create a WebAssembly function for the business logic (image processing) first, and then embed it into simple Dapr microservices.

Rust function for image processing

The Rust function is simple. It uses the wasmedge_bindgen macro to makes it easy to call the function from a Go or Rust host embedding the WebAssembly function. It takes and returns base64 encoded image data for the web.

```
#[wasmedge_bindgen]
pub fn grayscale(image_data: String) -> String {
    let image_bytes = image_data.split(",").map(|x| x.parse::
<u8>().unwrap()).collect::<Vec<u8>>();
    return grayscale::grayscale_internal(&image_bytes);
}
```

The Rust function that actually performs the task is as follows.

```
pub fn grayscale_internal(image_data: &[u8]) -> String {
    let image_format_detected: ImageFormat =
image::guess_format(&image_data).unwrap();
    let img = image::load_from_memory(&image_data).unwrap();
    let filtered = img.grayscale();
    let mut buf = vec![];
    match image_format_detected {
        ImageFormat::Gif => {
            filtered.write_to(&mut buf, ImageOutputFormat::Gif).unwrap();
        }
        _ => {
            filtered.write_to(&mut buf, ImageOutputFormat::Png).unwrap();
        }
    };
    let mut base64_encoded = String::new();
    base64::encode_config_buf(&buf, base64::STANDARD, &mut base64_encoded);
    return base64_encoded.to_string();
}
```

The Go host wrapper for microservice

The Go-based microservice embeds the above imaging processing function in WasmEdge. The microservice itself is a web server and utilizes the Dapr Go SDK.

```
func main() {
  s := daprd.NewService(":9003")

  if err := s.AddServiceInvocationHandler("/api/image", imageHandlerWASI); err
!= nil {
    log.Fatalf("error adding invocation handler: %v", err)
  }

  if err := s.Start(); err != nil && err != http.ErrServerClosed {
    log.Fatalf("error listenning: %v", err)
  }
}
```

The `imageHandlerWASI()` function starts a WasmEdge instance and calls the image processing (grayscale) function in it via wasmedge_bindgen.

Build and deploy the Go microservice to Dapr as follows.

```
cd image-api-go
go build
dapr run --app-id image-api-go \
         --app-protocol http \
         --app-port 9003 \
         --dapr-http-port 3501 \
         --log-level debug \
         --components-path ../config \
         ./image-api-go
```

The Rust host wrapper for microservice

The Rust-based microservice embeds the above imaging processing function in WasmEdge. The microservice itself is a Tokio and Warp based web server.

```
#[tokio::main]
pub async fn run_server(port: u16) {
    pretty_env_logger::init();
    let home = warp::get().map(warp::reply);

    let image = warp::post()
        .and(warp::path("api"))
        .and(warp::path("image"))
        .and(warp::body::bytes())
        .map(|bytes: bytes::Bytes| {
            let v: Vec<u8> = bytes.iter().map(|&x| x).collect();
            let res = image_process_wasmedge_sys(&v);
            let _encoded = base64::encode(&res);
            Response::builder()
                .header("content-type", "image/png")
                .body(res)
        });

    let routes = home.or(image);
    let routes = routes.with(warp::cors().allow_any_origin());

    let log = warp::log("dapr_wasm");
    let routes = routes.with(log);
    warp::serve(routes).run((Ipv4Addr::UNSPECIFIED, port)).await
}
```

The `image_process_wasmedge_sys()` function starts a WasmEdge instance and calls the image processing (grayscale) function in it via wasmedge_bindgen.

Build and deploy the Rust microservice to Dapr as follows.

```
cd image-api-rs
cargo build --release
dapr stop image-api-rs

# Change this to your own path for WasmEdge
export LD_LIBRARY_PATH=/home/coder/.wasmedge/lib64/

dapr run --app-id image-api-rs \
         --app-protocol http \
         --app-port 9004 \
         --dapr-http-port 3502 \
         --components-path ../config \
         --log-level debug \
         ./target/release/image-api-rs
```

That's it! Let us know your cool Dapr microservices in WebAssembly!

MOSN

Coming soon.

wasm-nginx-module

The wasm-nginx-module is an Nginx module built upon OpenResty. By implementing the Proxy Wasm ABI, any Wasm program written with Proxy Wasm SDK can be run inside it. Hence, you can write Go or Rust code, compile them into Wasm, then load & execute it in Nginx.

> The wasm-nginx-module is already used in APISIX and allows it to run Wasm plugin like Lua plugin.

In order to follow along the tutorials in this chapter, you will need to first build your Nginx with wasm-nginx-module included and WasmEdge shared library installed in the right path.

Once you have Nginx installed, let me show you a real world example - using Wasm to inject custom responses in Nginx.

Inject Custom Response via Go in Nginx, Step by Step

Go Step 1: Write code based on proxy-wasm-go-sdk

The implementation code (including `go.mod` and others) can be found at here.

It should be explained that although the proxy-wasm-go-sdk project carries the Go name, it actually uses tinygo instead of native Go, which has some problems supporting WASI (which you can think of as a non-browser WASM runtime interface), see here for more details.

We also provide a Rust version (including Cargo.toml and others) there.

Go Step 2: Build the corresponding Wasm file

```
tinygo build -o ./fault-injection/main.go.wasm -scheduler=none -target=wasi
./fault-injection/main.go
```

Go Step 3: Load and execute the Wasm file

Then, start Nginx with the configuration below:

```
worker_processes  1;

error_log  /tmp/error.log warn;

events {
    worker_connections  10240;
}

http {
    wasm_vm wasmedge;
    init_by_lua_block {
        local wasm = require("resty.proxy-wasm")
        package.loaded.plugin = assert(wasm.load("fault_injection",
            "/path/to/fault-injection/main.go.wasm"))
    }
    server {
        listen 1980;
        location / {
            content_by_lua_block {
                local wasm = require("resty.proxy-wasm")
                local ctx = assert(wasm.on_configure(package.loaded.plugin,
                    '{"http_status": 403, "body": "powered by wasm-nginx-
module"}'))
                assert(wasm.on_http_request_headers(ctx))
            }
        }
    }
}
```

This configuration loads the Wasm file we just built, executes it with the configuration `{"http_status": 403, "body": "powered by wasm-nginx-module"}`.

Go Step 4: verify the result

After Nginx starts, we can use `curl http://127.0.0.1:1980/ -i` to verify the execution result of the Wasm.

It is expected to see the output:

```
HTTP/1.1 403 Forbidden
...

powered by wasm-nginx-module
```

Inject Custom Response via Rust in Nginx, Step by Step

Rust Step 1: Write code based on proxy-wasm-rust-sdk

We also provide a Rust version (including Cargo.toml and others) here.

Rust Step 2: Build the corresponding Wasm file

```
cargo build --target=wasm32-wasi
```

Rust Step 3: Load and execute the Wasm file

Then, start Nginx with the configuration below:

```
worker_processes  1;

error_log  /tmp/error.log warn;

events {
    worker_connections  10240;
}

http {
    wasm_vm wasmedge;
    init_by_lua_block {
        local wasm = require("resty.proxy-wasm")
        package.loaded.plugin = assert(wasm.load("fault_injection",
            "/path/to/fault-injection/target/wasm32-wasi/debug
/fault_injection.wasm"))
    }
    server {
        listen 1980;
        location / {
            content_by_lua_block {
                local wasm = require("resty.proxy-wasm")
                local ctx = assert(wasm.on_configure(package.loaded.plugin,
                    '{"http_status": 403, "body": "powered by wasm-nginx-
module"}'))
                assert(wasm.on_http_request_headers(ctx))
            }
        }
    }
}
```

This configuration loads the Wasm file we just built, executes it with the configuration `{"http_status": 403, "body": "powered by wasm-nginx-module"}`.

Rust Step 4: verify the result

After Nginx starts, we can use `curl http://127.0.0.1:1980/ -i` to verify the execution result of the Wasm.

It is expected to see the output:

```
HTTP/1.1 403 Forbidden
...

powered by wasm-nginx-module
```

Apache EventMesh

Coming soon, or you can help out

App frameworks

WasmEdge provides a safe and efficient extension mechanism for applications. Of course, application developers can always use WasmEdge SDKs to embed WebAssembly functions. But some applications and frameworks opt to build their own extension / embedding APIs on top of the WasmEdge SDK, which supports more ergonomic integration with the application's native use cases and programming models.

- YoMo is a data stream processing framework. WasmEdge functions can be plugged into the framework to process data in-stream.
- Reactr is a Go language framework for managing and extending WebAssembly functions for the purpose of easy embedding into other Go applications.

YoMo

YoMo is a programming framework enabling developers to build a distributed cloud system (Geo-Distributed Cloud System). YoMo's communication layer is made on top of the QUIC protocol, which brings high-speed data transmission. In addition, it has a built-in Streaming Serverless "streaming function", which significantly improves the development experience of distributed cloud systems. The distributed cloud system built by YoMo provides an ultra-high-speed communication mechanism between near-field computing power and terminals. It has a wide range of use cases in Metaverse, VR/AR, IoT, etc.

> YoMo is written in the Go language. For streaming Serverless, Golang plugins and shared libraries are used to load users' code dynamically, which also have certain limitations for developers. Coupled with Serverless architecture's rigid demand for isolation, this makes WebAssembly an excellent choice for running user-defined functions.

For example, in the process of real-time AI inference in AR/VR devices or smart factories, the camera sends real-time unstructured data to the computing node in the near-field MEC (multi-access edge computing) device through YoMo. YoMo sends the AI computing result to the end device in real-time when the AI inference is completed. Thus, the hosted AI inference function will be automatically executed.

However, a challenge for YoMo is to incorporate and manage handler functions written by multiple outside developers in an edge computing node. It requires runtime isolation for those functions without sacrificing performance. Traditional software container solutions, such as Docker, are not up to the task. They are too heavy and slow to handle real-time tasks.

WebAssembly provides a lightweight and high-performance software container. It is ideally suited as a runtime for YoMo’s data processing handler functions.

In this article, we will show you how to create a Rust function for Tensorflow-based image classification, compile it into WebAssembly, and then use YoMo to run it as a stream data handler. We use WasmEdge as our WebAssembly runtime because it offers the highest performance and flexibility compared with other WebAssembly runtimes. It is the only WebAssembly VM that reliably supports Tensorflow. YoMo manages WasmEdge VM instances and the contained WebAssembly bytecode apps through WasmEdge’s Golang API.

> Source code: https://github.com/yomorun/yomo-wasmedge-tensorflow

Checkout the WasmEdge image classification function in action in YoMo

Prerequisite

Obviously, you will need to have Golang installed, but I will assume you already did.

> Golang version should be newer than 1.15 for our example to work.

You also need to install the YoMo CLI application. It orchestrates and coordinates data streaming and handler function invocations.

```
$ go install github.com/yomorun/cli/yomo@latest
$ yomo version
YoMo CLI version: v0.1.3
```

Next, please install the WasmEdge and its Tensorflow shared libraries. WasmEdge is a leading WebAssembly runtime hosted by the CNCF. We will use it to embed and run WebAssembly programs from YoMo.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
```

Finally, since our demo WebAssembly functions are written in Rust, you will also need a Rust compiler.

For the rest of the demo, fork and clone the source code repository.

```
git clone https://github.com/yomorun/yomo-wasmedge-tensorflow.git
```

The image classification function

The image classification function to process the YoMo image stream is written in Rust. It utilizes the WasmEdge Tensorflow API to process an input image.

```
#[wasmedge_bindgen]
pub fn infer(image_data: Vec<u8>) -> Result<Vec<u8>, String> {
  let start = Instant::now();

  // Load the TFLite model and its meta data (the text label for each
recognized object number)
  let model_data: &[u8] = include_bytes!("lite-
model_aiy_vision_classifier_food_V1_1.tflite");
  let labels = include_str!("aiy_food_V1_labelmap.txt");

  // Pre-process the image to a format that can be used by this model
  let flat_img =
wasmedge_tensorflow_interface::load_jpg_image_to_rgb8(&image_data[..], 192,
192);
  println!("RUST: Loaded image in ... {:?}", start.elapsed());

  // Run the TFLite model using the WasmEdge Tensorflow API
  let mut session = wasmedge_tensorflow_interface::Session::new(&model_data,
wasmedge_tensorflow_interface::ModelType::TensorFlowLite);
  session.add_input("input", &flat_img, &[1, 192, 192, 3])
         .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions/Softmax");

  // Find the object index in res_vec that has the greatest probability
  // Translate the probability into a confidence level
  // Translate the object index into a label from the model meta data food_name
  let mut i = 0;
  let mut max_index: i32 = -1;
  let mut max_value: u8 = 0;
  while i < res_vec.len() {
    let cur = res_vec[i];
    if cur > max_value {
      max_value = cur;
      max_index = i as i32;
    }
    i += 1;
  }
  println!("RUST: index {}, prob {}", max_index, max_value);

  let confidence: String;
  if max_value > 200 {
    confidence = "is very likely".to_string();
  } else if max_value > 125 {
    confidence = "is likely".to_string();
  } else {
    confidence = "could be".to_string();
  }

  let ret_str: String;
  if max_value > 50 {
    let mut label_lines = labels.lines();
    for _i in 0..max_index {
```

```
      label_lines.next();
    }
    let food_name = label_lines.next().unwrap().to_string();
    ret_str = format!(
      "It {} a <a href='https://www.google.com/search?q={}'>{}</a> in the
picture",
      confidence, food_name, food_name
    );
  } else {
    ret_str = "It does not appears to be a food item in the
picture.".to_string();
  }

  println!(
    "RUST: Finished post-processing in ... {:?}",
    start.elapsed()
  );
  return Ok(ret_str.as_bytes().to_vec());
}
```

You should add `wasm32-wasi` target to rust to compile this function into WebAssembly bytecode.

```
rustup target add wasm32-wasi

cd flow/rust_mobilenet_food
cargo build --target wasm32-wasi --release
# The output WASM will be target/wasm32-wasi/release
/rust_mobilenet_food_lib.wasm

# Copy the wasm bytecode file to the flow/ directory
cp target/wasm32-wasi/release/rust_mobilenet_food_lib.wasm ../
```

To release the best performance of WasmEdge, you should enable the AOT mode by compiling the `.wasm` file to the `.so`.

```
wasmedgec rust_mobilenet_food_lib.wasm rust_mobilenet_food_lib.so
```

Integration with YoMo

On the YoMo side, we use the WasmEdge Golang API to start and run WasmEdge VM for the image classification function. The app.go file in the source code project is as follows.

```
package main

import (
  "crypto/sha1"
  "fmt"
  "log"
  "os"
  "sync/atomic"

  "github.com/second-state/WasmEdge-go/wasmedge"
  bindgen "github.com/second-state/wasmedge-bindgen/host/go"
  "github.com/yomorun/yomo"
)

var (
  counter uint64
)

const ImageDataKey = 0x10

func main() {
  // Connect to Zipper service
  sfn := yomo.NewStreamFunction("image-recognition",
yomo.WithZipperAddr("localhost:9900"))
  defer sfn.Close()

  // set only monitoring data
  sfn.SetObserveDataID(ImageDataKey)

  // set handler
  sfn.SetHandler(Handler)

  // start
  err := sfn.Connect()
  if err != nil {
    log.Print("❌ Connect to zipper failure: ", err)
    os.Exit(1)
  }

  select {}
}

// Handler process the data in the stream
func Handler(img []byte) (byte, []byte) {
  // Initialize WasmEdge's VM
  vmConf, vm := initVM()
  bg := bindgen.Instantiate(vm)
  defer bg.Release()
  defer vm.Release()
  defer vmConf.Release()

  // recognize the image
```

```
  res, err := bg.Execute("infer", img)
  if err == nil {
    fmt.Println("GO: Run bindgen -- infer:", string(res))
  } else {
    fmt.Println("GO: Run bindgen -- infer FAILED")
  }

  // print logs
  hash := genSha1(img)
  log.Printf("✅ received image-%d hash %v, img_size=%d \n",
atomic.AddUint64(&counter, 1), hash, len(img))

  return 0x11, nil
}

// genSha1 generate the hash value of the image
func genSha1(buf []byte) string {
  h := sha1.New()
  h.Write(buf)
  return fmt.Sprintf("%x", h.Sum(nil))
}

// initVM initialize WasmEdge's VM
func initVM() (*wasmedge.Configure, *wasmedge.VM) {
  wasmedge.SetLogErrorLevel()
  // Set Tensorflow not to print debug info
  os.Setenv("TF_CPP_MIN_LOG_LEVEL", "3")
  os.Setenv("TF_CPP_MIN_VLOG_LEVEL", "3")

  // Create configure
  vmConf := wasmedge.NewConfigure(wasmedge.WASI)

  // Create VM with configure
  vm := wasmedge.NewVMWithConfig(vmConf)

  // Init WASI
  var wasi = vm.GetImportObject(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping directories
  )

  // Register WasmEdge-tensorflow and WasmEdge-image
  var tfobj = wasmedge.NewTensorflowImportObject()
  var tfliteobj = wasmedge.NewTensorflowLiteImportObject()
  vm.RegisterImport(tfobj)
  vm.RegisterImport(tfliteobj)
  var imgobj = wasmedge.NewImageImportObject()
  vm.RegisterImport(imgobj)

  // Instantiate wasm
  vm.LoadWasmFile("rust_mobilenet_food_lib.so")
```

```
  vm.Validate()

  return vmConf, vm
}
```

In action

Finally, we can start YoMo and see the entire data processing pipeline in action. Start the YoMo CLI application from the project folder. The yaml file defines port YoMo should listen on and the workflow handler to trigger for incoming data. Note that the flow name `image-recognition` matches the name in the aforementioned data handler app.go.

```
yomo serve -c ./zipper/workflow.yaml
```

Start the handler function by running the aforementioned app.go program.

```
cd flow
go run --tags "tensorflow image" app.go
```

Start a simulated data source by sending a video to YoMo. The video is a series of image frames. The WasmEdge function in app.go will be invoked against every image frame in the video.

```
# Download a video file
wget -P source 'https://github.com/yomorun/yomo-wasmedge-tensorflow/releases
/download/v0.1.0/hot-dog.mp4'

# Stream the video to YoMo
go run ./source/main.go ./source/hot-dog.mp4
```

You can see the output from the WasmEdge handler function in the console. It prints the names of the objects detected in each image frame in the video.

What's next

In this article, we have seen how to use the WasmEdge Tensorflow API and Golang SDK in YoMo framework to process an image stream in near real-time.

In collaboration with YoMo, we will soon deploy WasmEdge in production in smart factories

for a variety of assembly line tasks. WasmEdge is the software runtime for edge computing!

Reactr

Reactr is a fast, performant function scheduling library written in Go. Reactr is designed to be flexible, with the ability to run embedded in your Go applications and first-class support for WebAssembly. Taking advantage of Go's superior concurrency capabilities, Reactr can manage and execute hundreds of WebAssembly runtime instances all at once, making a great framework for server-side applications.

Reactr allows you to run WebAssembly functions in Go, so does the WasmEdge Go SDK. The unique feature of Reactr is that it provides a rich set of host functions in Go, which support access to networks and databases etc. Reactr then provides Rust (and Swift / AssemblyScript) APIs to call those host functions from within the WebAssembly function.

In this article, we will show you how to use WasmEdge together with Reactr to take advantage of the best of both worlds. WasmEdge is the fastest and most extensible WebAssembly runtime. It is also the fastest in Reactr's official test suite. We will show you how to run Rust functions compiled to WebAssembly as well as JavaScript programs in WasmEdge and Reactr.

> WasmEdge provides advanced support for JavaScript including mixing Rust with JavaScript for improved performance.

- Hello world
- Database query
- Embed JavaScript in Go

Prerequisites

You need have Rust, Go, and WasmEdge installed on your system. The GCC compiler (installed via the `build-essential` package) is also needed for WasmEdge.

```
sudo apt-get update
sudo apt-get -y upgrade
sudo apt install build-essential

curl --proto '=https' --tlsv1.2 -sSf https://sh.rustup.rs | sh
source $HOME/.cargo/env
rustup target add wasm32-wasi

curl -OL https://golang.org/dl/go1.17.5.linux-amd64.tar.gz
sudo tar -C /usr/local -xvf go1.17.5.linux-amd64.tar.gz
export PATH=$PATH:/usr/local/go/bin

wget -qO- https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash
source $HOME/.wasmedge/env
```

Hello world

A simple `hello world` example for Reactr is available here.

Hello world: Rust function compiled to WebAssembly

Let's first create a simple Rust function to echo hello. The Rust function `HelloEcho::run()` is as follows. It will be exposed to the Go host application through Reactr.

```
use suborbital::runnable::*;

struct HelloEcho{}

impl Runnable for HelloEcho {
  fn run(&self, input: Vec<u8>) -> Result<Vec<u8>, RunErr> {
    let in_string = String::from_utf8(input).unwrap();
    Ok(format!("hello {}", in_string).as_bytes().to_vec())
  }
}
```

Let's build the Rust function into a WebAssembly bytecode file.

```
cd hello-echo
cargo build --target wasm32-wasi --release
cp target/wasm32-wasi/release/hello_echo.wasm ..
cd ..
```

Hello world: Go host application

Next, lets look into the Go host app that executes the WebAssembly functions. The `runBundle()` function executes the `run()` function in the `Runnable` struct once.

```
func runBundle() {
  r := rt.New()
  doWasm := r.Register("hello-echo", rwasm.NewRunner("./hello_echo.wasm"))

  res, err := doWasm([]byte("wasmWorker!")).Then()
  if err != nil {
    fmt.Println(err)
    return
  }

  fmt.Println(string(res.([]byte)))
}
```

The `runGroup()` function executes the Rust-compiled WebAssembly `run()` function multiple times asynchronously in a group, and receives the results as they come in.

```
func runGroup() {
  r := rt.New()

  doWasm := r.Register("hello-echo", rwasm.NewRunner("./hello_echo.wasm"))

  grp := rt.NewGroup()
  for i := 0; i < 100000; i++ {
    grp.Add(doWasm([]byte(fmt.Sprintf("world %d", i))))
  }

  if err := grp.Wait(); err != nil {
    fmt.Println(err)
  }
}
```

Finally, let's run the Go host application and see the results printed to the console.

> You must use the `-tags wasmedge` flag to take advantage of the performance and extended WebAssembly APIs provided by WasmEdge.

```
go mod tidy
go run -tags wasmedge main.go
```

Database query

In this example, we will demonstrate how to use Reactr host functions and APIs to query a PostgreSQL database from your WebAssembly function.

Database query: Install and set up a PostgreSQL database

We will start a PostgreSQL instance through Docker.

```
docker pull postgres
docker run --name reactr-postgres -p 5432:5432 -e POSTGRES_PASSWORD=12345 -d
postgres
```

Next, let's create a database and populate it with some sample data.

```
$ docker run -it --rm --network host postgres psql -h 127.0.0.1 -U postgres
postgres=# CREATE DATABASE reactr;
postgres=# \c reactr;

# Create a table:
postgres=# CREATE TABLE users (
    uuid        varchar(100) CONSTRAINT firstkey PRIMARY KEY,
    email       varchar(50) NOT NULL,
    created_at  date,
    state       char(1),
    identifier  integer
);
```

Leave this running and start another terminal window to interact with this PostgreSQL server.

Database query: Rust function compiled to WebAssembly

Let's create a Rust function to access the PostgreSQL database. The Rust function `RsDbtest::run()` is as follows. It will be exposed to the Go host application through Reactr. It uses named queries such as `PGInsertUser` and `PGSelectUserWithUUID` to operate the database. Those queries are defined in the Go host application, and we will see them later.

```
use suborbital::runnable::*;
use suborbital::db;
use suborbital::util;
use suborbital::db::query;
use suborbital::log;
use uuid::Uuid;

struct RsDbtest{}

impl Runnable for RsDbtest {
  fn run(&self, _: Vec<u8>) -> Result<Vec<u8>, RunErr> {
    let uuid = Uuid::new_v4().to_string();

    let mut args: Vec<query::QueryArg> = Vec::new();
    args.push(query::QueryArg::new("uuid", uuid.as_str()));
    args.push(query::QueryArg::new("email", "connor@suborbital.dev"));

    match db::insert("PGInsertUser", args) {
      Ok(_) => log::info("insert successful"),
      Err(e) => {
        return Err(RunErr::new(500, e.message.as_str()))
      }
    };

    let mut args2: Vec<query::QueryArg> = Vec::new();
    args2.push(query::QueryArg::new("uuid", uuid.as_str()));

    match db::update("PGUpdateUserWithUUID", args2.clone()) {
      Ok(rows) => log::info(format!("update: {}",
util::to_string(rows).as_str()).as_str()),
      Err(e) => {
        return Err(RunErr::new(500, e.message.as_str()))
      }
    }

    match db::select("PGSelectUserWithUUID", args2.clone()) {
      Ok(result) => log::info(format!("select: {}",
util::to_string(result).as_str()).as_str()),
      Err(e) => {
        return Err(RunErr::new(500, e.message.as_str()))
      }
    }

    match db::delete("PGDeleteUserWithUUID", args2.clone()) {
      Ok(rows) => log::info(format!("delete: {}",
util::to_string(rows).as_str()).as_str()),
      Err(e) => {
        return Err(RunErr::new(500, e.message.as_str()))
      }
    }

    ... ...
```

```
  }
}
```

Let's build the Rust function into a WebAssembly bytecode file.

```
cd rs-db
cargo build --target wasm32-wasi --release
cp target/wasm32-wasi/release/rs_db.wasm ..
cd ..
```

Database query: Go host application

The Go host app first defines the SQL queries and gives each of them a name. We will then pass those queries to the Reactr runtime as a configuration.

```
func main() {
  dbConnString, exists := os.LookupEnv("REACTR_DB_CONN_STRING")
  if !exists {
    fmt.Println("skipping as conn string env var not set")
    return
  }

  q1 := rcap.Query{
    Type:     rcap.QueryTypeInsert,
    Name:     "PGInsertUser",
    VarCount: 2,
    Query: `
    INSERT INTO users (uuid, email, created_at, state, identifier)
    VALUES ($1, $2, NOW(), 'A', 12345)`,
  }

  q2 := rcap.Query{
    Type:     rcap.QueryTypeSelect,
    Name:     "PGSelectUserWithUUID",
    VarCount: 1,
    Query: `
    SELECT * FROM users
    WHERE uuid = $1`,
  }

  q3 := rcap.Query{
    Type:     rcap.QueryTypeUpdate,
    Name:     "PGUpdateUserWithUUID",
    VarCount: 1,
    Query: `
    UPDATE users SET state='B' WHERE uuid = $1`,
  }

  q4 := rcap.Query{
    Type:     rcap.QueryTypeDelete,
    Name:     "PGDeleteUserWithUUID",
    VarCount: 1,
    Query: `
    DELETE FROM users WHERE uuid = $1`,
  }

  config := rcap.DefaultConfigWithDB(vlog.Default(), rcap.DBTypePostgres,
dbConnString, []rcap.Query{q1, q2, q3, q4})

  r, err := rt.NewWithConfig(config)
  if err != nil {
    fmt.Println(err)
    return
  }

  ... ...
}
```

Then, we can run the WebAssembly function from Reactr.

```
func main() {
  ... ...

  doWasm := r.Register("rs-db", rwasm.NewRunner("./rs_db.wasm"))

  res, err := doWasm(nil).Then()
  if err != nil {
    fmt.Println(err)
    return
  }

  fmt.Println(string(res.([]byte)))
}
```

Finally, let's run the Go host application and see the results printed to the console.

You must use the `-tags wasmedge` flag to take advantage of the performance and extended WebAssembly APIs provided by WasmEdge.

```
export REACTR_DB_CONN_STRING='postgresql://postgres:12345@127.0.0.1:5432
/reactr'
go mod tidy
go run -tags wasmedge main.go
```

Embed JavaScript in Go

As we mentioned, a key feature of the WasmEdge Runtime is its advanced JavaScript support, which allows JavaScript programs to run in lightweight, high-performance, safe, multi-language, and Kubernetes-managed WasmEdge containers. A simple example of embedded JavaScript function in Reactr is available here.

JavaScript example

The JavaScript example function is very simple. It just returns a string value.

```
let h = 'hello';
let w = 'wasmedge';
`${h} ${w}`;
```

JavaScript example: Go host application

The Go host app uses the Reactr API to run WasmEdge's standard JavaScript interpreter rs_embed_js.wasm. You can build your own version of JavaScript interpreter by modifying this Rust project.

> Learn more about how to embed JavaScript code in Rust, and how to use Rust to implement JavaScript APIs in WasmEdge.

The Go host application just need to start the job for `rs_embed_js.wasm` and pass the JavaScript content to it. The Go application can then capture and print the return value from JavaScript.

```
func main() {
  r := rt.New()
  doWasm := r.Register("hello-quickjs", rwasm.NewRunner("./rs_embed_js.wasm"))

  code, err := ioutil.ReadFile(os.Args[1])
  if err != nil {
    fmt.Print(err)
  }
  res, err := doWasm(code).Then()
  if err != nil {
    fmt.Println(err)
    return
  }

  fmt.Println(string(res.([]byte)))
}
```

Run the Go host application as follows.

```
$ cd quickjs
$ go mod tidy
$ go run -tags wasmedge main.go hello.js
String(JsString(hello wasmedge))
```

The printed result shows the type information of the string in Rust and Go APIs. You can strip out this information by changing the Rust or Go applications.

JavaScript example: Feature examples

WasmEdge supports many advanced JavaScript features. For the next step, you could try our

React SSR example to generate an HTML UI from a Reactr function! You can just build the `dist/main.js` from the React SSR example, and copy it over to this example folder to see it in action!

```
$ cd quickjs
# copy over the dist/main.js file from the react ssr example
$ go mod tidy
$ go run -tags wasmedge main.go main.js
<div data-reactroot=""><div>This is home</div><div><div>This is page</div>
</div></div>
UnDefined
```

Serverless platforms

Our vision for the future is to run WebAssembly as an alternative lightweight runtime side-by-side with Docker and microVMs in cloud native infrastructure. WebAssembly offers much higher performance and consumes much less resources than Docker-like containers or microVMs. However, the public cloud only supports running WebAssembly inside a microVM. Nonetheless, running WebAssembly functions inside a microVM still offers many advantages over running containerized NaCl programs.

Running WebAssembly functions inside Docker-like containers offer advantages over running NaCl programs directly in Docker.

For starters, WebAssembly provides fine-grained runtime isolation for individual functions. A microservice could have multiple functions and support services running inside a Docker-like container. WebAssembly can make the microservice more secure and more stable.

Second, the WebAssembly bytecode is portable. Developers only need to build it once and do not need to worry about changes or updates to the underlying Vercel serverless container (OS and hardware). It also allows developers to reuse the same WebAssembly functions in other cloud environments.

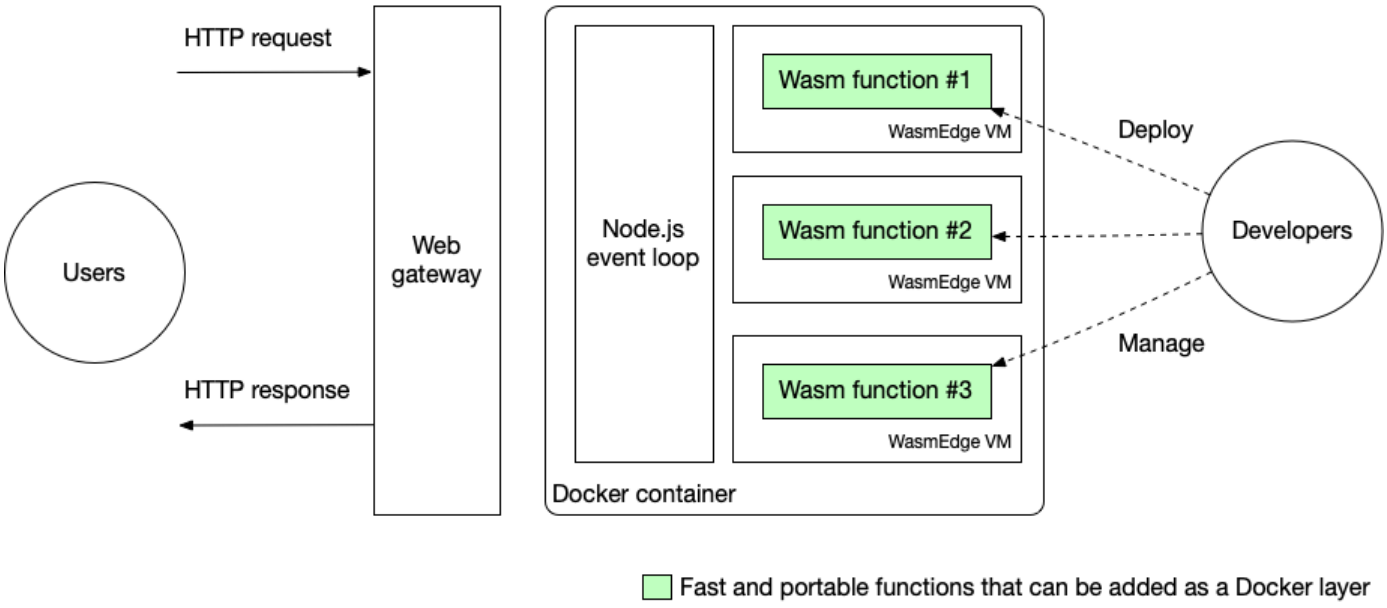
Third, WebAssembly apps are easy to deploy and manage. They have much less platform dependencies and complexities compared with NaCl dynamic libraries and executables.

Finally, the WasmEdge Tensorflow API provides the most ergonomic way to execute Tensorflow models in the Rust programming language. WasmEdge installs the correct combination of Tensorflow dependency libraries, and provides a unified API for developers.

In this section, we will show you how to run WebAssembly serverless functions in public clouds. Each platform has its own code template and contains two examples in Rust, one is the normal image processing, The other one is TensorFlow inference using the WasmEdge TensorFlow SDK.

- Vercel discuss how to leverage WasmEdge to accelerate the Jamstack application deployed on Vercel.
- Netlify discuss how to leverage WasmEdge to accelerate the Jamstack application deployed on Netlify.
- AWS Lambda discuss how to leverage WasmEdge to accelerate the serverless functions deployed on AWS Lambda.
- Tencent discuss how to leverage WasmEdge to accelerate the serverless functions deployed on Tencent cloud.

If you would like to add more WasmEdge examples on public cloud platform,like Google Cloud Functions, feel free to create a PR for WasmEdge and let the community know what you did.



Running WasmEdge from Docker containers deployed on public cloud is an easy way to add high-performance functions to web applications. Going forward an even better approach is to use WasmEdge as the container itself. There will be no Docker and no Node.js to bootstrap WasmEdge. This way, we can reach much higher efficiency for running serverless functions.

- Second State Functions will discuss how to use WasmEdge ad the container itself, since Second State Functions is a serverless platform with pure WebAssembly/WasmEdge.

Rust and WebAssembly Serverless functions in Vercel

In this article, we will show you two serverless functions in Rust and WasmEdge deployed on Vercel. One is the image processing function, the other one is the TensorFlow inference function.

> For more insights on why WasmEdge on Vercel, please refer to the article Rust and WebAssembly Serverless Functions in Vercel.

Prerequisite

Since our demo WebAssembly functions are written in Rust, you will need a Rust compiler. Make sure that you install the `wasm32-wasi` compiler target as follows, in order to generate WebAssembly bytecode.

```
rustup target add wasm32-wasi
```

The demo application front end is written in Next.js, and deployed on Vercel. We will assume that you already have the basic knowledge of how to work with Vercel.

Example 1: Image processing

Our first demo application allows users to upload an image and then invoke a serverless function to turn it into black and white. A live demo deployed on Vercel is available.

Fork the demo application's GitHub repo to get started. To deploy the application on Vercel, just import the Github repo from Vercel for Github web page.

This repo is a standard Next.js application for the Vercel platform. The backend serverless function is in the `api/functions/image_grayscale` folder. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the black-white image to the `STDOUT`.

```
use hex;
use std::io::{self, Read};
use image::{ImageOutputFormat, ImageFormat};

fn main() {
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  let image_format_detected: ImageFormat = image::guess_format(&buf).unwrap();
  let img = image::load_from_memory(&buf).unwrap();
  let filtered = img.grayscale();
  let mut buf = vec![];
  match image_format_detected {
    ImageFormat::Gif => {
      filtered.write_to(&mut buf, ImageOutputFormat::Gif).unwrap();
    },
    _ => {
      filtered.write_to(&mut buf, ImageOutputFormat::Png).unwrap();
    },
  };
  io::stdout().write_all(&buf).unwrap();
  io::stdout().flush().unwrap();
}
```

You can use Rust's `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-grayscale/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/grayscale.wasm ../../
```

> Vercel runs `api/pre.sh` upon setting up the serverless environment. It installs the WasmEdge runtime, and then compiles each WebAssembly bytecode program into a native `so` library for faster execution.

The `api/hello.js` file conforms Vercel serverless specification. It loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice `api/hello.js` runs the compiled `grayscale.so` file generated by `api/pre.sh` for better performance.

```
const fs = require('fs');
const { spawn } = require('child_process');
const path = require('path');

module.exports = (req, res) => {
  const wasmedge = spawn(
      path.join(__dirname, 'wasmedge'),
      [path.join(__dirname, 'grayscale.so')]);

  let d = [];
  wasmedge.stdout.on('data', (data) => {
    d.push(data);
  });

  wasmedge.on('close', (code) => {
    let buf = Buffer.concat(d);

    res.setHeader('Content-Type', req.headers['image-type']);
    res.send(buf);
  });

  wasmedge.stdin.write(req.body);
  wasmedge.stdin.end('');
}
```

That's it. Deploy the repo to Vercel and you now have a Vercel Jamstack app with a high-performance Rust and WebAssembly based serverless backend.

Example 2: AI inference

The second demo application allows users to upload an image and then invoke a serverless function to classify the main subject on the image.

It is in the same GitHub repo as the previous example but in the `tensorflow` branch. Note: when you import this GitHub repo on the Vercel website, it will create a preview URL for each branch. The `tensorflow` branch would have its own deployment URL.

The backend serverless function for image classification is in the `api/functions/image-classification` folder in the `tensorflow` branch. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the text output to the `STDOUT`. It utilizes the WasmEdge Tensorflow API to run the AI inference.

```
pub fn main() {
  // Step 1: Load the TFLite model
  let model_data: &[u8] = include_bytes!("models/mobilenet_v1_1.0_224
/mobilenet_v1_1.0_224_quant.tflite");
  let labels = include_str!("models/mobilenet_v1_1.0_224
/labels_mobilenet_quant_v1_224.txt");

  // Step 2: Read image from STDIN
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  // Step 3: Resize the input image for the tensorflow model
  let flat_img = wasmedge_tensorflow_interface::load_jpg_image_to_rgb8(&buf,
224, 224);

  // Step 4: AI inference
  let mut session = wasmedge_tensorflow_interface::Session::new(&model_data,
wasmedge_tensorflow_interface::ModelType::TensorFlowLite);
  session.add_input("input", &flat_img, &[1, 224, 224, 3])
         .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions
/Reshape_1");

  // Step 5: Find the food label that responds to the highest probability in
res_vec
  // ... ...
  let mut label_lines = labels.lines();
  for _i in 0..max_index {
    label_lines.next();
  }

  // Step 6: Generate the output text
  let class_name = label_lines.next().unwrap().to_string();
  if max_value > 50 {
    println!("It {} a <a href='https://www.google.com/search?q={}'>{}</a> in
the picture", confidence.to_string(), class_name, class_name);
  } else {
    println!("It does not appears to be any food item in the picture.");
  }
}
```

You can use the `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-classification/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/classify.wasm ../../
```

Again, the `api/pre.sh` script installs WasmEdge runtime and its Tensorflow dependencies in this application. It also compiles the `classify.wasm` bytecode program to the `classify.so` native shared library at the time of deployment.

The `api/hello.js` file conforms Vercel serverless specification. It loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice `api/hello.js` runs the compiled `classify.so` file generated by `api/pre.sh` for better performance.

```
const fs = require('fs');
const { spawn } = require('child_process');
const path = require('path');

module.exports = (req, res) => {
  const wasmedge = spawn(
    path.join(__dirname, 'wasmedge-tensorflow-lite'),
    [path.join(__dirname, 'classify.so')],
    {env: {'LD_LIBRARY_PATH': __dirname}}
  );

  let d = [];
  wasmedge.stdout.on('data', (data) => {
    d.push(data);
  });

  wasmedge.on('close', (code) => {
    res.setHeader('Content-Type', `text/plain`);
    res.send(d.join(''));
  });

  wasmedge.stdin.write(req.body);
  wasmedge.stdin.end('');
}
```

You can now deploy your forked repo to Vercel and have a web app for subject classification.

Next, it's your turn to use the vercel-wasm-runtime repo as a template to develop your own Rust serverless functions in Vercel. Looking forward to your great work.

WebAssembly Serverless Functions in Netlify

In this article we will show you two serverless functions in Rust and WasmEdge deployed on Netlify. One is the image processing function, the other one is the TensorFlow inference function.

> For more insights on why WasmEdge on Netlify, please refer to the article WebAssembly Serverless Functions in Netlify.

Prerequisite

Since our demo WebAssembly functions are written in Rust, you will need a Rust compiler. Make sure that you install the `wasm32-wasi` compiler target as follows, in order to generate WebAssembly bytecode.

```
rustup target add wasm32-wasi
```

The demo application front end is written in Next.js, and deployed on Netlify. We will assume that you already have the basic knowledge of how to work with Next.js and Netlify.

Example 1: Image processing

Our first demo application allows users to upload an image and then invoke a serverless function to turn it into black and white. A live demo deployed on Netlify is available.

Fork the demo application's GitHub repo to get started. To deploy the application on Netlify, just add your github repo to Netlify.

This repo is a standard Next.js application for the Netlify platform. The backend serverless function is in the `api/functions/image_grayscale` folder. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the black-white image to the `STDOUT`.

```
use hex;
use std::io::{self, Read};
use image::{ImageOutputFormat, ImageFormat};

fn main() {
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  let image_format_detected: ImageFormat = image::guess_format(&buf).unwrap();
  let img = image::load_from_memory(&buf).unwrap();
  let filtered = img.grayscale();
  let mut buf = vec![];
  match image_format_detected {
    ImageFormat::Gif => {
      filtered.write_to(&mut buf, ImageOutputFormat::Gif).unwrap();
    },
    _ => {
      filtered.write_to(&mut buf, ImageOutputFormat::Png).unwrap();
    },
  };
  io::stdout().write_all(&buf).unwrap();
  io::stdout().flush().unwrap();
}
```

You can use Rust's `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-grayscale/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/grayscale.wasm ../../
```

> The Netlify function runs `api/pre.sh` upon setting up the serverless environment. It installs the WasmEdge runtime, and then compiles each WebAssembly bytecode program into a native `so` library for faster execution.

The `api/hello.js` script loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice `api/hello.js` runs the compiled `grayscale.so` file generated by `api/pre.sh` for better performance.

```
const fs = require('fs');
const { spawn } = require('child_process');
const path = require('path');

module.exports = (req, res) => {
  const wasmedge = spawn(
      path.join(__dirname, 'wasmedge'),
      [path.join(__dirname, 'grayscale.so')]);

  let d = [];
  wasmedge.stdout.on('data', (data) => {
    d.push(data);
  });

  wasmedge.on('close', (code) => {
    let buf = Buffer.concat(d);

    res.setHeader('Content-Type', req.headers['image-type']);
    res.send(buf);
  });

  wasmedge.stdin.write(req.body);
  wasmedge.stdin.end('');
}
```

That's it. Deploy the repo to Netlify and you now have a Netlify Jamstack app with a high-performance Rust and WebAssembly based serverless backend.

Example 2: AI inference

The second demo application allows users to upload an image and then invoke a serverless function to classify the main subject on the image.

It is in the same GitHub repo as the previous example but in the `tensorflow` branch. The backend serverless function for image classification is in the `api/functions/image-classification` folder in the `tensorflow` branch. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the text output to the `STDOUT`. It utilizes the WasmEdge Tensorflow API to run the AI inference.

```
pub fn main() {
  // Step 1: Load the TFLite model
  let model_data: &[u8] = include_bytes!("models/mobilenet_v1_1.0_224
/mobilenet_v1_1.0_224_quant.tflite");
  let labels = include_str!("models/mobilenet_v1_1.0_224
/labels_mobilenet_quant_v1_224.txt");

  // Step 2: Read image from STDIN
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  // Step 3: Resize the input image for the tensorflow model
  let flat_img = wasmedge_tensorflow_interface::load_jpg_image_to_rgb8(&buf,
224, 224);

  // Step 4: AI inference
  let mut session = wasmedge_tensorflow_interface::Session::new(&model_data,
wasmedge_tensorflow_interface::ModelType::TensorFlowLite);
  session.add_input("input", &flat_img, &[1, 224, 224, 3])
         .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions
/Reshape_1");

  // Step 5: Find the food label that responds to the highest probability in
res_vec
  // ... ...
  let mut label_lines = labels.lines();
  for _i in 0..max_index {
    label_lines.next();
  }

  // Step 6: Generate the output text
  let class_name = label_lines.next().unwrap().to_string();
  if max_value > 50 {
    println!("It {} a <a href='https://www.google.com/search?q={}'>{}</a> in
the picture", confidence.to_string(), class_name, class_name);
  } else {
    println!("It does not appears to be any food item in the picture.");
  }
}
```

You can use the `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-classification/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/classify.wasm ../../
```

Again, the `api/pre.sh` script installs WasmEdge runtime and its Tensorflow dependencies in this application. It also compiles the `classify.wasm` bytecode program to the `classify.so` native shared library at the time of deployment.

The `api/hello.js` script loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice `api/hello.js` runs the compiled `classify.so` file generated by `api/pre.sh` for better performance.

```
const fs = require('fs');
const { spawn } = require('child_process');
const path = require('path');

module.exports = (req, res) => {
  const wasmedge = spawn(
    path.join(__dirname, 'wasmedge-tensorflow-lite'),
    [path.join(__dirname, 'classify.so')],
    {env: {'LD_LIBRARY_PATH': __dirname}}
  );

  let d = [];
  wasmedge.stdout.on('data', (data) => {
    d.push(data);
  });

  wasmedge.on('close', (code) => {
    res.setHeader('Content-Type', `text/plain`);
    res.send(d.join(''));
  });

  wasmedge.stdin.write(req.body);
  wasmedge.stdin.end('');
}
```

You can now deploy your forked repo to Netlify and have a web app for subject classification.

Next, it's your turn to develop Rust serverless functions in Netlify using the netlify-wasm-runtime repo as a template. Looking forward to your great work.

WebAssembly Serverless Functions in AWS Lambda

In this article, we will show you two serverless functions in Rust and WasmEdge deployed on AWS Lambda. One is the image processing function, the other one is the TensorFlow inference function.

> For the insight on why WasmEdge on AWS Lambda, please refer to the article WebAssembly Serverless Functions in AWS Lambda

---

Prerequisites

Since our demo WebAssembly functions are written in Rust, you will need a Rust compiler. Make sure that you install the `wasm32-wasi` compiler target as follows, in order to generate WebAssembly bytecode.

```
rustup target add wasm32-wasi
```

The demo application front end is written in Next.js, and deployed on AWS Lambda. We will assume that you already have the basic knowledge of how to work with Next.js and Lambda.

Example 1: Image processing

Our first demo application allows users to upload an image and then invoke a serverless function to turn it into black and white. A live demo deployed through GitHub Pages is available.

Fork the demo application's GitHub repo to get started. To deploy the application on AWS Lambda, follow the guide in the repository README.

Create the function

This repo is a standard Next.js application. The backend serverless function is in the

`api/functions/image_grayscale` folder. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the black-white image to the `STDOUT`.

```
use hex;
use std::io::{self, Read};
use image::{ImageOutputFormat, ImageFormat};

fn main() {
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  let image_format_detected: ImageFormat = image::guess_format(&buf).unwrap();
  let img = image::load_from_memory(&buf).unwrap();
  let filtered = img.grayscale();
  let mut buf = vec![];
  match image_format_detected {
    ImageFormat::Gif => {
      filtered.write_to(&mut buf, ImageOutputFormat::Gif).unwrap();
    },
    _ => {
      filtered.write_to(&mut buf, ImageOutputFormat::Png).unwrap();
    },
  };
  io::stdout().write_all(&buf).unwrap();
  io::stdout().flush().unwrap();
}
```

You can use Rust's `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-grayscale/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/grayscale.wasm ../../
```

When we build the docker image, `api/pre.sh` is executed. `pre.sh` installs the WasmEdge runtime, and then compiles each WebAssembly bytecode program into a native `so` library for faster execution.

Create the service script to load the function

The `api/hello.js` script loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice that `api/hello.js` runs the compiled `grayscale.so` file generated by `api/pre.sh` for better performance.

```
const { spawn } = require('child_process');
const path = require('path');

function _runWasm(reqBody) {
  return new Promise(resolve => {
    const wasmedge = spawn(path.join(__dirname, 'wasmedge'),
[path.join(__dirname, 'grayscale.so')]);

    let d = [];
    wasmedge.stdout.on('data', (data) => {
      d.push(data);
    });

    wasmedge.on('close', (code) => {
      let buf = Buffer.concat(d);
      resolve(buf);
    });

    wasmedge.stdin.write(reqBody);
    wasmedge.stdin.end('');
  });
}
```

The `exports.handler` part of `hello.js` exports an async function handler, used to handle different events every time the serverless function is called. In this example, we simply process the image by calling the function above and return the result, but more complicated event-handling behavior may be defined based on your need. We also need to return some `Access-Control-Allow` headers to avoid Cross-Origin Resource Sharing (CORS) errors when calling the serverless function from a browser. You can read more about CORS errors here if you encounter them when replicating our example.

```
exports.handler = async function(event, context) {
  var typedArray = new Uint8Array(event.body.match(/[\da-f]{2}/gi).map(function
(h) {
    return parseInt(h, 16);
  }));
  let buf = await _runWasm(typedArray);
  return {
    statusCode: 200,
    headers: {
      "Access-Control-Allow-Headers" : "Content-Type,X-Amz-
Date,Authorization,X-Api-Key,X-Amz-Security-Token",
      "Access-Control-Allow-Origin": "*",
      "Access-Control-Allow-Methods": "DELETE, GET, HEAD, OPTIONS, PATCH, POST,
PUT"
    },
    body: buf.toString('hex')
  };
}
```

Build the Docker image for Lambda deployment

Now we have the WebAssembly bytecode function and the script to load and connect to the web request. In order to deploy them as a function service on AWS Lambda, you still need to package the whole thing into a Docker image.

We are not going to cover in detail about how to build the Docker image and deploy on AWS Lambda, as there are detailed steps in the Deploy section of the repository README. However, we will highlight some lines in the `Dockerfile` for you to avoid some pitfalls.

```
FROM public.ecr.aws/lambda/nodejs:14

# Change directory to /var/task
WORKDIR /var/task

RUN yum update -y && yum install -y curl tar gzip

# Bundle and pre-compile the wasm files
COPY *.wasm ./
COPY pre.sh ./
RUN chmod +x pre.sh
RUN ./pre.sh

# Bundle the JS files
COPY *.js ./

CMD [ "hello.handler" ]
```

First, we are building the image from AWS Lambda's Node.js base image. The advantage of using AWS Lambda's base image is that it includes the Lambda Runtime Interface Client (RIC), which we need to implement in our Docker image as it is required by AWS Lambda. The Amazon Linux uses `yum` as the package manager.

> These base images contain the Amazon Linux Base operating system, the runtime for a given language, dependencies and the Lambda Runtime Interface Client (RIC), which implements the Lambda Runtime API. The Lambda Runtime Interface Client allows your runtime to receive requests from and send requests to the Lambda service.

Second, we need to put our function and all its dependencies in the `/var/task` directory. Files in other folders will not be executed by AWS Lambda.

Third, we need to define the default command when we start our container. `CMD [ "hello.handler" ]` means that we will call the `handler` function in `hello.js` whenever our serverless function is called. Recall that we have defined and exported the handler function in the previous steps through `exports.handler = ...` in `hello.js`.

Optional: test the Docker image locally

Docker images built from AWS Lambda's base images can be tested locally following this guide. Local testing requires AWS Lambda Runtime Interface Emulator (RIE), which is already installed in all of AWS Lambda's base images. To test your image, first, start the Docker container by running:

```
docker run -p 9000:8080  myfunction:latest
```

This command sets a function endpoint on your local machine at `http://localhost:9000/2015-03-31/functions/function/invocations`.

Then, from a separate terminal window, run:

```
curl -XPOST "http://localhost:9000/2015-03-31/functions/function/invocations"
-d '{}'
```

And you should get your expected output in the terminal.

If you don't want to use a base image from AWS Lambda, you can also use your own base image and install RIC and/or RIE while building your Docker image. Just follow **Create an image from an alternative base image** section from this guide.

That's it! After building your Docker image, you can deploy it to AWS Lambda following steps outlined in the repository README. Now your serverless function is ready to rock!

Example 2: AI inference

The second demo application allows users to upload an image and then invoke a serverless function to classify the main subject on the image.

It is in the same GitHub repo as the previous example but in the `tensorflow` branch. The backend serverless function for image classification is in the `api/functions/image-classification` folder in the `tensorflow` branch. The `src/main.rs` file contains the Rust program's source code. The Rust program reads image data from the `STDIN`, and then outputs the text output to the `STDOUT`. It utilizes the WasmEdge Tensorflow API to run the AI inference.

```
pub fn main() {
  // Step 1: Load the TFLite model
  let model_data: &[u8] = include_bytes!("models/mobilenet_v1_1.0_224
/mobilenet_v1_1.0_224_quant.tflite");
  let labels = include_str!("models/mobilenet_v1_1.0_224
/labels_mobilenet_quant_v1_224.txt");

  // Step 2: Read image from STDIN
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  // Step 3: Resize the input image for the tensorflow model
  let flat_img = wasmedge_tensorflow_interface::load_jpg_image_to_rgb8(&buf,
224, 224);

  // Step 4: AI inference
  let mut session = wasmedge_tensorflow_interface::Session::new(&model_data,
wasmedge_tensorflow_interface::ModelType::TensorFlowLite);
  session.add_input("input", &flat_img, &[1, 224, 224, 3])
         .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions
/Reshape_1");

  // Step 5: Find the food label that responds to the highest probability in
res_vec
  // ... ...
  let mut label_lines = labels.lines();
  for _i in 0..max_index {
    label_lines.next();
  }

  // Step 6: Generate the output text
  let class_name = label_lines.next().unwrap().to_string();
  if max_value > 50 {
    println!("It {} a <a href='https://www.google.com/search?q={}'>{}</a> in
the picture", confidence.to_string(), class_name, class_name);
  } else {
    println!("It does not appears to be any food item in the picture.");
  }
}
```

You can use the `cargo` tool to build the Rust program into WebAssembly bytecode or native code.

```
cd api/functions/image-classification/
cargo build --release --target wasm32-wasi
```

Copy the build artifacts to the `api` folder.

```
cp target/wasm32-wasi/release/classify.wasm ../../
```

Again, the `api/pre.sh` script installs WasmEdge runtime and its Tensorflow dependencies in this application. It also compiles the `classify.wasm` bytecode program to the `classify.so` native shared library at the time of deployment.

The `api/hello.js` script loads the WasmEdge runtime, starts the compiled WebAssembly program in WasmEdge, and passes the uploaded image data via `STDIN`. Notice `api/hello.js` runs the compiled `classify.so` file generated by `api/pre.sh` for better performance. The handler function is similar to our previous example, and is omitted here.

```
const { spawn } = require('child_process');
const path = require('path');

function _runWasm(reqBody) {
  return new Promise(resolve => {
    const wasmedge = spawn(
      path.join(__dirname, 'wasmedge-tensorflow-lite'),
      [path.join(__dirname, 'classify.so')],
      {env: {'LD_LIBRARY_PATH': __dirname}}
    );

    let d = [];
    wasmedge.stdout.on('data', (data) => {
      d.push(data);
    });

    wasmedge.on('close', (code) => {
      resolve(d.join(''));
    });

    wasmedge.stdin.write(reqBody);
    wasmedge.stdin.end('');
  });
}

exports.handler = ... // _runWasm(reqBody) is called in the handler
```

You can build your Docker image and deploy the function in the same way as outlined in the previous example. Now you have created a web app for subject classification!

Next, it's your turn to use the aws-lambda-wasm-runtime repo as a template to develop Rust serverless function on AWS Lambda. Looking forward to your great work.

WebAssembly serverless functions on Tencent Cloud

As the main users of Tencent Cloud are from China, so the tutorial is written in Chinese.

We also provide a code template for deploying serverless WebAssembly functions on Tencent Cloud, please check out the tencent-scf-wasm-runtime repo.

Fork the repo and start writing your own rust functions.

Second State Functions

Second State Functions, powered by WasmEdge, supports the Rust language as a first class citizen.

It could

- Handle text-based input and output
- Use Binary data as function input and output
- Mix bytes and strings in function argument and return value
- Use webhooks as function input and output
- Access internet resources via a `http_proxy` API
- Running TensorFlow models at native speed via the WasmEdge TensorFlow API

Check out the Second State Functions website for more tutorials.

Write a WebAssembly Application

A key value proposition of WebAssembly is that it supports multiple programming languages. WebAssembly is a "managed runtime" for many programming languages including C/C++, Rust, Go, Swift, Kotlin, AssemblyScript, Grain and even JavaScript and Python.

- For compiled languages (e.g., C and Rust), WasmEdge WebAssembly provides a safe, secure, isolated, and containerized runtime as opposed to Native Client (NaCl).
- For interpreted or managed languages (e.g., JavaScript and Python), WasmEdge WebAssembly provides a secure, fast, lightweight, and containerized runtime as opposed to Docker + guest OS + native interpreter.

In this chapter, we will discuss how to compile sources into WebAssembly in different languages and run them in WasmEdge.

C

A simple example for compiling C code into WebAssembly is SIMD.

WebAssembly SIMD Example in C

128-bit packed Single Instruction Multiple Data (SIMD) instructions provide simultaneous computations over packed data in just one instruction. It's commonly used to improve performance for multimedia applications. With the SIMD proposal, the modules can benefit from using these commonly used instructions in modern hardware to gain more speedup.

If you are interested in enabling the SIMD proposal will improve how much performance of the applications, please refer to our wasm32-wasi benchmark for more information. In our benchmark, the Mandelbrot Set application can have **2.65x** speedup.

C language Code - Mandelbrot Set

We modified the Mandelbrot Set example from our wasm32-wasi benchmark project.

```
#define LIMIT_SQUARED 4.0
#define MAXIMUM_ITERATIONS 50

#include <inttypes.h>
#include <math.h>
#include <stdbool.h>
#include <stdint.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

typedef double doublex2 __attribute__((vector_size(16)));
typedef uint64_t uint64x2_t __attribute__((vector_size(16)));

static inline void calcSum(doublex2 *r, doublex2 *i, doublex2 *sum,
                           const doublex2 init_r[4], const doublex2 init_i) {
  for (uint64_t x_Minor = 0; x_Minor < 4; x_Minor++) {
    doublex2 r2 = r[x_Minor] * r[x_Minor];
    doublex2 i2 = i[x_Minor] * i[x_Minor];
    doublex2 ri = r[x_Minor] * i[x_Minor];

    sum[x_Minor] = r2 + i2;

    r[x_Minor] = r2 - i2 + init_r[x_Minor];
    i[x_Minor] = ri + ri + init_i;
  }
}

static inline bool vec_gt(const doublex2 *v) {
  const doublex2 f = {LIMIT_SQUARED, LIMIT_SQUARED};
  const uint64x2_t r = (v[0] > f) & (v[1] > f) & (v[2] > f) & (v[3] > f);
  return r[0] && r[1];
}

static inline uint8_t clrPixels_gt(const doublex2 *v) {
  const doublex2 f = {LIMIT_SQUARED, LIMIT_SQUARED};
  const uint64x2_t r0 = v[0] <= f;
  const uint64x2_t r1 = v[1] <= f;
  const uint64x2_t r2 = v[2] <= f;
  const uint64x2_t r3 = v[3] <= f;
  return (r0[0] & 0x1) << 7 | (r0[1] & 0x1) << 6 | (r1[0] & 0x1) << 5 |
         (r1[1] & 0x1) << 4 | (r2[0] & 0x1) << 3 | (r2[1] & 0x1) << 2 |
         (r3[0] & 0x1) << 1 | (r3[1] & 0x1) << 0;
}

static inline uint8_t mand8(const doublex2 init_r[4], const doublex2 init_i) {
  doublex2 pixel_Group_r[4], pixel_Group_i[4];
  for (uint64_t x_Minor = 0; x_Minor < 4; x_Minor++) {
    pixel_Group_r[x_Minor] = init_r[x_Minor];
    pixel_Group_i[x_Minor] = init_i;
  }
```

```
  doublex2 sum[4];
  for (unsigned j = 0; j < 6; j++) {
    for (unsigned k = 0; k < 8; k++) {
      calcSum(pixel_Group_r, pixel_Group_i, sum, init_r, init_i);
    }
    if (vec_gt(sum)) {
      return 0x00;
    }
  }
  calcSum(pixel_Group_r, pixel_Group_i, sum, init_r, init_i);
  calcSum(pixel_Group_r, pixel_Group_i, sum, init_r, init_i);
  return clrPixels_gt(sum);
}

static inline uint64_t mand64(const doublex2 init_r[4], const doublex2 init_i)
{
  uint64_t sixtyfour_Pixels = 0;
  for (uint64_t byte = 0; byte < 8; byte++) {
    const uint64_t eight_Pixels = mand8(init_r + 4 * byte, init_i);
    sixtyfour_Pixels =
        (sixtyfour_Pixels >> UINT64_C(8)) | (eight_Pixels << UINT64_C(56));
  }
  return sixtyfour_Pixels;
}

int main(int argc, char **argv) {
  const uint64_t image_Width_And_Height =
      (__builtin_expect(atoi(argv[1]), 15000) + 7) / 8 * 8;

  uint8_t *const pixels =
      malloc(image_Width_And_Height * image_Width_And_Height / 8);

  doublex2 initial_r[image_Width_And_Height / 2];
  double initial_i[image_Width_And_Height];
  for (uint64_t xy = 0; xy < image_Width_And_Height; xy++) {
    initial_r[xy / 2] =
        2.0 / image_Width_And_Height * (doublex2){xy, xy + 1} - 1.5;
    initial_i[xy] = 2.0 / image_Width_And_Height * xy - 1.0;
  }

  if (image_Width_And_Height % 64) {
    // process 8 pixels (one byte) at a time
    for (uint64_t y = 0; y < image_Width_And_Height; y++) {
      const doublex2 prefetched_Initial_i = {initial_i[y], initial_i[y]};
      const size_t rowStart = y * image_Width_And_Height / 8;
      for (uint64_t x_Major = 0; x_Major < image_Width_And_Height;
           x_Major += 8) {
        const doublex2 *prefetched_Initial_r = &initial_r[x_Major / 2];
        pixels[rowStart + x_Major / 8] =
            mand8(prefetched_Initial_r, prefetched_Initial_i);
      }
    }
  } else {
```

```
    // process 64 pixels (8 bytes) at a time
    for (uint64_t y = 0; y < image_Width_And_Height; y++) {
      const doublex2 prefetched_Initial_i = {initial_i[y], initial_i[y]};
      const size_t rowStart = y * image_Width_And_Height / 8;
      for (uint64_t x_Major = 0; x_Major < image_Width_And_Height;
           x_Major += 8) {
        const doublex2 *prefetched_Initial_r = &initial_r[x_Major / 2];
        const uint64_t sixtyfour_Pixels =
            mand64(prefetched_Initial_r, prefetched_Initial_i);
        memcpy(&pixels[rowStart + x_Major / 8], &sixtyfour_Pixels, 8);
      }
    }
  }

  fprintf(stdout, "P4\n%" PRIu64 " %" PRIu64 "\n", image_Width_And_Height,
          image_Width_And_Height);
  fwrite(pixels, image_Width_And_Height * image_Width_And_Height / 8, 1,
         stdout);

  free(pixels);

  return 0;
}
```

Compile the C-SIMD application to Wasm-SIMD binary with emcc

Install emcc

To compile it, you will need to install the latest emcc toolchain. Please refer to the emcc official repository for the detailed instructions.

```
git clone --depth 1 https://github.com/emscripten-core/emsdk.git
cd emsdk
./emsdk install latest
./emsdk activate latest
source ./emsdk_env.sh
```

Compile with emcc

```
emcc -g -Oz --llvm-lto 1 -s STANDALONE_WASM -s INITIAL_MEMORY=32MB -s
MAXIMUM_MEMORY=4GB \
  -mmutable-globals \
  -mnontrapping-fptoint \
  -msign-ext \
  mandelbrot-simd.c -o mandelbrot-simd.wasm
```

Run with wasmedge

Interpreter mode

```
wasmedge mandelbrot-simd.wasm 15000
```

Ahead-of-Time mode

```
# Compile wasm-simd with wasmedge aot compiler
$ wasmedgec mandelbrot-simd.wasm mandelbrot-simd-out.wasm
# Run the native binary with wasmedge
$ wasmedge mandelbrot-simd-out.wasm 15000
```

Rust

Rust is one of the "first-class citizen" programming languages in the WebAssembly ecosystem. All WasmEdge extensions to WebAssembly also come with Rust APIs for developers. In this chapter, we will show you how to compile your Rust applications to WebAssembly and to run in the WasmEdge runtime.

Prerequisites

You need to install Rust and WasmEdge in order to get started. You should also install the `wasm32-wasi` target of the Rust toolchain.

```
rustup target add wasm32-wasi
```

Hello world

The Hello world example is a standalone Rust application that can be executed by the WasmEdge CLI. Its source code is available here.

The full source code for the Rust main.rs file is as follows. It echoes the command line arguments passed to this program at runtime.

```
use std::env;

fn main() {
  println!("hello");
  for argument in env::args().skip(1) {
    println!("{}", argument);
  }
}
```

Hello world: Build the WASM bytecode

```
cargo build --target wasm32-wasi
```

Hello world: Run the application from command line

We will use the `wasmedge` command to run the program.

```
$ wasmedge target/wasm32-wasi/debug/hello.wasm second state
hello
second
state
```

A simple function

The add example is a Rust library function that can be executed by the WasmEdge CLI in the reactor mode.

The full source code for the Rust lib.rs file is as follows. It provides a simple `add()` function.

```
#[no_mangle]
pub fn add(a: i32, b: i32) -> i32 {
  return a + b;
}
```

A simple function: Build the WASM bytecode

```
cargo build --target wasm32-wasi
```

A simple function: Run the application from command line

We will use `wasmedge` in reactor mode to run the program. We pass the function name and its input parameters as command line arguments.

```
$ wasmedge --reactor target/wasm32-wasi/debug/add.wasm add 2 2
4
```

Pass Parameters with Complex Data Types

Of course, in most cases, you will not call functions using CLI arguments. Instead, you will probably need to use a language SDK from WasmEdge to call the function, pass call parameters, and receive return values. Below are some SDK examples for complex call parameters and return values.

- Use wasmedge-bindgen in a Go host app
- Use direct memory passing in a Go host app

Improve the Performance

To achieve native Rust performance for those applications, you could use the `wasmedgec` command to AOT compile the `wasm` program, and then run it with the `wasmedge` command.

```
$ wasmedgec hello.wasm hello_aot.wasm

$ wasmedge hello_aot.wasm second state
hello
second
state
```

For the `--reactor` mode,

```
$ wasmedgec add.wasm add_aot.wasm

$ wasmedge --reactor add_aot.wasm add 2 2
4
```

Further readings

- Bindgen can helper developers to create the WebAssembly library from Rust.
- Access OS services via WASI shows how the WebAssembly program can access the underlying OS services, such as file system and environment variables.
- Tensorflow shows how to create Tensorflow-based AI inference applications for WebAssembly using the WasmEdge TensorFlow Rust SDK.
- Neural Network for WASI shows how the WebAssembly program can leverage OpenVINO model to access the Machine Learning (ML) functions.
- Crypto for WASI shows how the WebAssembly program can access the crypto functions.
- Simple networking socket shows how to create simple HTTP client and server

applications using the WasmEdge networking socket Rust SDK.

- Simple networking socket in https shows how to create simple HTTPS client and server applications using the WasmEdge networking socket Rust SDK.
- Non-blocking networking socket shows how to create a high-performance non-blocking networking applications with concurrent open connections using the WasmEdge networking socket Rust SDK.
- Server-side rendering shows how to build an interactive web app with Rust, and then render the HTML DOM UI on the server using WasmEdge. The Rust source code is compiled to WebAssembly to render the HTML DOM in the browser or on the server.
- Command interface shows how to create native command applications for WebAssembly using the Wasmedge command interface Rust SDK.

Bindgen of Rust Functions

If your Rust program has a `main()` function, you could compile it into WebAssembly, and run it using the `wasmedge` CLI tool as a standalone application. However, a far more common use case is to compile a Rust function into WebAssembly, and then call it from a host application. That is known as an embedded WASM function. The host application uses WasmEdge language SDKs (e.g., Go, Rust, C, Python and Node.js) to call those WASM functions compiled from Rust source code.

All the WasmEdge host language SDKs support simple function calls. However, the WASM spec only supports a few simple data types as call parameters and return values, such as `i32`, `i64`, `f32`, `f64`, and `v128`. The `wasmedge-bindgen` crate would transform parameters and return values of Rust functions into simple integer types when the Rust function is compiled into WASM. For example, a string is automatically converted into two integers, a memory address and a length, which can be handled by the standard WASM spec. It is very easy to do this in Rust source code. Just annotate your function with the `#[wasmedge-bindgen]` macro. You can compile the annotated Rust code using the standard Rust compiler toolchain (e.g., the latest `Cargo`).

```
use wasmedge_bindgen::*;
use wasmedge_bindgen_macro::*;

#[wasmedge_bindgen]
pub fn say(s: String) -> Result<Vec<u8>, String> {
  let r = String::from("hello ");
  return Ok((r + s.as_str()).as_bytes().to_vec());
}
```

Of course, once the above Rust code is compiled into WASM, the function `say()` no longer takes the `String` parameter nor returns the `Vec<u8>`. So, the caller (i.e., the host application) must also deconstruct the call parameter into the memory pointer first before the call, and assemble the return value from the memory pointer after the call. These actions can be handled automagically by the WasmEdge language SDKs. To see a complete example, including the Rust WASM function and the Go host application, check out our tutorial in the Go SDK documentation.

A complete wasmedge-bindgen example in Rust (WASM) and Go (host)

Of course, the developer could choose to do `wasmedge-bindgen`'s work by hand and pass a memory pointer directly. If you are interested in this approach to call Rust compiled WASM functions, check out our examples in the Go SDK.

Access OS services

The WASI (WebAssembly Systems Interface) standard is designed to allow WebAssembly applications to access operating system services. The `wasm32-wasi` target in the Rust compiler supports WASI. In this section, we will use an example project to show how to use Rust standard APIs to access operating system services.

Random numbers

The WebAssembly VM is a pure software construct. It does not have a hardware entropy source for random numbers. That's why WASI defines a function for WebAssembly programs to call its host operating system to get a random seed. As a Rust developer, all you need is to use the popular (de facto standard) `rand` and/or `getrandom` crates. With the `wasm32-wasi` compiler backend, these crates generate the correct WASI calls in the WebAssembly bytecode. The `Cargo.toml` dependencies are as follows.

```
[dependencies]
rand = "0.7.3"
getrandom = "0.1.14"
```

The Rust code to get random number from WebAssembly is this.

```
use rand::prelude::*;

pub fn get_random_i32() -> i32 {
  let x: i32 = random();
  return x;
}

pub fn get_random_bytes() -> Vec<u8> {
  let mut rng = thread_rng();
  let mut arr = [0u8; 128];
  rng.fill(&mut arr[..]);
  return arr.to_vec();
}
```

Printing and debugging from Rust

The Rust `println!` marco just works in WASI. The statements print to the `STDOUT` of the

process that runs the WasmEdge.

```
pub fn echo(content: &str) -> String {
  println!("Printed from wasi: {}", content);
  return content.to_string();
}
```

Arguments and environment variables

It is possible to pass CLI arguments to and access OS environment variables in a WasmEdge application. They are just `env::args()` and `env::vars()` arrays in Rust.

```
use std::env;

pub fn print_env() {
  println!("The env vars are as follows.");
  for (key, value) in env::vars() {
    println!("{}: {}", key, value);
  }

  println!("The args are as follows.");
  for argument in env::args() {
    println!("{}", argument);
  }
}
```

Reading and writing files

WASI allows your Rust functions to access the host computer's file system through the standard Rust `std::fs` API. In the Rust program, you operate on files through a relative path. The relative path's root is specified when you start the WasmEdge runtime.

```
use std::fs;
use std::fs::File;
use std::io::{Write, Read};

pub fn create_file(path: &str, content: &str) {
  let mut output = File::create(path).unwrap();
  output.write_all(content.as_bytes()).unwrap();
}

pub fn read_file(path: &str) -> String {
  let mut f = File::open(path).unwrap();
  let mut s = String::new();
  match f.read_to_string(&mut s) {
    Ok(_) => s,
    Err(e) => e.to_string(),
  }
}

pub fn del_file(path: &str) {
  fs::remove_file(path).expect("Unable to delete");
}
```

A main() app

With a `main()` function, the Rust program can be compiled into a standalone WebAssembly program.

```
fn main() {
  println!("Random number: {}", get_random_i32());
  println!("Random bytes: {:?}", get_random_bytes());
  println!("{}", echo("This is from a main function"));
  print_env();
  create_file("tmp.txt", "This is in a file");
  println!("File content is {}", read_file("tmp.txt"));
  del_file("tmp.txt");
}
```

Use the command below to compile the Rust project.

```
cargo build --target wasm32-wasi
```

To run it in `wasmedge`, do the following. The `--dir` option maps the current directory of the command shell to the file system current directory inside the WebAssembly app.

```
$ wasmedge --dir .:. target/wasm32-wasi/debug/wasi.wasm hello
Random number: -68634548
Random bytes: [87, 117, 194, 122, 74, 189, 29, 1, 113, 26, 90, 6, 151, 20, 11,
169, 131, 212, 161, 220, 216, 190, 77, 234, 30, 10, 159, 7, 14, 89, 81, 111,
247, 136, 39, 195, 83, 90, 153, 225, 66, 16, 150, 217, 137, 172, 216, 203, 251,
37, 4, 27, 32, 57, 76, 237, 99, 147, 24, 175, 208, 157, 3, 220, 46, 224, 199,
153, 144, 96, 120, 89, 160, 38, 171, 239, 87, 218, 41, 184, 220, 78, 157, 57,
229, 198, 222, 72, 219, 118, 237, 27, 229, 28, 51, 116, 88, 101, 40, 139, 160,
51, 156, 102, 66, 233, 101, 50, 131, 9, 253, 186, 73, 148, 85, 36, 155, 254,
168, 202, 23, 96, 181, 99, 120, 136, 28, 147]
This is from a main function
The env vars are as follows.
... ...
The args are as follows.
target/wasm32-wasi/debug/wasi.wasm
hello
File content is This is in a file
```

Functions

As we have seen, you can create WebAssembly functions in a Rust `lib.rs` project. You can also use WASI functions in those functions. However, an important caveat is that, without a `main()` function, you will need to explicitly call a helper function to initialize environment for WASI functions to work properly. In the Rust program, add a helper crate in Cargo.toml so that the WASI initialization code can be applied to your exported public library functions.

```
[dependencies]
... ...
wasmedge-wasi-helper = "=0.2.0"
```

In the Rust function, we need to call `_initialize()` before we access any arguments and environment variables or operate any files.

```
pub fn print_env() -> i32 {
  _initialize();
  ... ...
}

pub fn create_file(path: &str, content: &str) -> String {
  _initialize();
  ... ...
}

pub fn read_file(path: &str) -> String {
  _initialize();
  ... ...
}

pub fn del_file(path: &str) -> String {
  _initialize();
  ... ...
}
```

Tensorflow

AI inference is a computationally intensive task that could benefit greatly from the speed of Rust and WebAssembly. However, the standard WebAssembly sandbox provides very limited access to the native OS and hardware, such as multi-core CPUs, GPU and specialized AI inference chips. It is not ideal for the AI workload.

The popular WebAssembly System Interface (WASI) provides a design pattern for sandboxed WebAssembly programs to securely access native host functions. The WasmEdge Runtime extends the WASI model to support access to native Tensorflow libraries from WebAssembly programs. The WasmEdge Tensorflow Rust SDK provides the security, portability, and ease-of-use of WebAssembly and native speed for Tensorflow.

> If you are not familiar with Rust, you can try our experimental AI inference DSL or try our JavaScript examples.

Table of contents

A Rust example

Prerequisite

You need to install WasmEdge and Rust.

Build

Check out the example source code.

```
git clone https://github.com/second-state/wasm-learning/
cd cli/tflite
```

Use Rust `Cargo` to build the WebAssembly target.

```
rustup target add wasm32-wasi
cargo build --target wasm32-wasi --release
```

Run

The `wasmedge-tensorflow-lite` utility is the WasmEdge build that includes the Tensorflow and Tensorflow Lite extensions.

```
$ wasmedge-tensorflow-lite target/wasm32-wasi/release/classify.wasm <
grace_hopper.jpg
It is very likely a <a href='https://www.google.com/search?q=military
uniform'>military uniform</a> in the picture
```

Make it run faster

To make Tensorflow inference run *much* faster, you could AOT compile it down to machine native code, and then use WasmEdge sandbox to run the native code.

```
$ wasmedgec target/wasm32-wasi/release/classify.wasm classify.wasm
$ wasmedge-tensorflow-lite classify.wasm < grace_hopper.jpg
It is very likely a <a href='https://www.google.com/search?q=military
uniform'>military uniform</a> in the picture
```

Code walkthrough

It is fairly straightforward to use the WasmEdge Tensorflow API. You can see the entire source code in main.rs.

First, it reads the trained TFLite model file (ImageNet) and its label file. The label file maps numeric output from the model to English names for the classified objects.

```
  let model_data: &[u8] = include_bytes!("models/mobilenet_v1_1.0_224
/mobilenet_v1_1.0_224_quant.tflite");
  let labels = include_str!("models/mobilenet_v1_1.0_224
/labels_mobilenet_quant_v1_224.txt");
```

Next, it reads the image from `STDIN` and converts it to the size and RGB pixel arrangement

required by the Tensorflow Lite model.

```
  let mut buf = Vec::new();
  io::stdin().read_to_end(&mut buf).unwrap();

  let flat_img = wasmedge_tensorflow_interface::load_jpg_image_to_rgb8(&buf,
224, 224);
```

Then, the program runs the TFLite model with its required input tensor (i.e., the flat image in this case), and receives the model output. In this case, the model output is an array of numbers. Each number corresponds to the probability of an object name in the label text file.

```
  let mut session = wasmedge_tensorflow_interface::Session::new(&model_data,
wasmedge_tensorflow_interface::ModelType::TensorFlowLite);
  session.add_input("input", &flat_img, &[1, 224, 224, 3])
         .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions
/Reshape_1");
```

Let's find the object with the highest probability, and then look up the name in the labels file.

```
  let mut i = 0;
  let mut max_index: i32 = -1;
  let mut max_value: u8 = 0;
  while i < res_vec.len() {
    let cur = res_vec[i];
    if cur > max_value {
      max_value = cur;
      max_index = i as i32;
    }
    i += 1;
  }

  let mut label_lines = labels.lines();
  for _i in 0..max_index {
    label_lines.next();
  }
```

Finally, it prints the result to `STDOUT`.

```
    let class_name = label_lines.next().unwrap().to_string();
    if max_value > 50 {
      println!("It {} a <a href='https://www.google.com/search?q={}'>{}</a> in
 the picture", confidence.to_string(), class_name, class_name);
    } else {
      println!("It does not appears to be any food item in the picture.");
    }
```

Deployment options

All the tutorials below use the WasmEdge Rust API for Tensorflow to create AI inference functions. Those Rust functions are then compiled to WebAssembly and deployed together with WasmEdge on the cloud.

Serverless functions

The following tutorials showcase how to deploy WebAssembly programs (written in Rust) on public cloud serverless platforms. The WasmEdge Runtime runs inside a Docker container on those platforms. Each serverless platform provides APIs to get data into and out of the WasmEdge runtime through STDIN and STDOUT.

- Vercel Serverless Functions
- Netlify Functions
- AWS Lambda
- Tencent Serverless Functions (in Chinese)

Second State FaaS and Node.js

The following tutorials showcase how to deploy WebAssembly functions (written in Rust) on the Second State FaaS. Since the FaaS service is running on Node.js, you can follow the same tutorials for running those functions in your own Node.js server.

- Tensorflow: Image classification using the MobileNet models | Live demo
- Tensorflow: Face detection using the MTCNN models | Live demo

Service mesh

The following tutorials showcase how to deploy WebAssembly functions and programs (written in Rust) as sidecar microservices.

- The Dapr template shows how to build and deploy Dapr sidecars in Go and Rust languages. The sidecars then use the WasmEdge SDK to start WebAssembly programs to process workloads to the microservices.

Data streaming framework

The following tutorials showcase how to deploy WebAssembly functions (written in Rust) as embedded handler functions in data streaming frameworks for AIoT.

- The YoMo template starts the WasmEdge Runtime to process image data as the data streams in from a camera in a smart factory.

Neural Network for WASI

In WasmEdge, we implemented the WASI-NN (Neural Network for WASI) proposal to allow access the Machine Learning (ML) functions with the fashion of graph loader APIs by the following functions:

- `Load` a model using variable opaque byte arrays
- `Init_execution_context` and bind some tensors to it using `set_input`
- `Compute` the ML inference using the bound context
- Retrieve the inference result tensors using `get_output`

You can find more detail about the WASI-NN proposal in Reference.

In this section, we will use the example repository to demonstrate how to use the WASI-NN rust crate to write the WASM and run an image classification demo with WasmEdge WASI-NN plug-in.

Prerequisites

Currently, WasmEdge used OpenVINO™ or PyTorch as the WASI-NN backend implementation. For using WASI-NN on WasmEdge, you need to install OpenVINO™(2021) or PyTorch 1.8.2 LTS for the backend.

You can also build WasmEdge with WASI-NN plug-in from source.

Get WasmEdge with WASI-NN Plug-in OpenVINO Backend

Note: In current, the OpenVINO™ backend of WASI-NN in WasmEdge supports Ubuntu 20.04 or above only.

First you should install the OpenVINO dependency:

```
export OPENVINO_VERSION="2021.4.582"
export OPENVINO_YEAR="2021"
curl -sSL https://apt.repos.intel.com/openvino/$OPENVINO_YEAR/GPG-PUB-KEY-
INTEL-OPENVINO-$OPENVINO_YEAR | sudo gpg --dearmor > /usr/share/keyrings/GPG-
PUB-KEY-INTEL-OPENVINO-$OPENVINO_YEAR.gpg
echo "deb [signed-by=/usr/share/keyrings/GPG-PUB-KEY-INTEL-
OPENVINO-$OPENVINO_YEAR.gpg] https://apt.repos.intel.com/openvino
/$OPENVINO_YEAR all main" | sudo tee /etc/apt/sources.list.d/intel-
openvino-$OPENVINO_YEAR.list
sudo apt update
sudo apt install -y intel-openvino-runtime-ubuntu20-$OPENVINO_VERSION
source /opt/intel/openvino_2021/bin/setupvars.sh
ldconfig
```

And then get the WasmEdge and the WASI-NN plug-in with OpenVINO backend:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 --plugins wasi_nn-openvino
```

Get WasmEdge with WASI-NN Plug-in PyTorch Backend

First you should install the PyTorch dependency:

```
export PYTORCH_VERSION="1.8.2"
# For the Ubuntu 20.04 or above, use the libtorch with cxx11 abi.
export PYTORCH_ABI="libtorch-cxx11-abi"
# For the manylinux2014, please use the without cxx11 abi version:
#   export PYTORCH_ABI="libtorch"
curl -s -L -O --remote-name-all https://download.pytorch.org/libtorch/lts/1.8
/cpu/${PYTORCH_ABI}-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip
unzip -q "${PYTORCH_ABI}-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
rm -f "${PYTORCH_ABI}-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
export LD_LIBRARY_PATH=${LD_LIBRARY_PATH}:$(pwd)/libtorch/lib
```

And then get the WasmEdge and the WASI-NN plug-in with PyTorch backend:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 --plugins wasi_nn-pytorch
```

Note: Please check that the Ubuntu version of WasmEdge and plug-in should use the cxx11-abi version of PyTorch, and the manylinux2014 version of WasmEdge and plug-in should use the PyTorch without cxx11-abi.

Get WasmEdge with WASI-NN Plug-in TensorFlow-Lite Backend

First you should install the TensorFlow-Lite dependency:

```
curl -s -L -O --remote-name-all https://github.com/second-state/WasmEdge-
tensorflow-deps/releases/download/0.11.2/WasmEdge-tensorflow-deps-TFLite-
0.11.2-manylinux2014_x86_64.tar.gz
tar -zxf WasmEdge-tensorflow-deps-TFLite-0.11.2-manylinux2014_x86_64.tar.gz
rm -f WasmEdge-tensorflow-deps-TFLite-0.11.2-manylinux2014_x86_64.tar.gz
```

The shared library will be extracted in the current directory `./libtensorflowlite_c.so`.

Then you can move the library to the installation path:

```
mv libtensorflowlite_c.so /usr/local/lib
```

Or set the environment variable `export LD_LIBRARY_PATH=$(pwd):${LD_LIBRARY_PATH}`.

And then get the WasmEdge and the WASI-NN plug-in with TensorFlow-Lite backend:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 --plugins wasi_nn-tensorflowlite
```

Write WebAssembly Using WASI-NN

You can refer to the OpenVINO backend example and the PyTorch backend example.

(Optional) Rust Installation

If you want to build the example WASM from Rust by yourself, the Rust inatallation is required.

```
curl --proto '=https' --tlsv1.2 https://sh.rustup.rs -sSf | sh -s -- -y
source "$HOME/.cargo/env"
```

And make sure to add `wasm32-wasi` target with the following command:

```
rustup target add wasm32-wasi
```

(Optional) Building the WASM File From Rust Source

First get the example repository:

```
git clone https://github.com/second-state/WasmEdge-WASINN-examples.git
cd WasmEdge-WASINN-examples
```

To build the OpenVINO example WASM, run:

```
cd openvino-mobilenet-image/rust
cargo build --release --target=wasm32-wasi
```

The outputted `wasmedge-wasinn-example-mobilenet-image.wasm` will be under `openvino-mobilenet-image/rust/target/wasm32-wasi/release/` .

To build the PyTorch example WASM, run:

```
cd pytorch-mobilenet-image/rust
cargo build --release --target=wasm32-wasi
```

The outputted `wasmedge-wasinn-example-mobilenet-image.wasm` will be under `pytorch-mobilenet-image/rust/target/wasm32-wasi/release/` .

To build the TensorFlow-Lite example WASM, run:

```
cd tflite-birds_v1-image/rust/tflite-bird
cargo build --release --target=wasm32-wasi
```

The outputted `wasmedge-wasinn-example-tflite-bird-image.wasm` will be under `tflite-birds_v1-image/rust/tflite-bird/target/wasm32-wasi/release/` .

We can find that the outputted WASM files import the necessary WASI-NN functions by converting into WAT format with tools like `wasm2wat`:

```
 ...
 (import "wasi_ephemeral_nn" "load" (func
$_ZN7wasi_nn9generated17wasi_ephemeral_nn4load17hdca997591f45db43E (type 8)))
  (import "wasi_ephemeral_nn" "init_execution_context" (func
$_ZN7wasi_nn9generated17wasi_ephemeral_nn22init_execution_context17h2cb3b4398c1
8d1fdE (type 4)))
  (import "wasi_ephemeral_nn" "set_input" (func
$_ZN7wasi_nn9generated17wasi_ephemeral_nn9set_input17h4d10422433f5c246E (type
7)))
  (import "wasi_ephemeral_nn" "get_output" (func
$_ZN7wasi_nn9generated17wasi_ephemeral_nn10get_output17h117ce8ea097ddbebE (type
8)))
  (import "wasi_ephemeral_nn" "compute" (func
$_ZN7wasi_nn9generated17wasi_ephemeral_nn7compute17h96ef5b407fe8173aE (type
5)))
  ...
```

Using WASI-NN with OpenVINO Backend in Rust

The main.rs is the full example Rust source.

First, read the model description and weights into memory:

```
let args: Vec<String> = env::args().collect();
let model_xml_name: &str = &args[1]; // File name for the model xml
let model_bin_name: &str = &args[2]; // File name for the weights
let image_name: &str = &args[3]; // File name for the input image

let xml = fs::read_to_string(model_xml_name).unwrap();
let weights = fs::read(model_bin_name).unwrap();
```

We should use a helper function to convert the input image into the tensor data (the tensor type is `F32`):

```
fn image_to_tensor(path: String, height: u32, width: u32) -> Vec<u8> {
  let pixels = Reader::open(path).unwrap().decode().unwrap();
  let dyn_img: DynamicImage = pixels.resize_exact(width, height,
image::imageops::Triangle);
  let bgr_img = dyn_img.to_bgr8();
  // Get an array of the pixel values
  let raw_u8_arr: &[u8] = &bgr_img.as_raw()[..];
  // Create an array to hold the f32 value of those pixels
  let bytes_required = raw_u8_arr.len() * 4;
  let mut u8_f32_arr: Vec<u8> = vec![0; bytes_required];

  for i in 0..raw_u8_arr.len() {
    // Read the number as a f32 and break it into u8 bytes
    let u8_f32: f32 = raw_u8_arr[i] as f32;
    let u8_bytes = u8_f32.to_ne_bytes();

    for j in 0..4 {
      u8_f32_arr[(i * 4) + j] = u8_bytes[j];
    }
  }
  return u8_f32_arr;
}
```

And use this helper function to convert the input image:

```
let tensor_data = image_to_tensor(image_name.to_string(), 224, 224);
```

Now we can start our inference with WASI-NN:

```
// load model
let graph = unsafe {
  wasi_nn::load(
    &[&xml.into_bytes(), &weights],
    wasi_nn::GRAPH_ENCODING_OPENVINO,
    wasi_nn::EXECUTION_TARGET_CPU,
  )
  .unwrap()
};
// initialize the computation context
let context = unsafe { wasi_nn::init_execution_context(graph).unwrap() };
// initialize the input tensor
let tensor = wasi_nn::Tensor {
  dimensions: &[1, 3, 224, 224],
  type_: wasi_nn::TENSOR_TYPE_F32,
  data: &tensor_data,
};
// set_input
unsafe {
  wasi_nn::set_input(context, 0, tensor).unwrap();
}
// Execute the inference.
unsafe {
  wasi_nn::compute(context).unwrap();
}
// retrieve output
let mut output_buffer = vec![0f32; 1001];
unsafe {
  wasi_nn::get_output(
    context,
    0,
    &mut output_buffer[..] as *mut [f32] as *mut u8,
    (output_buffer.len() * 4).try_into().unwrap(),
  )
  .unwrap();
}
```

Where the `wasi_nn::GRAPH_ENCODING_OPENVINO` means using the OpenVINO™ backend, and `wasi_nn::EXECUTION_TARGET_CPU` means running the computation on CPU.

Finally, we sort the output and then print the top-5 classification result:

```
let results = sort_results(&output_buffer);
for i in 0..5 {
  println!(
    "   {}.) [{}]({:.4}){}",
    i + 1,
    results[i].0,
    results[i].1,
    imagenet_classes::IMAGENET_CLASSES[results[i].0]
  );
}
```

Using WASI-NN with PyTorch Backend in Rust

The main.rs is the full example Rust source.

First, read the model description and weights into memory:

```
let args: Vec<String> = env::args().collect();
let model_bin_name: &str = &args[1]; // File name for the pytorch model
let image_name: &str = &args[2]; // File name for the input image

let weights = fs::read(model_bin_name).unwrap();
```

We should use a helper function to convert the input image into the tensor data (the tensor type is `F32`):

```
fn image_to_tensor(path: String, height: u32, width: u32) -> Vec<u8> {
  let mut file_img = File::open(path).unwrap();
  let mut img_buf = Vec::new();
  file_img.read_to_end(&mut img_buf).unwrap();
  let img = image::load_from_memory(&img_buf).unwrap().to_rgb8();
  let resized =
      image::imageops::resize(&img, height, width,
::image::imageops::FilterType::Triangle);
  let mut flat_img: Vec<f32> = Vec::new();
  for rgb in resized.pixels() {
    flat_img.push((rgb[0] as f32 / 255. - 0.485) / 0.229);
    flat_img.push((rgb[1] as f32 / 255. - 0.456) / 0.224);
    flat_img.push((rgb[2] as f32 / 255. - 0.406) / 0.225);
  }
  let bytes_required = flat_img.len() * 4;
  let mut u8_f32_arr: Vec<u8> = vec![0; bytes_required];

  for c in 0..3 {
    for i in 0..(flat_img.len() / 3) {
      // Read the number as a f32 and break it into u8 bytes
      let u8_f32: f32 = flat_img[i * 3 + c] as f32;
      let u8_bytes = u8_f32.to_ne_bytes();

      for j in 0..4 {
        u8_f32_arr[((flat_img.len() / 3 * c + i) * 4) + j] = u8_bytes[j];
      }
    }
  }
  return u8_f32_arr;
}
```

And use this helper function to convert the input image:

```
let tensor_data = image_to_tensor(image_name.to_string(), 224, 224);
```

Now we can start our inference with WASI-NN:

```
// load model
let graph = unsafe {
  wasi_nn::load(
    &[&weights],
    wasi_nn::GRAPH_ENCODING_PYTORCH,
    wasi_nn::EXECUTION_TARGET_CPU,
  )
  .unwrap()
};
// initialize the computation context
let context = unsafe { wasi_nn::init_execution_context(graph).unwrap() };
// initialize the input tensor
let tensor = wasi_nn::Tensor {
  dimensions: &[1, 3, 224, 224],
  type_: wasi_nn::TENSOR_TYPE_F32,
  data: &tensor_data,
};
// set_input
unsafe {
  wasi_nn::set_input(context, 0, tensor).unwrap();
}
// Execute the inference.
unsafe {
  wasi_nn::compute(context).unwrap();
}
// retrieve output
let mut output_buffer = vec![0f32; 1001];
unsafe {
  wasi_nn::get_output(
    context,
    0,
    &mut output_buffer[..] as *mut [f32] as *mut u8,
    (output_buffer.len() * 4).try_into().unwrap(),
  )
  .unwrap();
}
```

Where the `wasi_nn::GRAPH_ENCODING_PYTORCH` means using the PyTorch backend, and `wasi_nn::EXECUTION_TARGET_CPU` means running the computation on CPU.

Finally, we sort the output and then print the top-5 classification result:

```
let results = sort_results(&output_buffer);
for i in 0..5 {
  println!(
    "   {}.) [{}]({:.4}){}",
    i + 1,
    results[i].0,
    results[i].1,
    imagenet_classes::IMAGENET_CLASSES[results[i].0]
  );
}
```

Using WASI-NN with TensorFlow-Lite Backend in Rust

The main.rs is the full example Rust source.

First, read the model description and weights into memory:

```
let args: Vec<String> = env::args().collect();
let model_bin_name: &str = &args[1]; // File name for the tflite model
let image_name: &str = &args[2]; // File name for the input image

let weights = fs::read(model_bin_name).unwrap();
```

We should use a helper function to convert the input image into the tensor data (the tensor type is `U8`):

```
fn image_to_tensor(path: String, height: u32, width: u32) -> Vec<u8> {
    let pixels = Reader::open(path).unwrap().decode().unwrap();
    let dyn_img: DynamicImage = pixels.resize_exact(width, height,
image::imageops::Triangle);
    let bgr_img = dyn_img.to_rgb8();
    // Get an array of the pixel values
    let raw_u8_arr: &[u8] = &bgr_img.as_raw()[..];
    return raw_u8_arr.to_vec();
}
```

And use this helper function to convert the input image:

```
let tensor_data = image_to_tensor(image_name.to_string(), 224, 224);
```

Now we can start our inference with WASI-NN:

```
// load model
let graph = unsafe {
  wasi_nn::load(
    &[&weights],
    4, //wasi_nn::GRAPH_ENCODING_TENSORFLOWLITE
    wasi_nn::EXECUTION_TARGET_CPU,
  )
  .unwrap()
};
// initialize the computation context
let context = unsafe { wasi_nn::init_execution_context(graph).unwrap() };
// initialize the input tensor
let tensor = wasi_nn::Tensor {
  dimensions: &[1, 3, 224, 224],
  r#type: wasi_nn::TENSOR_TYPE_F32,
  data: &tensor_data,
};
// set_input
unsafe {
  wasi_nn::set_input(context, 0, tensor).unwrap();
}
// Execute the inference.
unsafe {
  wasi_nn::compute(context).unwrap();
}
// retrieve output
let mut output_buffer = vec![0f32; 1001];
unsafe {
  wasi_nn::get_output(
    context,
    0,
    &mut output_buffer[..] as *mut [f32] as *mut u8,
    (output_buffer.len() * 4).try_into().unwrap(),
  )
  .unwrap();
}
```

Where the `wasi_nn::GRAPH_ENCODING_TENSORFLOWLITE` means using the PyTorch backend (now use the value `4` instead), and `wasi_nn::EXECUTION_TARGET_CPU` means running the computation on CPU.

> Note: Here we use the `wasi-nn 0.1.0` in current. After the `TENSORFLOWLITE` added into the graph encoding, we'll update this example to use the newer version.

Finally, we sort the output and then print the top-5 classification result:

```
let results = sort_results(&output_buffer);
for i in 0..5 {
  println!(
    "   {}.) [{}]({:.4}){}",
    i + 1,
    results[i].0,
    results[i].1,
    imagenet_classes::IMAGENET_CLASSES[results[i].0]
  );
}
```

Run

OpenVINO Backend Example

Please install WasmEdge with the WASI-NN OpenVINO backend plug-in first.

For the example demo of Mobilenet, we need the fixture files:

- `wasmedge-wasinn-example-mobilenet.wasm` : the built WASM from rust
- `mobilenet.xml` : the model description.
- `mobilenet.bin` : the model weights.
- `input.jpg` : the input image (224x224 JPEG).

The above Mobilenet artifacts are generated by OpenVINO™ Model Optimizer. Thanks for the amazing jobs done by Andrew Brown, you can find the artifacts and a `build.sh` which can regenerate the artifacts here.

You can download these files by the following commands:

```
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/openvino-mobilenet-image/wasmedge-wasinn-example-mobilenet-image.wasm
curl -sLO https://github.com/intel/openvino-rs/raw/v0.3.3/crates/openvino/tests
/fixtures/mobilenet/mobilenet.bin
curl -sLO https://github.com/intel/openvino-rs/raw/v0.3.3/crates/openvino/tests
/fixtures/mobilenet/mobilenet.xml
curl -sL -o input.jpg https://github.com/bytecodealliance/wasi-nn/raw/main/rust
/examples/images/1.jpg
```

Then you can use the OpenVINO-enabled WasmEdge which was compiled above to execute the WASM file (in interpreter mode):

```
wasmedge --dir .:. wasmedge-wasinn-example-mobilenet-image.wasm mobilenet.xml
mobilenet.bin input.jpg
# If you didn't install the project, you should give the `WASMEDGE_PLUGIN_PATH`
environment variable for specifying the WASI-NN plugin path.
```

If everything goes well, you should have the terminal output:

```
Read graph XML, size in bytes: 143525
Read graph weights, size in bytes: 13956476
Loaded graph into wasi-nn with ID: 0
Created wasi-nn execution context with ID: 0
Read input tensor, size in bytes: 602112
Executed graph inference
   1.) [954](0.9789)banana
   2.) [940](0.0074)spaghetti squash
   3.) [951](0.0014)lemon
   4.) [969](0.0005)eggnog
   5.) [942](0.0005)butternut squash
```

For the AOT mode which is much more quickly, you can compile the WASM first:

```
wasmedgec wasmedge-wasinn-example-mobilenet.wasm out.wasm
wasmedge --dir .:. out.wasm mobilenet.xml mobilenet.bin input.jpg
```

PyTorch Backend Example

Please install WasmEdge with the WASI-NN PyTorch backend plug-in first.

For the example demo of Mobilenet, we need these following files:

- `wasmedge-wasinn-example-mobilenet.wasm` : the built WASM from rust
- `mobilenet.pt` : the PyTorch Mobilenet model.
- `input.jpg` : the input image (224x224 JPEG).

The above Mobilenet PyTorch model is generated by the Python code.

You can download these files by the following commands:

```
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/pytorch-mobilenet-image/wasmedge-wasinn-example-mobilenet-image.wasm
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/pytorch-mobilenet-image/mobilenet.pt
curl -sL -o input.jpg https://github.com/bytecodealliance/wasi-nn/raw/main/rust
/examples/images/1.jpg
```

Then you can use the PyTorch-enabled WasmEdge which was compiled above to execute the WASM file (in interpreter mode):

```
# Please check that you've already install the libtorch and set the
`LD_LIBRARY_PATH`.
wasmedge --dir .:. wasmedge-wasinn-example-mobilenet-image.wasm mobilenet.pt
input.jpg
# If you didn't install the project, you should give the `WASMEDGE_PLUGIN_PATH`
environment variable for specifying the WASI-NN plugin path.
```

If everything goes well, you should have the terminal output:

```
Read torchscript binaries, size in bytes: 14376924
Loaded graph into wasi-nn with ID: 0
Created wasi-nn execution context with ID: 0
Read input tensor, size in bytes: 602112
Executed graph inference
   1.) [954](20.6681)banana
   2.) [940](12.1483)spaghetti squash
   3.) [951](11.5748)lemon
   4.) [950](10.4899)orange
   5.) [953](9.4834)pineapple, ananas
```

For the AOT mode which is much more quickly, you can compile the WASM first:

```
wasmedgec wasmedge-wasinn-example-mobilenet.wasm out.wasm
wasmedge --dir .:. out.wasm mobilenet.pt input.jpg
```

TensorFlow-Lite Backend Example

Please install WasmEdge with the WASI-NN TensorFlow-Lite backend plug-in first.

For the example demo of Bird v1, we need these following files:

- `wasmedge-wasinn-example-tflite-bird-image.wasm` : the built WASM from rust
- `lite-model_aiy_vision_classifier_birds_V1_3.tflite` : the TensorFlow-Lite bird_v1 model.
- `input.jpg` : the input image (224x224 JPEG).

The above Mobilenet PyTorch model is generated by the Python code.

You can download these files by the following commands:

```
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/tflite-birds_v1-image/wasmedge-wasinn-example-tflite-bird-image.wasm
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/tflite-birds_v1-image/lite-model_aiy_vision_classifier_birds_V1_3.tflite
curl -sLO https://github.com/second-state/WasmEdge-WASINN-examples/raw/master
/tflite-birds_v1-image/bird.jpg
```

Then you can use the PyTorch-enabled WasmEdge which was compiled above to execute the WASM file (in interpreter mode):

```
# Please check that you've already install the libtensorflowlite_c.so and set
the `LD_LIBRARY_PATH`.
wasmedge --dir .:. wasmedge-wasinn-example-tflite-bird-image.wasm lite-
model_aiy_vision_classifier_birds_V1_3.tflite bird.jpg
# If you didn't install the project, you should give the `WASMEDGE_PLUGIN_PATH`
environment variable for specifying the WASI-NN plugin path.
```

If everything goes well, you should have the terminal output:

```
Read graph weights, size in bytes: 3561598
Loaded graph into wasi-nn with ID: 0
Created wasi-nn execution context with ID: 0
Read input tensor, size in bytes: 150528
Executed graph inference
   1.) [166](198)Aix galericulata
   2.) [158](2)Coccothraustes coccothraustes
   3.) [34](1)Gallus gallus domesticus
   4.) [778](1)Sitta europaea
   5.) [819](1)Anas platyrhynchos
```

For the AOT mode which is much more quickly, you can compile the WASM first:

```
wasmedgec wasmedge-wasinn-example-tflite-bird-image.wasm out.wasm
wasmedge --dir .:. out.wasm lite-model_aiy_vision_classifier_birds_V1_3.tflite
bird.jpg
```

Reference

The intoduction of WASI-NN can be referred to this amazing blog written by Andrew Brown. This demo is greatly adapted from another demo.

Crypto for WASI

While optimizing compilers could allow efficient implementation of cryptographic features in WebAssembly, there are several occasions as below where a host implementation is more desirable. WASI-crypto aims to fill those gaps by defining a standard interface as a set of APIs. Current not support android.

Prerequisites

For installation with the installer, you can follow the commands:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 --plugins wasi_crypto
```

You can also build WasmEdge with WASI-Crypto plug-in from source.

Write WebAssembly Using WASI-Crypto

(Optional) Rust Installation

For importing WASI-Crypto in rust, you should use the wasi-crypto binding in your cargo.toml

```
[dependencies]
wasi-crypto = "0.1.5"
```

High Level Operations

Hash Function

Identifier	Algorithm
`SHA-256`	SHA-256 hash function
`SHA-512`	SHA-512 hash function

Identifier	Algorithm
SHA-512/256	SHA-512/256 hash function with a specific IV

```
// hash "test" by SHA-256
let hash : Vec<u8> = Hash::hash("SHA-256", b"test", 32, None)?;
assert_eq!(hash.len(), 32);
```

Message Authentications function

Identifier	Algorithm
HMAC/SHA-256	RFC2104 MAC using the SHA-256 hash function
HMAC/SHA-512	RFC2104 MAC using the SHA-512 hash function

```
// generate key
let key = AuthKey::generate("HMAC/SHA-512")?;
// generate tag
let tag = Auth::auth("test", &key)?;
// verify
Auth::auth_verify("test", &key, tag)?;
```

Key Driven function

Identifier	Algorithm
HKDF-EXTRACT/SHA-256	RFC5869 EXTRACT function using the SHA-256 hash function
HKDF-EXTRACT/SHA-512	RFC5869 EXTRACT function using the SHA-512 hash function
HKDF-EXPAND/SHA-256	RFC5869 EXPAND function using the SHA-256 hash function
HKDF-EXPAND/SHA-512	RFC5869 EXPAND function using the SHA-512 hash function

Example:

```
let key = HkdfKey::generate("HKDF-EXTRACT/SHA-512")?;
let prk = Hkdf::new("HKDF-EXPAND/SHA-512", &key, Some(b"salt"))?;
let derived_key = prk.expand("info", 100)?;
assert_eq!(derived_key.len(), 100);
```

Signatures Operation

Identifier	Algorithm
`ECDSA_P256_SHA256`	ECDSA over the NIST p256 curve with the SHA-256 hash function
`ECDSA_K256_SHA256`	ECDSA over the secp256k1 curve with the SHA-256 hash function
`Ed25519`	Edwards Curve signatures over Edwards25519 (pure EdDSA) as specified in RFC8032
`RSA_PKCS1_2048_SHA256`	RSA signatures with a 2048 bit modulus, PKCS1 padding and the SHA-256 hash function
`RSA_PKCS1_2048_SHA384`	RSA signatures with a 2048 bit modulus, PKCS1 padding and the SHA-384 hash function
`RSA_PKCS1_2048_SHA512`	RSA signatures with a 2048 bit modulus, PKCS1 padding and the SHA-512 hash function
`RSA_PKCS1_3072_SHA384`	RSA signatures with a 3072 bit modulus, PKCS1 padding and the SHA-384 hash function
`RSA_PKCS1_3072_SHA512`	RSA signatures with a 3072 bit modulus, PKCS1 padding and the SHA-512 hash function
`RSA_PKCS1_4096_SHA512`	RSA signatures with a 4096 bit modulus, PKCS1 padding and the SHA-512 hash function
`RSA_PSS_2048_SHA256`	RSA signatures with a 2048 bit modulus, PSS padding and the SHA-256 hash function
`RSA_PSS_2048_SHA384`	RSA signatures with a 2048 bit modulus, PSS padding and the SHA-384 hash function
`RSA_PSS_2048_SHA512`	RSA signatures with a 2048 bit modulus, PSS padding and the SHA-512 hash function
`RSA_PSS_3072_SHA384`	RSA signatures with a 2048 bit modulus, PSS padding and the SHA-384 hash function
`RSA_PSS_3072_SHA512`	RSA signatures with a 3072 bit modulus, PSS padding and the SHA-512 hash function
`RSA_PSS_4096_SHA512`	RSA signatures with a 4096 bit modulus, PSS padding and the SHA-512 hash function

Example:

```
let pk = SignaturePublicKey::from_raw("Ed25519", &[0; 32])?;

let kp = SignatureKeyPair::generate("Ed25519")?;
let signature = kp.sign("hello")?;

kp.publickey()?.signature_verify("hello", &signature)?;
```

Simple Networking Sockets

The wasmedge_wasi_socket crate enables Rust developers to create networking applications and compile them into WebAssembly for WasmEdge Runtime. One of the key features of WasmEdge is that it supports non-blocking sockets. That allows even a single threaded WASM application to handle concurrent network requests. For example, while the program is waiting for data to stream in from one connection, it can start or handle another connection.

In this chapter, we will start with simple HTTP client and server examples. Then in the next chapter, we will cover the more complex non-blocking examples. And in this chapter, we will give the examples for HTTPS requests.

An HTTP client example

The source code for the HTTP client is available as follows.

```
use wasmedge_http_req::request;

fn main() {
  let mut writer = Vec::new(); //container for body of a response
  let res = request::get("http://127.0.0.1:1234/get", &mut writer).unwrap();

  println!("GET");
  println!("Status: {} {}", res.status_code(), res.reason());
  println!("Headers {}", res.headers());
  println!("{}", String::from_utf8_lossy(&writer));

  let mut writer = Vec::new(); //container for body of a response
  const BODY: &[u8; 27] = b"field1=value1&field2=value2";
  // let res = request::post("https://httpbin.org/post", BODY, &mut
writer).unwrap();
  // no https , no dns
  let res = request::post("http://127.0.0.1:1234/post", BODY, &mut
writer).unwrap();

  println!("POST");
  println!("Status: {} {}", res.status_code(), res.reason());
  println!("Headers {}", res.headers());
  println!("{}", String::from_utf8_lossy(&writer));
}
```

The following command compiles the Rust program.

```
cargo build --target wasm32-wasi --release
```

The following command runs the application in WasmEdge.

```
wasmedge target/wasm32-wasi/release/http_client.wasm
```

Noticed that you should install the WasmEdge-HttpsReq plug-in.

An HTTP server example

The source code for the HTTP server application is available as follows.

```
use bytecodec::DecodeExt;
use httpcodec::{HttpVersion, ReasonPhrase, Request, RequestDecoder, Response,
StatusCode};
use std::io::{Read, Write};
#[cfg(feature = "std")]
use std::net::{Shutdown, TcpListener, TcpStream};
#[cfg(not(feature = "std"))]
use wasmedge_wasi_socket::{Shutdown, TcpListener, TcpStream};

fn handle_http(req: Request<String>) -> bytecodec::Result<Response<String>> {
  Ok(Response::new(
    HttpVersion::V1_0,
    StatusCode::new(200)?,
    ReasonPhrase::new("")?,
    format!("echo: {}", req.body()),
  ))
}

fn handle_client(mut stream: TcpStream) -> std::io::Result<()> {
  let mut buff = [0u8; 1024];
  let mut data = Vec::new();

  loop {
    let n = stream.read(&mut buff)?;
    data.extend_from_slice(&buff[0..n]);
    if n < 1024 {
      break;
    }
  }

  let mut decoder =
    RequestDecoder::
<httpcodec::BodyDecoder<bytecodec::bytes::Utf8Decoder>>::default();

  let req = match decoder.decode_from_bytes(data.as_slice()) {
    Ok(req) => handle_http(req),
    Err(e) => Err(e),
  };

  let r = match req {
    Ok(r) => r,
    Err(e) => {
      let err = format!("{:?}", e);
      Response::new(
        HttpVersion::V1_0,
        StatusCode::new(500).unwrap(),
        ReasonPhrase::new(err.as_str()).unwrap(),
        err.clone(),
      )
    }
  };
```

```
  let write_buf = r.to_string();
  stream.write(write_buf.as_bytes())?;
  stream.shutdown(Shutdown::Both)?;
  Ok(())
}

fn main() -> std::io::Result<()> {
  let port = std::env::var("PORT").unwrap_or(1234.to_string());
  println!("new connection at {}", port);
  let listener = TcpListener::bind(format!("0.0.0.0:{}", port))?;
  loop {
    let _ = handle_client(listener.accept()?.0);
  }
}
```

The following command compiles the Rust program.

```
cargo build --target wasm32-wasi --release
```

The following command runs the application in WasmEdge.

```
$ wasmedge target/wasm32-wasi/release/http_server.wasm
new connection at 1234
```

To test the HTTP server, you can submit a HTTP request to it via `curl`.

```
$ curl -d "name=WasmEdge" -X POST http://127.0.0.1:1234
echo: name=WasmEdge
```

Networking for HTTPS

The WasmEdge WASI socket API supports HTTP networking in Wasm apps. In order to achieve the goal of supporting HTTPS requests with the same API as an HTTP request, we now create a WasmEdge plugin using the OpenSSL library. In this chapter, we will give the example of HTTPS requests and explain the design.

Prerequisites

For installation with the installer, you can follow the commands:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 --plugins wasmedge_httpsreq
```

An HTTPS request example

The example source code for the HTTPS request is available as follows. The HTTP and HTTPS APIs are the same. The Err messages are presented differently because the HTTP uses the rust code while the HTTPS request uses a wasmedge host function.

```
use wasmedge_http_req::request;

fn main() {
    // get request
    let mut writer = Vec::new(); //container for body of a response
    let mut res = request::get("https://httpbin.org/get", &mut
writer).unwrap();

    println!("Status: {} {}", res.status_code(), res.reason());
    println!("Headers {}", res.headers());
    //println!("{}", String::from_utf8_lossy(&writer));  // uncomment this line
to display the content of writer

    // head request
    res = request::head("https://httpbin.org/head").unwrap();

    println!("Status: {} {}", res.status_code(), res.reason());
    println!("{:?}", res.headers());

    // post request
    writer = Vec::new(); //container for body of a response
    const BODY: &[u8; 27] = b"field1=value1&field2=value2";
    res = request::post("https://httpbin.org/post", BODY, &mut
writer).unwrap();

    println!("Status: {} {}", res.status_code(), res.reason());
    println!("Headers {}", res.headers());
    //println!("{}", String::from_utf8_lossy(&writer));  // uncomment this line
to display the content of writer

    // add headers and set version
    let uri = Uri::try_from("http://httpbin.org/get").unwrap();
    // let uri = Uri::try_from("https://httpbin.org/get").unwrap(); //
uncomment the line for https request

    // add headers to the request
    let mut headers = Headers::new();
    headers.insert("Accept-Charset", "utf-8");
    headers.insert("Accept-Language", "en-US");
    headers.insert("Host", "rust-lang.org");
    headers.insert("Connection", "Close");

    let mut response = Request::new(&uri)
        .headers(headers)
        .send(&mut writer)
        .unwrap();

    println!("{}", String::from_utf8_lossy(&writer));

    // set version
    response = Request::new(&uri)
        .version(HttpVersion::Http10)
```

```
        .send(&mut writer)
        .unwrap();

    println!("{}", String::from_utf8_lossy(&writer));
}
```

The following command compiles the Rust program

```
# build the wasmedge httpsreq plugin module
sudo apt-get install libssl-dev
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_BUILD_TESTS=OFF
-DWASMEDGE_PLUGIN_HTTPSREQ=On  .. && make -j4

cargo build --target wasm32-wasi --release
```

The following command runs the application in WasmEdge.

```
wasmedge target/wasm32-wasi/release/get_https.wasm
wasmedge target/wasm32-wasi/release/post_https.wasm
wasmedge target/wasm32-wasi/release/head_https.wasm
```

Explanation of design

It is observed that the request is first parsed and then added to a stream which sends the parsed request to the server. We remain the first step that is HTTPS request is parsed in the original Rust code. We modify the second step by replacing it with a function called `send_data` that is implemented by the wasmedge_httpsreq host function. We also let the original Rust source code to process the received content by implementing two additional functions `get_rcv_len` and `get_rcv`.

The advantage of this design is that because the first step is retained, we can use the same API for HTTP and HTTPS request. Besides, one function (i.e. send_data in httpsreq plugin) is needed for all types of requests as long as it is supported in wasmedge_http_req. `send_data` function receives three parameters namely the host, the port and the parsed request. An example for using the send_data function is available as follows.

```
send_data("www.google.com", 443, "GET / HTTP/1.1\nHost: www.google.com\r
\nConnection: Close\r\nReferer: https://www.google.com/\r\n\r\n");
```

So, We only do a little change to the original Rust code.

```
if self.inner.uri.scheme() == "https" {
let buf = &self.inner.parse_msg();
    let body = String::from_utf8_lossy(buf);
    send_data(host, port.into(), &body);
    let output = get_receive();
    let tmp = String::from_utf8(output.rcv_vec).unwrap();
    let res = Response::try_from(tmp.as_bytes(), writer).unwrap();
    return Ok(res);
}
```

To add the host function to a crate that can be used by Rust code, we also implement the httpreq module.

Implementation of httpsreq host function

The httpsreq host has three functions (i.e. `send_data`, `get_rcv_len` and `get_rcv`) The `send_data` function uses the OpenSSL library to send the data to the server. The `send_data` function receives three inputs, that is, the host, the port and the parsed request.

```
Expect<void> WasmEdgeHttpsReqSendData::body(const Runtime::CallingFrame &Frame,
                                            uint32_t HostPtr, uint32_t HostLen,
                                            uint32_t Port, uint32_t BodyPtr,
                                            uint32_t BodyLen)
```

The `get_rcv` function and `get_rcv_len` function pass the received content out of the host function which is later processed by the original Rust code. The get_rcv function receives the pointer while the get_rcv_len function returns the length of the received content.

```
Expect<void> WasmEdgeHttpsReqGetRcv::body(const Runtime::CallingFrame &Frame,
                                          uint32_t BufPtr)

Expect<uint32_t>
WasmEdgeHttpsReqGetRcvLen::body(const Runtime::CallingFrame &)
```

It then opens the connection. Next, use the `SSL_write` to write the parsed request to the connection. Finally, it receives by using `SSL_read` and prints the receive to the console.

Non-blocking Networking Sockets

While the simple HTTP connections from the previous chapter are easy to implement, they are not ready for production use. If the program can only have one connection open at a time (e.g., blocking), the fast CPU would be waiting for the slow network. Non-blocking I/O means that the application program can keep multiple connections open at the same time, and process data in and out of those connections as they come in. The program can either alternatingly poll those open connections or wait for incoming data to trigger async functions. That allows I/O intensive programs to run much faster even in a single-threaded environment. In this chapter, we will cover both polling and async programming models.

A non-blocking HTTP client example

The source code for a non-blocking HTTP client application is available. The following `main()` function starts two HTTP connections. The program keeps both connections open, and alternatingly checks for incoming data from them. In another word, the two connections are not blocking each other. Their data are handled concurrently (or alternatingly) as the data comes in.

```
use httparse::{Response, EMPTY_HEADER};
use std::io::{self, Read, Write};
use std::str::from_utf8;
use wasmedge_wasi_socket::TcpStream;

fn main() {
    let req = "GET / HTTP/1.0\n\n";
    let mut first_connection = TcpStream::connect("127.0.0.1:80").unwrap();
    first_connection.set_nonblocking(true).unwrap();
    first_connection.write_all(req.as_bytes()).unwrap();

    let mut second_connection = TcpStream::connect("127.0.0.1:80").unwrap();
    second_connection.set_nonblocking(true).unwrap();
    second_connection.write_all(req.as_bytes()).unwrap();

    let mut first_buf = vec![0; 4096];
    let mut first_bytes_read = 0;
    let mut second_buf = vec![0; 4096];
    let mut second_bytes_read = 0;

    loop {
        let mut first_complete = false;
        let mut second_complete = false;
        if !first_complete {
            match read_data(&mut first_connection, &mut first_buf,
first_bytes_read) {
                Ok((bytes_read, false)) => {
                    first_bytes_read = bytes_read;
                }
                Ok((bytes_read, true)) => {
                    println!("First connection completed");
                    if bytes_read != 0 {
                        parse_data(&first_buf, bytes_read);
                    }
                    first_complete = true;
                }
                Err(e) => {
                    println!("First connection error: {}", e);
                    first_complete = true;
                }
            }
        }
        if !second_complete {
            match read_data(&mut second_connection, &mut second_buf,
second_bytes_read) {
                Ok((bytes_read, false)) => {
                    second_bytes_read = bytes_read;
                }
                Ok((bytes_read, true)) => {
                    println!("Second connection completed");
                    if bytes_read != 0 {
                        parse_data(&second_buf, bytes_read);
```

```
                    }
                    second_complete = true;
                }
                Err(e) => {
                    println!("Second connection error: {}", e);
                    second_complete = true;
                }
            }
        }
        if first_complete && second_complete {
            break;
        }
    }
}
```

The following command compiles the Rust program.

```
cargo build --target wasm32-wasi --release
```

The following command runs the application in WasmEdge.

```
wasmedge target/wasm32-wasi/release/nonblock_http_client.wasm
```

A non-blocking HTTP server example

The source code for a non-blocking HTTP server application is available. The following `main()` function starts an HTTP server. It receives events from multiple open connections, and processes those events as they are received by calling the async handler functions registered to each connection. This server can process events from multiple open connections concurrently.

```
fn main() -> std::io::Result<()> {
    let mut poll = Poll::new();
    let server = TcpListener::bind("127.0.0.1:1234", true)?;
    println!("Listening on 127.0.0.1:1234");
    let mut connections = HashMap::new();
    let mut handlers = HashMap::new();
    const SERVER: Token = Token(0);
    let mut unique_token = Token(SERVER.0 + 1);

    poll.register(&server, SERVER, Interest::Read);

    loop {
        let events = poll.poll().unwrap();

        for event in events {
            match event.token {
                SERVER => loop {
                    let (connection, address) = match
server.accept(FDFLAGS_NONBLOCK) {
                        Ok((connection, address)) => (connection, address),
                        Err(ref e) if e.kind() ==
std::io::ErrorKind::WouldBlock => break,
                        Err(e) => panic!("accept error: {}", e),
                    };

                    println!("Accepted connection from: {}", address);

                    let token = unique_token.add();
                    poll.register(&connection, token, Interest::Read);
                    connections.insert(token, connection);
                },
                token => {
                    let done = if let Some(connection) =
connections.get_mut(&token) {
                        let handler = match handlers.get_mut(&token) {
                            Some(handler) => handler,
                            None => {
                                let handler = Handler::new();
                                handlers.insert(token, handler);
                                handlers.get_mut(&token).unwrap()
                            }
                        };
                        handle_connection(&mut poll, connection, handler,
&event)?
                    } else {
                        false
                    };
                    if done {
                        if let Some(connection) = connections.remove(&token) {
                            connection.shutdown(Shutdown::Both)?;
                            poll.unregister(&connection);
                            handlers.remove(&token);
```

```
                        }
                    }
                }
            }
        }
    }
}
```

The `handle_connection()` function processes the data from those open connections. In this case, it just writes the request body into the response. It is also done asynchronously -- meaning that the `handle_connection()` function creates an event for the response, and puts it in the queue. The main application loop processes the event and sends the response when it is waiting for data from other connections.

```
fn handle_connection(
    poll: &mut Poll,
    connection: &mut TcpStream,
    handler: &mut Handler,
    event: &Event,
) -> io::Result<bool> {
    if event.is_readable() {
        let mut connection_closed = false;
        let mut received_data = vec![0; 4096];
        let mut bytes_read = 0;
        loop {
            match connection.read(&mut received_data[bytes_read..]) {
                Ok(0) => {
                    connection_closed = true;
                    break;
                }
                Ok(n) => {
                    bytes_read += n;
                    if bytes_read == received_data.len() {
                        received_data.resize(received_data.len() + 1024, 0);
                    }
                }
                Err(ref err) if would_block(err) => {
                    if bytes_read != 0 {
                        let received_data = &received_data[..bytes_read];
                        let mut bs: parsed::stream::ByteStream =
                            match String::from_utf8(received_data.to_vec()) {
                                Ok(s) => s,
                                Err(_) => {
                                    continue;
                                }
                            }
                            .into();
                        let req = match parsed::http::parse_http_request(&mut
bs) {
                            Some(req) => req,
                            None => {
                                break;
                            }
                        };
                        for header in req.headers.iter() {
                            if header.name.eq("Conntent-Length") {
                                let content_length = header.value.parse::
<usize>().unwrap();
                                if content_length > received_data.len() {
                                    return Ok(true);
                                }
                            }
                        }
                        println!(
                            "{:?} request: {:?} {:?}",
                            connection.peer_addr().unwrap(),
```

```
                            req.method,
                            req.path
                        );
                        let res = Response {
                            protocol: "HTTP/1.1".to_string(),
                            code: 200,
                            message: "OK".to_string(),
                            headers: vec![
                                Header {
                                    name: "Content-Length".to_string(),
                                    value: req.content.len().to_string(),
                                },
                                Header {
                                    name: "Connection".to_string(),
                                    value: "close".to_string(),
                                },
                            ],
                            content: req.content,
                        };

                        handler.response = Some(res.into());

                        poll.reregister(connection, event.token,
Interest::Write);
                        break;
                    } else {
                        println!("Empty request");
                        return Ok(true);
                    }
                }
                Err(ref err) if interrupted(err) => continue,
                Err(err) => return Err(err),
            }
        }

        if connection_closed {
            println!("Connection closed");
            return Ok(true);
        }
    }

    if event.is_writable() && handler.response.is_some() {
        let resp = handler.response.clone().unwrap();
        match connection.write(resp.as_bytes()) {
            Ok(n) if n < resp.len() => return
Err(io::ErrorKind::WriteZero.into()),
            Ok(_) => {
                return Ok(true);
            }
            Err(ref err) if would_block(err) => {}
            Err(ref err) if interrupted(err) => {
                return handle_connection(poll, connection, handler, event)
            }
```

```
                Err(err) => return Err(err),
            }
        }

        Ok(false)
    }
```

The following command compiles the Rust program.

```
cargo build --target wasm32-wasi --release
```

The following command runs the application in WasmEdge.

```
$ wasmedge target/wasm32-wasi/release/poll_http_server.wasm
new connection at 1234
```

To test the HTTP server, you can submit a HTTP request to it via `curl`.

```
$ curl -d "name=WasmEdge" -X POST http://127.0.0.1:1234
echo: name=WasmEdge
```

Server-side rendering

Frontend web frameworks allow developers to create web apps in a high level language and component model. The web app is built into a static web site to be rendered in the browser. While many frontend web frameworks are based on JavaScript, such as React and Vue, Rust-based frameworks are also emerging as the Rust language gains traction among developers. Those web frameworks render the HTML DOM UI using the WebAssembly, which is compiled from Rust source code. They use wasm-bindgen to tie the Rust to the HTML DOM. While all of these frameworks send `.wasm` files to the browser to render the UI on the client-side, some provide the additional choice for Server-side rendering. That is to run the WebAssembly code and build the HTML DOM UI on the server, and stream the HTML content to the browser for faster performance and startup time on slow devices and networks.

> If you are interested in JavaScript-based Jamstack and SSR frameworks, such as React, please checkout our JavaScript SSR chapter.

This article will explore how to render the web UI on the server using WasmEdge. We pick Percy as our framework because it is relatively mature in SSR and Hydration. Percy already provides an example for SSR. It's highly recommended to read it first to understand how it works. The default SSR setup with Percy utilizes a native Rust web server. The Rust code is compiled to machine native code for the server. However, in order to host user applications on the server, we need a sandbox. While we could run native code inside a Linux container (Docker), a far more efficient (and safer) approach is to run the compiled code in a WebAssembly VM on the server, especially considerring the rendering code is already compiled into WebAssembly.

Now, let's go through the steps to run a Percy SSR service in a WasmEdge server.

Assuming we are in the `examples/isomorphic` directory, make a new crate beside the existing `server`.

```
cargo new server-wasmedge
```

You'll receive a warning to let you put the new crate into the workspace, so insert below into `members` of `[workspace]`. The file is `../../Cargo.toml`.

```
"examples/isomorphic/server-wasmedge"
```

With the file open, put these two lines in the bottom:

```
[patch.crates-io]
wasm-bindgen = { git = "https://github.com/KernelErr/wasm-bindgen.git", branch
= "wasi-compat" }
```

> Why do we need a forked `wasm-bindgen`? That is because `wasm-bindgen` is the required glue between Rust and HTML in the browser. On the server, however, we need to build the Rust code to the `wasm32-wasi` target, which is incompatible with `wasm-bindgen`. Our forked `wasm-bindgen` has conditional configs that removes browser-specific code in the generated `.wasm` file for the `wasm32-wasi` target.

Then replace the crate's `Cargo.toml` with following content.

```
[package]
name = "isomorphic-server-wasmedge"
version = "0.1.0"
edition = "2021"

# See more keys and their definitions at https://doc.rust-lang.org/cargo
/reference/manifest.html

[dependencies]
wasmedge_wasi_socket = "0"
querystring = "1.1.0"
parsed = { version = "0.3", features = ["http"] }
anyhow = "1"
serde = { version = "1.0", features = ["derive"] }
isomorphic-app = { path = "../app" }
```

The `wasmedge_wasi_socket` crate is the socket API of WasmEdge. This project is under development. Next copy the `index.html` file into the crate's root.

```
cp server/src/index.html server-wasmedge/src/
```

Then let's create some Rust code to start a web service in WasmEdge! The `main.rs` program listens to the request and sends the response via the stream.

```
use std::io::Write;
use wasmedge_wasi_socket::{Shutdown, TcpListener};

mod handler;
mod mime;
mod response;

fn main() {
    let server = TcpListener::bind("127.0.0.1:3000", false).unwrap();
    println!("Server listening on 127.0.0.1:3000");

    // Simple single thread HTTP server
    // For server with Pool support, see https://github.com/second-
state/wasmedge_wasi_socket/tree/main/examples/poll_http_server
    loop {
        let (mut stream, addr) = server.accept(0).unwrap();
        println!("Accepted connection from {}", addr);
        match handler::handle_req(&mut stream, addr) {
            Ok((res, binary)) => {
                let res: String = res.into();
                let bytes = res.as_bytes();
                stream.write_all(bytes).unwrap();
                if let Some(binary) = binary {
                    stream.write_all(&binary).unwrap();
                }
            }
            Err(e) => {
                println!("Error: {:?}", e);
            }
        };
        stream.shutdown(Shutdown::Both).unwrap();
    }
}
```

The `handler.rs` parses the received data to the path and query objects and return the corresponding response.

```
use crate::response;
use anyhow::Result;
use parsed::http::Response;
use std::io::Read;
use wasmedge_wasi_socket::{SocketAddr, TcpStream};

pub fn handle_req(stream: &mut TcpStream, addr: SocketAddr) ->
Result<(Response, Option<Vec<u8>>)> {
    let mut buf = [0u8; 1024];
    let mut received_data: Vec<u8> = Vec::new();

    loop {
        let n = stream.read(&mut buf)?;
        received_data.extend_from_slice(&buf[..n]);
        if n < 1024 {
            break;
        }
    }

    let mut bs: parsed::stream::ByteStream = match
String::from_utf8(received_data) {
        Ok(s) => s.into(),
        Err(_) => return Ok((response::bad_request(), None)),
    };

    let req = match parsed::http::parse_http_request(&mut bs) {
        Some(req) => req,
        None => return Ok((response::bad_request(), None)),
    };

    println!("{:?} request: {:?} {:?}", addr, req.method, req.path);

    let mut path_split = req.path.split("?");
    let path = path_split.next().unwrap_or("/");
    let query_str = path_split.next().unwrap_or("");
    let query = querystring::querify(&query_str);
    let mut init_count: Option<u32> = None;
    for (k, v) in query {
        if k.eq("init") {
            match v.parse::<u32>() {
                Ok(v) => init_count = Some(v),
                Err(_) => return Ok((response::bad_request(), None)),
            }
        }
    }

    let (res, binary) = if path.starts_with("/static") {
        response::file(&path)
    } else {
        // render page
        response::ssr(&path, init_count)
    }
```

```
        .unwrap_or_else(|_| response::internal_error());

    Ok((res, binary))
}
```

The `response.rs` program packs the response object for static assets and for server rendered content. For the latter, you could see that SSR happens at `app.render().to_string()`, the result string is put into HTML by replacing the placeholder text.

```
use crate::mime::MimeType;
use anyhow::Result;
use parsed::http::{Header, Response};
use std::fs::{read};
use std::path::Path;
use isomorphic_app::App;

const HTML_PLACEHOLDER: &str = "#HTML_INSERTED_HERE_BY_SERVER#";
const STATE_PLACEHOLDER: &str = "#INITIAL_STATE_JSON#";

pub fn ssr(path: &str, init: Option<u32>) -> Result<(Response,
Option<Vec<u8>>)> {
    let html = format!("{}", include_str!("./index.html"));

    let app = App::new(init.unwrap_or(1001), path.to_string());
    let state = app.store.borrow();

    let html = html.replace(HTML_PLACEHOLDER, &app.render().to_string());
    let html = html.replace(STATE_PLACEHOLDER, &state.to_json());

    Ok((Response {
        protocol: "HTTP/1.0".to_string(),
        code: 200,
        message: "OK".to_string(),
        headers: vec![
            Header {
                name: "content-type".to_string(),
                value: MimeType::from_ext("html").get(),
            },
            Header {
                name: "content-length".to_string(),
                value: html.len().to_string(),
            },
        ],
        content: html.into_bytes(),
    }, None))
}

/// Get raw file content
pub fn file(path: &str) -> Result<(Response, Option<Vec<u8>>)> {
    let path = Path::new(&path);
    if path.exists() {
        let content_type: MimeType = match path.extension() {
            Some(ext) => MimeType::from_ext(ext.to_str().get_or_insert("")),
            None => MimeType::from_ext(""),
        };
        let content = read(path)?;

        Ok((Response {
            protocol: "HTTP/1.0".to_string(),
            code: 200,
            message: "OK".to_string(),
```

```
            headers: vec![
                Header {
                    name: "content-type".to_string(),
                    value: content_type.get(),
                },
                Header {
                    name: "content-length".to_string(),
                    value: content.len().to_string(),
                },
            ],
            content: vec![],
        }, Some(content)))
    } else {
        Ok((Response {
            protocol: "HTTP/1.0".to_string(),
            code: 404,
            message: "Not Found".to_string(),
            headers: vec![],
            content: vec![],
        }, None))
    }
}

/// Bad Request
pub fn bad_request() -> Response {
    Response {
        protocol: "HTTP/1.0".to_string(),
        code: 400,
        message: "Bad Request".to_string(),
        headers: vec![],
        content: vec![],
    }
}

/// Internal Server Error
pub fn internal_error() -> (Response, Option<Vec<u8>>) {
    (Response {
        protocol: "HTTP/1.0".to_owned(),
        code: 500,
        message: "Internal Server Error".to_owned(),
        headers: vec![],
        content: vec![],
    }, None)
}
```

The `mime.rs` program is a map for assets' extension name and the Mime type.

```
pub struct MimeType {
    pub r#type: String,
}

impl MimeType {
    pub fn new(r#type: &str) -> Self {
        MimeType {
            r#type: r#type.to_string(),
        }
    }

    pub fn from_ext(ext: &str) -> Self {
        match ext {
            "html" => MimeType::new("text/html"),
            "css" => MimeType::new("text/css"),
            "map" => MimeType::new("application/json"),
            "js" => MimeType::new("application/javascript"),
            "json" => MimeType::new("application/json"),
            "svg" => MimeType::new("image/svg+xml"),
            "wasm" => MimeType::new("application/wasm"),
            _ => MimeType::new("text/plain"),
        }
    }

    pub fn get(self) -> String {
        self.r#type
    }
}
```

That's it! Now let's build and run the web application. If you have tested the original example, you probably have already built the client WebAssembly.

```
cd client
./build-wasm.sh
```

Next, build and run the server.

```
cd ../server-wasmedge
cargo build --target wasm32-wasi
OUTPUT_CSS="$(pwd)/../client/build/app.css" wasmedge --dir /static:../client
/build ../../../target/wasm32-wasi/debug/isomorphic-server-wasmedge.wasm
```

Navigate to `http://127.0.0.1:3000` and you will see the web application in action.

Furthermore, you can place all the steps into a shell script `../start-wasmedge.sh`.

```
#!/bin/bash

cd $(dirname $0)

cd ./client

./build-wasm.sh

cd ../server-wasmedge

OUTPUT_CSS="$(pwd)/../client/build/app.css" cargo run -p isomorphic-server-
wasmedge
```

Add the following to the `.cargo/config.toml` file.

```
[build]
target = "wasm32-wasi"

[target.wasm32-wasi]
runner = "wasmedge --dir /static:../client/build"
```

After that, a single CLI command `./start-wasmedge.sh` would perform all the tasks to build and run the web application!

We forked the Percy repository and made a ready-to-build server-wasmedge example project for you. Happy coding!

Command interface

WASI enables WebAssembly programs to call standard library functions in the host operating system. It does so through a fine-grained security model known as “capability-based security”. The WebAssembly VM owner can grant access to host system resources when the VM starts up. The program cannot access any resources (e.g., file folders) that are not explicitly allowed.

Now, why limit ourselves to standard library functions? The same approach can be used to call just any host functions from WebAssembly. WasmEdge provides a WASI-like extension to access any command line programs in the host operating system.

The command line program can

- Take input via command line arguments, as well as the `STDIN` stream.
- Return value and data via the `STDOUT` stream.

Application developers for WasmEdge can use our Rust interface crate to access this functionality. In `Cargo.toml`, make sure that you have this dependency.

```
[dependencies]
rust_process_interface_library = "0.1.3"
```

In the Rust application, you can now use the API methods to start a new process for the operating system command program, pass in arguments via the `arg()` method as well as via the `STDIN`, and receives the return values via the `STDOUT`.

```
let mut cmd = Command::new("http_proxy");

cmd.arg("post")
   .arg("https://api.sendgrid.com/v3/mail/send")
   .arg(auth_header);
cmd.stdin_u8vec(payload.to_string().as_bytes());

let out = cmd.output();
```

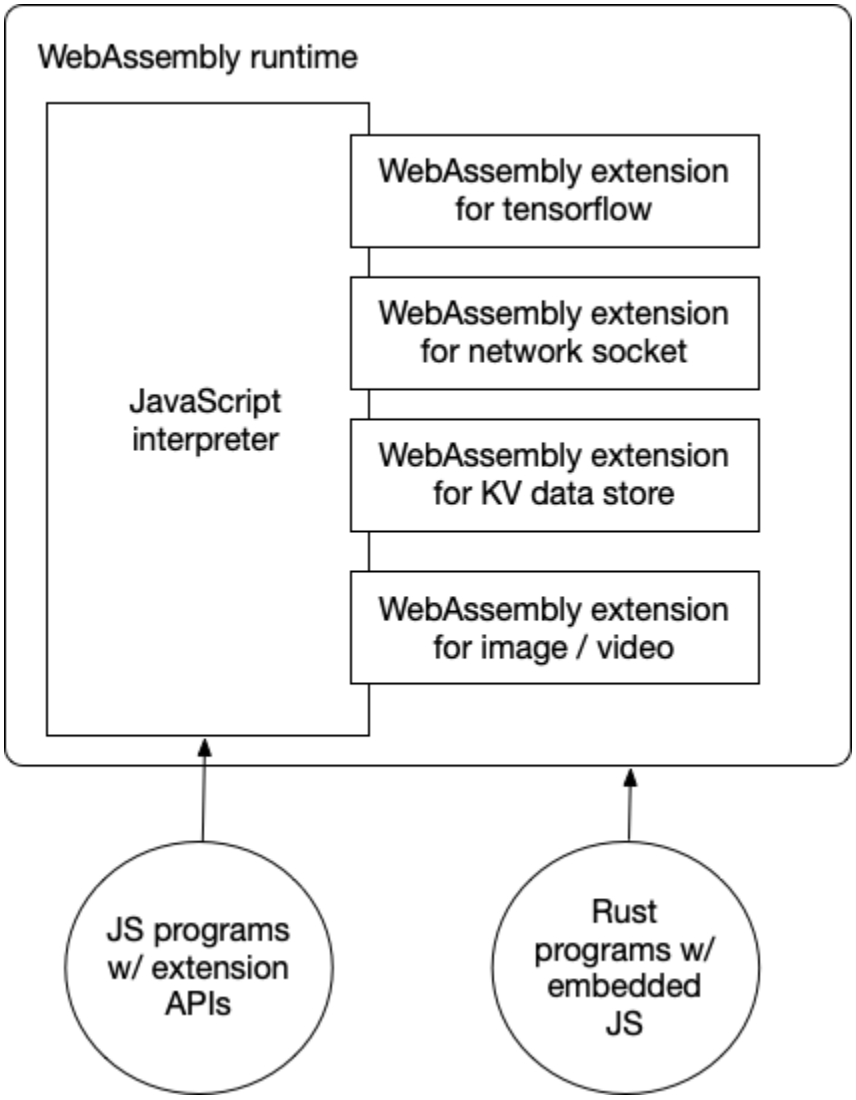
The Rust function is then compiled into WebAssembly and can run in the WasmEdge.

JavaScript

WebAssembly started as a "JavaScript alternative for browsers". The idea is to run high-performance applications compiled from languages like C/C++ or Rust safely in browsers. In the browser, WebAssembly runs side by side with JavaScript.

As WebAssembly is increasingly used in the cloud, it is now a universal runtime for cloud-native applications. Compared with Linux containers, WebAssembly runtimes achieve higher performance with lower resource consumption.

In cloud-native use cases, developers often want to use JavaScript to write business applications. That means we must now support JavaScript in WebAssembly. Furthermore, we should support calling C/C++ or Rust functions from JavaScript in a WebAssembly runtime to take advantage of WebAssembly's computational efficiency. The WasmEdge WebAssembly runtime allows you to do exactly that.



In this section, we will demonstrate how to run and enhance JavaScript in WasmEdge.

- Getting started demonstrates how to run simple JavaScript programs in WasmEdge.
- Node.js compatibility describes Node.js APIs support in WasmEdge QuickJS.
- Networking sockets shows how to create non-blocking (async) HTTP clients, including the `fetch` API, and server applications in JavaScript.
- React SSR shows example React SSR applications, including streaming SSR support.
- TensorFlow shows how to use WasmEdge's TensorFlow extension from its JavaScript API.
- ES6 modules shows how to incorporate ES6 modules in WasmEdge.
- Node.js and NPM modules shows how to incorporate NPM modules in WasmEdge.
- Built-in modules shows how to add JavaScript functions into the WasmEdge runtime as built-in API functions.
- Use Rust to implement JS API discusses how to use Rust to implement and support a JavaScript API.

A note on v8

Now, the choice of QuickJS as our JavaScript engine might raise the question of performance. Isn't QuickJS a lot slower than v8 due to a lack of JIT support? Yes, but ...

First of all, QuickJS is a lot smaller than v8. In fact, it only takes 1/40 (or 2.5%) of the runtime resources v8 consumes. You can run a lot more QuickJS functions than v8 functions on a single physical machine.

Second, for most business logic applications, raw performance is not critical. The application may have computationally intensive tasks, such as AI inference on the fly. WasmEdge allows the QuickJS applications to drop to high-performance WebAssembly for these tasks while it is not so easy with v8 to add such extensions modules.

Third, WasmEdge is itself an OCI compliant container. It is secure by default, supports resource isolation, and can be managed by container tools to run side by side with Linux containers in a single k8s cluster.

Finally, v8 has a very large attack surface and requires major efforts to run securely in a public cloud environment. It is known that many JavaScript security issues arise from JIT. Maybe turning off JIT in the cloud-native environment is not such a bad idea!

In the end, running v8 in a cloud-native environment often requires a full stack of software tools consisting of "Linux container + guest OS + node or deno + v8", which makes it much heavier and slower than a simple WasmEdge + QuickJS container runtime.

Quick Start with JavaScript on WasmEdge

First, let's download the WebAssembly-based JavaScript interpreter program for WasmEdge. It is based on QuickJS. See the build it yourself section to learn how to compile it from Rust source code.

```
curl -OL https://github.com/second-state/wasmedge-quickjs/releases/download
/v0.4.0-alpha/wasmedge_quickjs.wasm
```

You can now try a simple "hello world" JavaScript program (example_js/hello.js), which prints out the command line arguments to the console.

```
import * as os from 'os';
import * as std from 'std';

args = args.slice(1);
print('Hello', ...args);
setTimeout(() => {
  print('timeout 2s');
}, 2000);
```

Run the `hello.js` file in WasmEdge's QuickJS runtime as follows. Make sure you have installed WasmEdge.

```
$ wasmedge --dir .:. wasmedge_quickjs.wasm example_js/hello.js WasmEdge Runtime
Hello WasmEdge Runtime
```

Note: the `--dir .:.` on the command line is to give `wasmedge` permission to read the local directory in the file system for the `hello.js` file.

Build it yourself

This section is optional. Read on if you are interested in adding custom built-in JavaScript APIs to the runtime.

Fork or clone the wasmedge-quickjs Github repository.

```
git clone https://github.com/second-state/wasmedge-quickjs
```

Following the instructions from that repo, you will be able to build a JavaScript interpreter for WasmEdge.

```
# Install GCC
sudo apt update
sudo apt install build-essential

# Install wasm32-wasi target for Rust
rustup target add wasm32-wasi

# Build the QuickJS JavaScript interpreter
cargo build --target wasm32-wasi --release
```

The WebAssembly-based JavaScript interpreter program is located in the build `target` directory.

WasmEdge provides a `wasmedgec` utility to compile and add a native machine code section to the `wasm` file. You can use `wasmedge` to run the natively instrumented `wasm` file to get much faster performance.

```
wasmedgec target/wasm32-wasi/release/wasmedge_quickjs.wasm
wasmedge_quickjs.wasm
wasmedge --dir .:. wasmedge_quickjs.wasm example_js/hello.js
```

Next, we will discuss more advanced use case for JavaScript in WasmEdge.

Node.js support

Many existing JavaScript apps simply use Node.js built-in APIs. In order to support and reuse these JavaScript apps, we are in the process of implementing many Node.JS APIs for WasmEdge QuickJS. The goal is to have unmodified Node.js programs running in WasmEdge QuickJS.

In order to use Node.js APIs in WasmEdge, you must make the `modules` directory from wasmedge-quickjs accessible to the WasmEdge Runtime. The simplest approach is to clone the wasmedge-quickjs repo, and run the Node.js app from the repo's top directory.

```
git clone https://github.com/second-state/wasmedge-quickjs
cd wasmedge-quickjs
curl -OL https://github.com/second-state/wasmedge-quickjs/releases/download
/v0.4.0-alpha/wasmedge_quickjs.wasm
cp -r /path/to/my_node_app .
wasmedge --dir .:. wasmedge_quickjs.wasm my_node_app/index.js
```

> If you want to run `wasmedge` from a directory outside of the repo, you will need to tell it where to find the `modules` directory using the `--dir` option. A typical command will look like this: `wasmedge --dir .:. --dir ./modules:/path/to/modules wasmedge_quickjs.wasm app.js`

The progress of Node.js support in WasmEdge QuickJS is **tracked in this issue.** There are two approaches for supporting Node.js APIs in WasmEdge QuickJS.

The JavaScript modules

Some Node.js functions can be implemented in pure JavaScript using the modules approach. For example,

- The querystring functions just perform string manipulations.
- The buffer functions manage and encode arrays and memory structures.
- The encoding and http functions support corresponding Node.js APIs by wrapping around Rust internal modules.

The Rust internal modules

Other Node.js functions must be implemented in Rust using the internal_module approach. There are two reasons for that. First, some Node.js API functions are CPU intensive (e.g., encoding) and is most efficiently implemented in Rust. Second, some Node.js API functions require access to the underlying system (e.g., networking and file system) through native host functions.

- The core module provides OS level functions such as `timeout`.
- The encoding module provides high-performance encoding and decoding functions, which are in turn wrapped into Node.js encoding APIs.
- The wasi_net_module provides JavaScript networking functions implemented via the Rust-based WasmEdge WASI socket API. It is then wrapped into the Node.js http module.

Node.js compatibility support in WasmEdge QuickJS is a work in progress. It is a great way for new developers to get familiar with WasmEdge QuickJS. Join us!

HTTP and networking apps

The QuickJS WasmEdge Runtime supports Node.js's `http` and `fetch` APIs via the WasmEdge networking socket extension. That enables WasmEdge developers to create HTTP server and client, as well as TCP/IP server and client, applications in JavaScript.

The networking API in WasmEdge is non-blocking and hence supports asynchronous I/O intensive applications. With this API, the JavaScript program can open multiple connections concurrently. It polls those connections, or registers async callback functions, to process data whenever data comes in, without waiting for any one connection to complete its data transfer. That allows the single-threaded application to handle multiple multiple concurrent requests.

- Fetch client
- HTTP server
- HTTP client
- TCP server
- TCP client

Fetch client

The `fetch` API is widely used in browser and node-based JavaScript applications to fetch content over the network. Building on top of its non-blocking async network socket API, the WasmEdge QuickJS runtime supports the `fetch` API. That makes a lot of JS APIs and modules reusable out of the box.

The example_js/wasi_http_fetch.js example demonstrates how to use the `fetch` API in WasmEdge. The code snippet below shows an async HTTP GET from the `httpbin.org` test server. While the program waits for and processes the GET content, it can start another request.

```
async function test_fetch() {
  try {
    let r = await fetch('http://httpbin.org/get?id=1')
    print('test_fetch\n', await r.text())
  } catch (e) {
    print(e)
  }
}
test_fetch()
```

The code snippet below shows how to do an sync HTTP POST to a remote server.

```
async function test_fetch_post() {
  try {
    let r = await fetch("http://httpbin.org/post", { method: 'post', 'body':
'post_body' })
    print('test_fetch_post\n', await r.text())
  } catch (e) {
    print(e)
  }
}
test_fetch_post()
```

An async HTTP PUT request is as follows.

```
async function test_fetch_put() {
  try {
    let r = await fetch("http://httpbin.org/put",
      {
        method: "put",
        body: JSON.stringify({ a: 1 }),
        headers: { 'Context-type': 'application/json' }
      })
    print('test_fetch_put\n', await r.text())
  } catch (e) {
    print(e)
  }
}
test_fetch_put()
```

To run this example, use the following WasmEdge CLI command.

```
wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm example_js/wasi_http_fetch.js
```

You can see the HTTP responses printed to the console.

HTTP server

If you want to run microservices in the WasmEdge runtime, you will need to create a HTTP server with it. The example_js/wasi_http_echo.js example shows you how to create an HTTP server listening on port 8001 using Node.js compatible APIs. It prepends "echo:" to any incoming request and sends it back as the response.

```
import { createServer, request, fetch } from 'http';

createServer((req, resp) => {
  req.on('data', (body) => {
    resp.write('echo:')
    resp.end(body)
  })
}).listen(8001, () => {
  print('listen 8001 ...\n');
})
```

HTTP client

Once the HTTP server starts, you can connect to it and send in a request using the Node.js `request` API.

```
async function test_request() {
  let client = request({ href: "http://127.0.0.1:8001/request", method: 'POST'
}, (resp) => {
    var data = '';
    resp.on('data', (chunk) => {
      data += chunk;
    })
    resp.on('end', () => {
      print('request client recv:', data)
      print()
    })
  })

  client.end('hello server')
}
```

Of course, you can also use the simpler `fetch` API.

```
async function test_fetch() {
  let resp = await fetch('http://127.0.0.1:8001/fetch', { method: 'POST', body:
'hello server' })
  print('fetch client recv:', await resp.text())
  print()
}
```

To run this example, use the following WasmEdge CLI command.

```
wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm example_js/wasi_http_echo.js
```

TCP server

The WasmEdge runtime goes beyond the Node.js API. With the `WasiTcpServer` API, it can create a server that accepts non-HTTP requests. The example_js/wasi_net_echo.js example shows you how to this.

```
import * as net from 'wasi_net';
import { TextDecoder } from 'util'

async function server_start() {
  print('listen 8000 ...');
  try {
    let s = new net.WasiTcpServer(8000);
    for (var i = 0; i < 100; i++) {
      let cs = await s.accept();
      handle_client(cs);
    }
  } catch (e) {
    print('server accept error:', e)
  }
}

server_start();
```

The `handle_client()` function contains the logic on how to process and respond to the incoming request. You will need to read and parse the data stream in the request yourself in this function. In this example, it simply echoes the data back with a prefix.

```
async function handle_client(cs) {
  print('server accept:', cs.peer());
  try {
    while (true) {
      let d = await cs.read();
      if (d == undefined || d.byteLength <= 0) {
        break;
      }
      let s = new TextDecoder().decode(d);
      print('server recv:', s);
      cs.write('echo:' + s);
    }
  } catch (e) {
    print('server handle_client error:', e);
  }
  print('server: conn close');
}
```

TCP client

The TCP client uses WasmEdge's `WasiTcpConn` API to send in a request and receive the echoed response.

```
async function connect_test() {
  try {
    let ss = await net.WasiTcpConn.connect('127.0.0.1:8000')
    ss.write('hello');
    let msg = await ss.read() || "";
    print('client recv:', new TextDecoder().decode(msg));
  } catch (e) {
    print('client catch:', e);
  } finally {
    nextTick(() => {
      exit(0)
    })
  }
}

connect_test();
```

To run this example, use the following WasmEdge CLI command.

```
wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm example_js/wasi_net_echo.js
```

With async HTTP networking, developers can create I/O intensive applications, such as database-driven microservices, in JavaScript and run them safely and efficiently in WasmEdge.

React SSR

React is very popular JavaScript web UI framework. A React application is "compiled" into an HTML and JavaScript static web site. The web UI is rendered through the generated JavaScript code. However, it is often too slow and resource consuming to execute the complex generated JavaScript entirely in the browser to build the interactive HTML DOM objects. React Server Side Rendering (SSR) delegates the JavaScript UI rendering to a server, and have the server stream rendered HTML DOM objects to the browser. The WasmEdge JavaScript runtime provides a lightweight and high performance container to run React SSR functions on edge servers.

> Server-side rendering (SSR) is a popular technique for rendering a client-side single page application (SPA) on the server and then sending a fully rendered page to the client. This allows for dynamic components to be served as static HTML markup. This approach can be useful for search engine optimization (SEO) when indexing does not handle JavaScript properly. It may also be beneficial in situations where downloading a large JavaScript bundle is impaired by a slow network. -- from Digital Ocean.

In this article, we will show you how to use the WasmEdge QuickJS runtime to implement a React SSR function. Compared with the Docker + Linux + nodejs + v8 approach, WasmEdge is safer (suitable for multi-tenancy environments) and much lighter (1% of the footprint) with similar performance.

We will start from a complete tutorial to create and deploy a simple React Streaming SSR web application, and then move on to a full React 18 demo.

- Getting started with React streaming SSR
- A full React 18 app
- Appendix: the create-react-app template

Getting started

The example_js/react_ssr_stream folder in the GitHub repo contains the example's source code. It showcases how to streaming render an HTML string from templates in a JavaScript app running in WasmEdge.

The component/LazyHome.jsx file is the main page template in React. It "lazy" loads the inner page template after a 2s delay once the outer HTML is rendered and returned to the

user.

```
import React, { Suspense } from 'react';
import * as LazyPage from './LazyPage.jsx';

async function sleep(ms) {
  return new Promise((r, _) => {
    setTimeout(() => r(), ms)
  });
}

async function loadLazyPage() {
  await sleep(2000);
  return LazyPage
}

class LazyHome extends React.Component {
  render() {
    let LazyPage1 = React.lazy(() => loadLazyPage());
    return (
      <html lang="en">
        <head>
          <meta charSet="utf-8" />
          <title>Title</title>
        </head>
        <body>
          <div>
            <div> This is LazyHome </div>
            <Suspense fallback={<div> loading... </div>}>
              <LazyPage1 />
            </Suspense>
          </div>
        </body>
      </html>
    );
  }
}

export default LazyHome;
```

The LazyPage.jsx is the inner page template. It is rendered 2s after the outer page is already returned to the user.

```
import React from 'react';

class LazyPage extends React.Component {
  render() {
    return (
      <div>
        <div>
          This is lazy page
        </div>
      </div>
    );
  }
}

export default LazyPage;
```

The main.mjs file starts a non-blocking HTTP server using standard Node.js APIs, and then renders the HTML page in multiple chunks to the response.

```
import * as React from 'react';
import { renderToPipeableStream } from 'react-dom/server';
import { createServer } from 'http';

import LazyHome from './component/LazyHome.jsx';

createServer((req, res) => {
  res.setHeader('Content-type', 'text/html; charset=utf-8');
  renderToPipeableStream(<LazyHome />).pipe(res);
}).listen(8001, () => {
  print('listen 8001...');
})
```

The rollup.config.js and package.json files are to build the React SSR dependencies and components into a bundled JavaScript file for WasmEdge. You should use the `npm` command to build it. The output is in the `dist/main.mjs` file.

```
npm install
npm run build
```

Copy over the system's `modules` to the working directory for Node.js API support as noted here.

```
cp -r ../../modules .
```

To run the example, do the following on the CLI to start the server.

```
nohup wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm dist/main.mjs &
```

Send the server a HTTP request via `curl` or the browser.

```
curl http://localhost:8001
```

The results are as follows. The service first returns an HTML page with an empty inner section (i.e., the `loading` section), and then 2s later, the HTML content for the inner section and the JavaScript to display it.

```
  % Total    % Received % Xferd  Average Speed   Time    Time     Time  Current
                                 Dload  Upload   Total   Spent    Left  Speed

  0     0    0     0    0     0      0      0 --:--:-- --:--:-- --:--:--     0
100   211    0   211    0     0   1029      0 --:--:-- --:--:-- --:--:--  1024
100   275    0   275    0     0    221      0 --:--:--  0:00:01 --:--:--   220
100   547    0   547    0     0    245      0 --:--:--  0:00:02 --:--:--   245
100  1020    0  1020    0     0    413      0 --:--:--  0:00:02 --:--:--   413

<!DOCTYPE html><html lang="en"><head><meta charSet="utf-
8"/><title>Title</title></head><body><div><div> This is LazyHome </div>
<!--$?--><template id="B:0"></template><div> loading... </div><!--/$--></div>
</body></html><div hidden id="S:0"><template id="P:1"></template></div><div
hidden id="S:1"><div><div>This is lazy page</div></div></div><script>function
$RS(a,b){a=document.getElementById(a);b=document.getElementById(b);
for(a.parentNode.removeChild(a);
a.firstChild;)b.parentNode.insertBefore(a.firstChild,b);
b.parentNode.removeChild(b)};$RS("S:1","P:1")</script><script>function $RC(a,b)
{a=document.getElementById(a);b=document.getElementById(b);
b.parentNode.removeChild(b);if(a){a=a.previousSibling;var
f=a.parentNode,c=a.nextSibling,e=0;do{if(c&&8===c.nodeType){var d=c.data;
if("/$"===d)if(0===e)break;else
e--;else"$"!==d&&"$?"!==d&&"$!"!==d||e++}d=c.nextSibling;f.removeChild(c);
c=d}while(c);for(;b.firstChild;)f.insertBefore(b.firstChild,c);a.data="$";
a._reactRetry&&a._reactRetry()}};$RC("B:0","S:0")</script>
```

A full React 18 app

In this section, we will demonstrate a complete React 18 SSR application. It renders the web UI through streaming SSR. The example_js/react18_ssr folder in the GitHub repo contains the example's source code. The component folder contains the entire React 18 application's source code, and the public folder contains the public resources (CSS and images) for the web application. The application also demonstrates a data provider for the UI.

The main.mjs file starts a non-blocking HTTP server, fetches data from a data provider, maps the `main.css` and `main.js` files in the `public` folder to web URLs, and then renders the HTML page for each request in `renderToPipeableStream()`.

```
import * as React from 'react';
import { renderToPipeableStream } from 'react-dom/server';
import { createServer } from 'http';
import * as std from 'std';

import App from './component/App.js';
import { DataProvider } from './component/data.js'

let assets = {
  'main.js': '/main.js',
  'main.css': '/main.css',
};

const css = std.loadFile('./public/main.css')

function createServerData() {
  let done = false;
  let promise = null;
  return {
    read() {
      if (done) {
        return;
      }
      if (promise) {
        throw promise;
      }
      promise = new Promise(resolve => {
        setTimeout(() => {
          done = true;
          promise = null;
          resolve();
        }, 2000);
      });
      throw promise;
    },
  };
}

createServer((req, res) => {
  print(req.url)
  if (req.url == '/main.css') {
    res.setHeader('Content-Type', 'text/css; charset=utf-8')
    res.end(css)
  } else if (req.url == '/favicon.ico') {
    res.end()
  } else {
    res.setHeader('Content-type', 'text/html');

    res.on('error', (e) => {
      print('res error', e)
    })
    let data = createServerData()
```

```
    print('createServerData')

    const stream = renderToPipeableStream(
      <DataProvider data={data}>
        <App assets={assets} />
      </DataProvider>, {
      onShellReady: () => {
        stream.pipe(res)
      },
      onShellError: (e) => {
        print('onShellError:', e)
      }
    }
    );
  }
}).listen(8002, () => {
  print('listen 8002...')
})
```

The rollup.config.js and package.json files are to build the React 18 SSR dependencies and components into a bundled JavaScript file for WasmEdge. You should use the `npm` command to build it. The output is in the `dist/main.mjs` file.

```
npm install
npm run build
```

Copy over the system's `modules` to the working directory for Node.js API support as noted here.

```
cp -r ../../modules .
```

To run the example, do the following on the CLI to start the server.

```
nohup wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm dist/main.mjs &
```

Send the server a HTTP request via `curl` or the browser.

```
curl http://localhost:8002
```

The results are as follows. The service first returns an HTML page with an empty inner section (i.e., the `loading` section), and then 2s later, the HTML content for the inner section and the JavaScript to display it.

```
  % Total    % Received % Xferd  Average Speed   Time    Time     Time  Current
                                 Dload  Upload   Total   Spent    Left  Speed

  0     0    0     0    0     0      0      0 --:--:-- --:--:-- --:--:--     0
100   439    0   439    0     0   1202      0 --:--:-- --:--:-- --:--:--  1199
100  2556    0  2556    0     0   1150      0 --:--:--  0:00:02 --:--:--  1150
100  2556    0  2556    0     0    926      0 --:--:--  0:00:02 --:--:--   926
100  2806    0  2806    0     0    984      0 --:--:--  0:00:02 --:--:--   984
<!DOCTYPE html><html lang="en"><head><meta charSet="utf-8"/><meta
name="viewport
" content="width=device-width, initial-scale=1"/><link rel="stylesheet"
href="/m
ain.css"/><title>Hello</title></head><body><noscript><b>Enable JavaScript to
run
 this app.</b></noscript><!--$--><main><nav><a href="/">Home</a></nav><aside
cla
ss="sidebar"><!--$?--><template id="B:0"></template><div class="spinner
spinner-
-active" role="progressbar" aria-busy="true"></div><!--/$--></aside><article
cla
ss="post"><!--$?--><template id="B:1"></template><div class="spinner spinner--
ac
tive" role="progressbar" aria-busy="true"></div><!--/$--><section
class="comment
s"><h2>Comments</h2><!--$?--><template id="B:2"></template><div class="spinner
s
pinner--active" role="progressbar" aria-busy="true"></div><!--/$--></section>
<h2
>Thanks for reading!</h2></article></main><!--/$--><script>assetManifest =
{"mai
n.js":"/main.js","main.css":"/main.css"};</script></body></html><div hidden
id="
S:0"><template id="P:3"></template></div><div hidden id="S:1"><template
id="P:4"
></template></div><div hidden id="S:2"><template id="P:5"></template></div><div
hidden id="S:3"><h1>Archive</h1><ul><li>May 2021</li><li>April 2021</li>
<li>Marc
h 2021</li><li>February 2021</li><li>January 2021</li><li>December 2020</li>
<li>
November 2020</li><li>October 2020</li><li>September 2020</li></ul></div>
<script
>function $RS(a,b){a=document.getElementById(a);b=document.getElementById(b);
for
(a.parentNode.removeChild(a);
a.firstChild;)b.parentNode.insertBefore(a.firstChil
d,b);b.parentNode.removeChild(b)};$RS("S:3","P:3")</script><script>function
$RC(
a,b){a=document.getElementById(a);b=document.getElementById(b);
b.parentNode.remo
veChild(b);if(a){a=a.previousSibling;var f=a.parentNode,c=a.nextSibling,e=0;
do{i
f(c&&8===c.nodeType){var d=c.data;if("/$"===d)if(0===e)break;else
```

```
e--;else"$"!==
d&&"$?"!==d&&"$!"!==d||e++}d=c.nextSibling;f.removeChild(c);c=d}while(c);for(;
b.
firstChild;)f.insertBefore(b.firstChild,c);a.data="$";a._reactRetry&&
a._reactRet
ry()}};$RC("B:0","S:0")</script><div hidden id="S:4"><h1>Hello world</h1>
<p>This
 demo is <!-- --><b>artificially slowed down</b>. Open<!-- --> <!--
--><code>ser
ver/delays.js</code> to adjust how much different things are slowed down.<!--
--
></p><p>Notice how HTML for comments &quot;streams in&quot; before the JS (or
Re
act) has loaded on the page.</p><p>Also notice that the JS for comments and
side
bar has been code-split, but HTML for it is still included in the server
output.
</p></div><script>$RS("S:4","P:4")</script><script>$RC("B:1","S:1")
</script><div
 hidden id="S:5"><p class="comment">Wait, it doesn&#x27;t wait for React to
load
?</p><p class="comment">How does this even work?</p><p class="comment">I like
ma
rshmallows</p></div><script>$RS("S:5","P:5")</script><script>$RC("B:2","S:2")
</s
cript>
```

The streaming SSR examples make use of WasmEdge's unique asynchronous networking capabilities and ES6 module support (i.e., the rollup bundled JS file contains ES6 modules). You can learn more about async networking and ES6 in this book.

Appendix the create-react-app template

The `create-react-app` template is a popular starting point for many developers to create React apps. In this tutorial, we will provide a step-by-step guide on how to use it to create React streaming SSR applications that run on WasmEdge.

Step 1 — Create the React App

First, use `npx` to create a new React app. Let's name the app `react-ssr-example`.

```
npx create-react-app react-ssr-example
```

Then, `cd` into the directory for the newly created app.

```
cd react-ssr-example
```

Start the new app in order to verify the installation.

```
npm start
```

You should see the example React app displayed in your browser window. At this stage, the app is rendered in the browser. The browser runs the generated React JavaScript to build the HTML DOM UI.

Now in order to prepare for SSR, you will need to make some changes to the app's `index.js` file. Change ReactDOM's `render` method to `hydrate` to indicate to the DOM renderer that you intend to rehydrate the app after it is rendered on the server. Replace the contents of the `index.js` file with the following.

```
import React from 'react';
import ReactDOM from 'react-dom';
import App from './App';
ReactDOM.hydrate(
  <React.StrictMode>
    <App />
  </React.StrictMode>,
  document.getElementById('root')
);
```

Note: you should import `React` redundantly in the `src/App.js`, so the server will recognize it.

```
import React from 'react';
//...
```

That concludes setting up the application, you can move on to setting up the server-side rendering functions.

Step 2 — Create an WasmEdge QuickJS Server and Render the App Component

Now that you have the app in place, let's set up a server that will render the HTML DOM by running the React JavaScript and then send the rendered elements to the browser. We will use WasmEdge as a secure, high-performance and lightweight container to run React JavaScript.

Create a new `server` directory in the project's root directory.

```
mkdir server
```

Then, inside the `server` directory, create a new `index.js` file with the server code.

```
import * as React from 'react';
import ReactDOMServer from 'react-dom/server';
import * as std from 'std';
import * as http from 'wasi_http';
import * as net from 'wasi_net';

import App from '../src/App.js';

async function handle_client(cs) {
  print('open:', cs.peer());
  let buffer = new http.Buffer();

  while (true) {
    try {
      let d = await cs.read();
      if (d == undefined || d.byteLength <= 0) {
        return;
      }
      buffer.append(d);
      let req = buffer.parseRequest();
      if (req instanceof http.WasiRequest) {
        handle_req(cs, req);
        break;
      }
    } catch (e) {
      print(e);
    }
  }
  print('end:', cs.peer());
}

function enlargeArray(oldArr, newLength) {
  let newArr = new Uint8Array(newLength);
  oldArr && newArr.set(oldArr, 0);
  return newArr;
}

async function handle_req(s, req) {
  print('uri:', req.uri)

  let resp = new http.WasiResponse();
  let content = '';
  if (req.uri == '/') {
    const app = ReactDOMServer.renderToString(<App />);
    content = std.loadFile('./build/index.html');
    content = content.replace('<div id="root"></div>', `<div id="root">${app}
</div>`);
  } else {
    let chunk = 1000; // Chunk size of each reading
    let length = 0; // The whole length of the file
    let byteArray = null; // File content as Uint8Array
```

```
    // Read file into byteArray by chunk
    let file = std.open('./build' + req.uri, 'r');
    while (true) {
      byteArray = enlargeArray(byteArray, length + chunk);
      let readLen = file.read(byteArray.buffer, length, chunk);
      length += readLen;
      if (readLen < chunk) {
        break;
      }
    }
    content = byteArray.slice(0, length).buffer;
    file.close();
  }
  let contentType = 'text/html; charset=utf-8';
  if (req.uri.endsWith('.css')) {
    contentType = 'text/css; charset=utf-8';
  } else if (req.uri.endsWith('.js')) {
    contentType = 'text/javascript; charset=utf-8';
  } else if (req.uri.endsWith('.json')) {
    contentType = 'text/json; charset=utf-8';
  } else if (req.uri.endsWith('.ico')) {
    contentType = 'image/vnd.microsoft.icon';
  } else if (req.uri.endsWith('.png')) {
    contentType = 'image/png';
  }
  resp.headers = {
    'Content-Type': contentType
  };

  let r = resp.encode(content);
  s.write(r);
}

async function server_start() {
  print('listen 8002...');
  try {
    let s = new net.WasiTcpServer(8002);
    for (var i = 0; ; i++) {
      let cs = await s.accept();
      handle_client(cs);
    }
  } catch (e) {
    print(e);
  }
}

server_start();
```

The server renders the `<App>` component, and then sends the rendered HTML string back to the browser. Three important things are taking place here.

- ReactDOMServer's `renderToString` is used to render the `<App/>` to an HTML string.

- The `index.html` file from the app's `build` output directory is loaded as a template. The app's content is injected into the `<div>` element with an id of `"root"`. It is then sent back as HTTP response.
- Other files from the `build` directory are read and served as needed at the requests of the browser.

Step 3 — Build and deploy

For the server code to work, you will need to bundle and transpile it. In this section, we will show you how to use webpack and Babel. In this next section, we will demonstrate an alternative (and potentially easier) approach using rollup.js.

Create a new Babel configuration file named `.babelrc.json` in the project's root directory and add the `env` and `react-app` presets.

```
{
  "presets": [
    "@babel/preset-env",
    "@babel/preset-react"
  ]
}
```

Create a webpack config for the server that uses Babel Loader to transpile the code. Start by creating the `webpack.server.js` file in the project's root directory.

```
const path = require('path');
module.exports = {
  entry: './server/index.js',
  externals: [
    {"wasi_http": "wasi_http"},
    {"wasi_net": "wasi_net"},
    {"std": "std"}
  ],
  output: {
    path: path.resolve('server-build'),
    filename: 'index.js',
    chunkFormat: "module",
    library: {
      type: "module"
    },
  },
  experiments: {
    outputModule: true
  },
  module: {
    rules: [
      {
        test: /\.js$/,
        use: 'babel-loader'
      },
      {
        test: /\.css$/,
        use: ["css-loader"]
      },
      {
        test: /\.svg$/,
        use: ["svg-url-loader"]
      }
    ]
  }
};
```

With this configuration, the transpiled server bundle will be output to the `server-build` folder in a file called `index.js`.

Next, add the `svg-url-loader` package by entering the following commands in your terminal.

```
npm install svg-url-loader --save-dev
```

This completes the dependency installation and webpack and Babel configuration.

Now, revisit `package.json` and add helper npm scripts. Add `dev:build-server`, `dev:start-server` scripts to the `package.json` file to build and serve the SSR application.

```
"scripts": {
  "dev:build-server": "NODE_ENV=development webpack --config webpack.server.js
--mode=development",
  "dev:start-server": "wasmedge --dir .:. wasmedge_quickjs.wasm ./server-
build/index.js",
  // ...
},
```

- The `dev:build-server` script sets the environment to `"development"` and invokes webpack with the configuration file you created earlier.
- The `dev:start-server` script runs the WasmEdge server from the `wasmedge` CLI tool to serve the built output. The `wasmedge_quickjs.wasm` program contains the QuickJS runtime. Learn more

Now you can run the following commands to build the client-side app, bundle and transpile the server code, and start up the server on `:8002` .

```
npm run build
npm run dev:build-server
npm run dev:start-server
```

Open `http://localhost:8002/` in your web browser and observe your server-side rendered app.

Previously, the HTML source in the browser is simply the template with SSR placeholders.

```
Output
<div id="root"></div>
```

Now, with the SSR function running on the server, the HTML source in the browser is as follows.

```
Output
<div id="root"><div class="App" data-reactroot="">...</div></div>
```

Step 4 (alternative) -- build and deploy with rollup.js

Alternatively, you could use the rollup.js tool to package all application components and library modules into a single file for WasmEdge to execute.

Create a rollup config for the server that uses Babel Loader to transpile the code. Start by creating the `rollup.config.js` file in the project's root directory.

```
const {babel} = require('@rollup/plugin-babel');
const nodeResolve = require('@rollup/plugin-node-resolve');
const commonjs = require('@rollup/plugin-commonjs');
const replace = require('@rollup/plugin-replace');

const globals = require('rollup-plugin-node-globals');
const builtins = require('rollup-plugin-node-builtins');
const plugin_async = require('rollup-plugin-async');
const css = require("rollup-plugin-import-css");
const svg = require('rollup-plugin-svg');

const babelOptions = {
  babelrc: false,
  presets: [
    '@babel/preset-react'
  ],
  babelHelpers: 'bundled'
};

module.exports = [
  {
    input: './server/index.js',
    output: {
      file: 'server-build/index.js',
      format: 'esm',
    },
    external: [ 'std', 'wasi_net','wasi_http'],
    plugins: [
      plugin_async(),
      babel(babelOptions),
      nodeResolve({preferBuiltins: true}),
      commonjs({ignoreDynamicRequires: false}),
      css(),
      svg({base64: true}),
      globals(),
      builtins(),
      replace({
        preventAssignment: true,
        'process.env.NODE_ENV': JSON.stringify('production'),
        'process.env.NODE_DEBUG': JSON.stringify(''),
      }),
    ],
  },
];
```

With this configuration, the transpiled server bundle will be output to the `server-build` folder in a file called `index.js`.

Next, add the dependent packages to the `package.json` then install with `npm`.

```
  "devDependencies": {
    //...
    "@rollup/plugin-babel": "^5.3.0",
    "@rollup/plugin-commonjs": "^21.0.1",
    "@rollup/plugin-node-resolve": "^7.1.3",
    "@rollup/plugin-replace": "^3.0.0",
    "rollup": "^2.60.1",
    "rollup-plugin-async": "^1.2.0",
    "rollup-plugin-import-css": "^3.0.3",
    "rollup-plugin-node-builtins": "^2.1.2",
    "rollup-plugin-node-globals": "^1.4.0",
    "rollup-plugin-svg": "^2.0.0"
  }
```

```
npm install
```

This completes the dependency installation and rollup configuration.

Now, revisit `package.json` and add helper npm scripts. Add `dev:build-server`, `dev:start-server` scripts to the `package.json` file to build and serve the SSR application.

```
"scripts": {
  "dev:build-server": "rollup -c rollup.config.js",
  "dev:start-server": "wasmedge --dir .:. wasmedge_quickjs.wasm ./server-
build/index.js",
  // ...
},
```

- The `dev:build-server` script sets the environment to `"development"` and invokes webpack with the configuration file you created earlier.
- The `dev:start-server` script runs the WasmEdge server from the `wasmedge` CLI tool to serve the built output. The `wasmedge_quickjs.wasm` program contains the QuickJS runtime. Learn more

Now you can run the following commands to build the client-side app, bundle and transpile the server code, and start up the server on `:8002`.

```
npm run build
npm run dev:build-server
npm run dev:start-server
```

Open `http://localhost:8002/` in your web browser and observe your server-side rendered app.

Previously, the HTML source in the browser is simply the template with SSR placeholders.

```
Output
<div id="root"></div>
```

Now, with the SSR function running on the server, the HTML source in the browser is as follows.

```
Output
<div id="root"><div class="App" data-reactroot="">...</div></div>
```

TensorFlow

The interpreter supports the WasmEdge TensorFlow lite inference extension so that your JavaScript can run an ImageNet model for image classification. This article will show you how to use the TensorFlow Rust SDK for WasmEdge from your javascript program. You will first download the WasmEdge QuickJS Runtime with tensorflow support built-in.

```
curl -OL https://github.com/second-state/wasmedge-quickjs/releases/download
/v0.4.0-alpha/wasmedge_quickjs_tf.wasm
```

Here is an example of JavaScript. You could find the full code from example_js/tensorflow_lite_demo/.

```
import {Image} from 'image';
import * as std from 'std';
import {TensorflowLiteSession} from 'tensorflow_lite';

let img = new Image(__dirname + '/food.jpg');
let img_rgb = img.to_rgb().resize(192, 192);
let rgb_pix = img_rgb.pixels();

let session = new TensorflowLiteSession(
    __dirname + '/lite-model_aiy_vision_classifier_food_V1_1.tflite');
session.add_input('input', rgb_pix);
session.run();
let output = session.get_output('MobilenetV1/Predictions/Softmax');
let output_view = new Uint8Array(output);
let max = 0;
let max_idx = 0;
for (var i in output_view) {
  let v = output_view[i];
  if (v > max) {
    max = v;
    max_idx = i;
  }
}
let label_file = std.open(__dirname + '/aiy_food_V1_labelmap.txt', 'r');
let label = '';
for (var i = 0; i <= max_idx; i++) {
  label = label_file.getline();
}
label_file.close();

print('label:');
print(label);
print('confidence:');
print(max / 255);
```

To run the JavaScript in the WasmEdge runtime, you can do the following on the CLI. You should now see the name of the food item recognized by the TensorFlow lite ImageNet model.

```
$ wasmedge-tensorflow-lite --dir .:. /path/to/wasmedge_quickjs_tf.wasm
example_js/tensorflow_lite_demo/main.js
label:
Hot dog
confidence:
0.8941176470588236
```

The `wasmedge-tensorflow-lite` program is part of the WasmEdge package. It is the WasmEdge runtime with the Tensorflow extension built in.

ES6 module support

The WasmEdge QuickJS runtime supports ES6 modules. In fact, the rollup commands we used in the React SSR examples convert and bundle CommonJS and NPM modules into ES6 modules so that they can be executed in WasmEdge QuickJS. This article will show you how to use ES6 module in WasmEdge.

We will take the example in example_js/es6_module_demo folder as an example. The module_def.js file defines and exports a simple JS function.

```
function hello(){
  console.log('hello from module_def.js');
}

export {hello};
```

The module_def_async.js file defines and exports an async function and a variable.

```
export async function hello() {
  console.log('hello from module_def_async.js');
  return 'module_def_async.js : return value';
}

export var something = 'async thing';
```

The demo.js file imports functions and variables from those modules and executes them.

```
import {hello as module_def_hello} from './module_def.js';

module_def_hello();

var f = async () => {
  let {hello, something} = await import('./module_def_async.js');
  await hello();
  console.log('./module_def_async.js `something` is ', something);
};

f();
```

To run the example, you can do the following on the CLI.

```
$ wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm example_js/es6_module_demo
/demo.js
hello from module_def.js
hello from module_def_async.js
./module_def_async.js `something` is  async thing
```

NodeJS and NPM module

With rollup.js, we can run CommonJS (CJS) and NodeJS (NPM) modules in WasmEdge too. The simple_common_js_demo/npm_main.js demo shows how it works. It utilizes the third-party `md5` and `mathjs` modules.

```
const md5 = require('md5');
console.log('md5(message)=', md5('message'));

const {sqrt} = require('mathjs');
console.log('sqrt(-4)=', sqrt(-4).toString());
```

In order to run it, we must first use the rollup.js tool to build all dependencies into a single file. In the process, `rollup.js` converts CommonJS modules into WasmEdge-compatible ES6 modules. The build script is rollup.config.js.

```
const {babel} = require('@rollup/plugin-babel');
const nodeResolve = require('@rollup/plugin-node-resolve');
const commonjs = require('@rollup/plugin-commonjs');
const replace = require('@rollup/plugin-replace');

const globals = require('rollup-plugin-node-globals');
const builtins = require('rollup-plugin-node-builtins');
const plugin_async = require('rollup-plugin-async');

const babelOptions = {
  'presets': ['@babel/preset-react']
};

module.exports = [
  {
    input: './npm_main.js',
    output: {
      inlineDynamicImports: true,
      file: 'dist/npm_main.mjs',
      format: 'esm',
    },
    external: ['process', 'wasi_net','std'],
    plugins: [
      plugin_async(),
      nodeResolve(),
      commonjs({ignoreDynamicRequires: false}),
      babel(babelOptions),
      globals(),
      builtins(),
      replace({
        'process.env.NODE_ENV': JSON.stringify('production'),
        'process.env.NODE_DEBUG': JSON.stringify(''),
      }),
    ],
  },
];
```

The package.json file specifies the `rollup.js` dependencies and the command to build the npm_main.js demo program into a single bundle.

```
{
  "dependencies": {
    "mathjs": "^9.5.1",
    "md5": "^2.3.0"
  },
  "devDependencies": {
    "@babel/core": "^7.16.5",
    "@babel/preset-env": "^7.16.5",
    "@babel/preset-react": "^7.16.5",
    "@rollup/plugin-babel": "^5.3.0",
    "@rollup/plugin-commonjs": "^21.0.1",
    "@rollup/plugin-node-resolve": "^7.1.3",
    "@rollup/plugin-replace": "^3.0.0",
    "rollup": "^2.60.1",
    "rollup-plugin-babel": "^4.4.0",
    "rollup-plugin-node-builtins": "^2.1.2",
    "rollup-plugin-node-globals": "^1.4.0",
    "rollup-plugin-async": "^1.2.0"
  },
  "scripts": {
    "build": "rollup -c rollup.config.js"
  }
}
```

Run the following NPM commands to build npm_main.js demo program into `dist/npm_main.mjs`.

```
npm install
npm run build
cd ../../
```

Run the result JS file in WasmEdge CLI as follows.

```
$ wasmedge --dir .:. /path/to/wasmedge_quickjs.wasm
example_js/simple_common_js_demo/dist/npm_main.mjs
md5(message)= 78e731027d8fd50ed642340b7c9a63b3
sqrt(-4)= 2i
```

You can import and run any NPM packages in WasmEdge this way.

System modules

The WasmEdge QuickJS runtime supports ES6 and NPM modules for application developers. However, those approaches are too cumbersome for system developers. They need an easier way to add multiple JavaScript modules and APIs into the runtime without having to go through build tools like rollup.js. The WasmEdge QuickJS modules system allow developers to just drop JavaScript files into a `modules` folder, and have the JavaScript functions defined in the files immediately available to all JavaScript programs in the runtime. A good use case for this modules system is to support Node.js APIs in WasmEdge.

The module system is just a collection of JavaScript files in the `modules` directory in the WasmEdge QuickJS distribution. To use the JavaScript functions and APIs defined in those modules, you just need to map this directory to the `/modules` directory inside the WasmEdge Runtime instance. The following example shows how to do this on the WasmEdge CLI. You can do this with any of the host language SDKs that support embedded use of WasmEdge.

```
$ ls modules

    buffer.js encoding.js events.js http.js
    ... JavaScript files for the modules ...

$ wasmedge --dir .:. target/wasm32-wasi/release/wasmedge_quickjs.wasm
example_js/hello.js WasmEdge Runtime
```

The module_demo shows how you can use the modules system to add your own JavaScript APIs. To run the demo, first copy the two files in the demo's modules directory to your WasmEdge QuickJS's `modules` directory.

```
cp example_js/module_demo/modules/* modules/
```

The two JavaScript files in the `modules` directory provide two simple functions. Below is the modules/my_mod_1.js file.

```
export function hello_mod_1(){
  console.log('hello from "my_mod_1.js"')
}
```

And the modules/my_mod_2.js file.

```
export function hello_mod_2(){
  console.log('hello from "my_mod_2.js"')
}
```

Then, just run the demo.js file to call the two exported functions from the modules.

```
import { hello_mod_1 } from 'my_mod_1'
import { hello_mod_2 } from 'my_mod_2'

hello_mod_1()
hello_mod_2()
```

Here is the command to run the demo and the output.

```
$ wasmedge --dir .:. target/wasm32-wasi/release/wasmedge_quickjs.wasm
example_js/module_demo/demo.js

hello from "my_mod_1.js"
hello from "my_mod_2.js"
```

Following the above tutorials, you can easily add third-party JavaScript functions and APIs into your WasmEdge QuickJS runtime. For the official distribution, we included JavaScript files to support Node.js APIs. You can use those files as further examples.

Use Rust to implement JS API

For JavaScript developers, incorporating Rust functions into JavaScript APIs is useful. That enables developers to write programs in "pure JavaScript" and yet still take advantage of the high performance Rust functions. With the WasmEdge Runtime, you can do exactly that.

> The internal_module folder in the official WasmEdge QuickJS distribution provides Rust-based implementations of some built-in JavaScript API functions. Those functions typically require interactions with host functions in the WasmEdge runtime (e.g., networking and tensorflow), and hence cannot be accessed by pure JavaScript implementations in modules.

Check out the wasmedge-quickjs Github repo and change to the `examples/embed_js` folder to follow along.

```
git clone https://github.com/second-state/wasmedge-quickjs
cd examples/embed_js
```

> You must have Rust and WasmEdge installed to build and run the examples we show you.

The `embed_js` demo showcases several different examples on how to embed JavaScript inside Rust. You can build and run all the examples as follows.

```
cargo build --target wasm32-wasi --release
wasmedge --dir .:. target/wasm32-wasi/release/embed_js.wasm
```

> Note: The `--dir .:.` on the command line is to give wasmedge permission to read the local directory in the file system.

Create a JavaScript function API

The following code snippet defines a Rust function that can be incorporate into the JavaScript interpreter as an API.

```
fn run_rust_function(ctx: &mut Context) {

  struct HelloFn;
  impl JsFn for HelloFn {
    fn call(_ctx: &mut Context, _this_val: JsValue, argv: &[JsValue]) ->
JsValue {
      println!("hello from rust");
      println!("argv={:?}", argv);
      JsValue::UnDefined
    }
  }

  ...
}
```

The following code snippet shows how to add this Rust function into the JavaScript interpreter, give a name `hi()` as its JavaScript API, and then call it from JavaScript code.

```
fn run_rust_function(ctx: &mut Context) {
  ...

  let f = ctx.new_function::<HelloFn>("hello");
  ctx.get_global().set("hi", f.into());
  let code = r#"hi(1,2,3)"#;
  let r = ctx.eval_global_str(code);
  println!("return value:{:?}", r);
}
```

The execution result is as follows.

```
hello from rust
argv=[Int(1), Int(2), Int(3)]
return value:UnDefined
```

Using this approach, you can create a JavaScript interpreter with customized API functions. The interpreter runs inside WasmEdge, and can execute JavaScript code, which calls such API functions, from CLI or the network.

Create a JavaScript object API

In the JavaScript API design, we sometimes need to provide an object that encapsulates both data and function. In the following example, we define a Rust function for the JavaScript API.

```
fn rust_new_object_and_js_call(ctx: &mut Context) {
  struct ObjectFn;
  impl JsFn for ObjectFn {
    fn call(_ctx: &mut Context, this_val: JsValue, argv: &[JsValue]) -> JsValue
{
      println!("hello from rust");
      println!("argv={:?}", argv);
      if let JsValue::Object(obj) = this_val {
        let obj_map = obj.to_map();
        println!("this={:#?}", obj_map);
      }
      JsValue::UnDefined
    }
  }

  ...
}
```

We then create an "object" on the Rust side, set its data fields, and then register the Rust function as a JavaScript function associated with the objects.

```
let mut obj = ctx.new_object();
obj.set("a", 1.into());
obj.set("b", ctx.new_string("abc").into());

let f = ctx.new_function::<ObjectFn>("anything");
obj.set("f", f.into());
```

Next, we make the Rust "object" available as JavaScript object `test_obj` in the JavaScript interpreter.

```
ctx.get_global().set("test_obj", obj.into());
```

In the JavaScript code, you can now directly use `test_obj` as part of the API.

```
let code = r#"
  print('test_obj keys=',Object.keys(test_obj))
  print('test_obj.a=',test_obj.a)
  print('test_obj.b=',test_obj.b)
  test_obj.f(1,2,3,"hi")
"#;

ctx.eval_global_str(code);
```

The execution result is as follows.

```
test_obj keys= a,b,f
test_obj.a= 1
test_obj.b= abc
hello from rust
argv=[Int(1), Int(2), Int(3), String(JsString(hi))]
this=Ok(
  {
    "a": Int(
      1,
    ),
    "b": String(
      JsString(
        abc,
      ),
    ),
    "f": Function(
      JsFunction(
        function anything() {
          [native code]
        },
      ),
    ),
  },
)
```

A complete JavaScript object API

In the previous example, we demonstrated simple examples to create JavaScript APIs from Rust. In this example, we will create a complete Rust module and make it available as a JavaScript object API. The project is in the examples/embed_rust_module folder. You can build and run it as a standard Rust application in WasmEdge.

```
cargo build --target wasm32-wasi --release
wasmedge --dir .:. target/wasm32-wasi/release/embed_rust_module.wasm
```

The Rust implementation of the object is a module as follows. It has data fields, constructor, getters and setters, and functions.

```
mod point {
  use wasmedge_quickjs::*;

  #[derive(Debug)]
  struct Point(i32, i32);

  struct PointDef;

  impl JsClassDef<Point> for PointDef {
    const CLASS_NAME: &'static str = "Point\0";
    const CONSTRUCTOR_ARGC: u8 = 2;

    fn constructor(_: &mut Context, argv: &[JsValue]) -> Option<Point> {
      println!("rust-> new Point {:?}", argv);
      let x = argv.get(0);
      let y = argv.get(1);
      if let ((Some(JsValue::Int(ref x)), Some(JsValue::Int(ref y)))) = (x, y)
{
        Some(Point(*x, *y))
      } else {
        None
      }
    }

    fn proto_init(p: &mut JsClassProto<Point, PointDef>) {
      struct X;
      impl JsClassGetterSetter<Point> for X {
        const NAME: &'static str = "x\0";

        fn getter(_: &mut Context, this_val: &mut Point) -> JsValue {
          println!("rust-> get x");
          this_val.0.into()
        }

        fn setter(_: &mut Context, this_val: &mut Point, val: JsValue) {
          println!("rust-> set x:{:?}", val);
          if let JsValue::Int(x) = val {
            this_val.0 = x
          }
        }
      }

      struct Y;
      impl JsClassGetterSetter<Point> for Y {
        const NAME: &'static str = "y\0";

        fn getter(_: &mut Context, this_val: &mut Point) -> JsValue {
          println!("rust-> get y");
          this_val.1.into()
        }

        fn setter(_: &mut Context, this_val: &mut Point, val: JsValue) {
```

```
            println!("rust-> set y:{:?}", val);
            if let JsValue::Int(y) = val {
              this_val.1 = y
            }
          }
        }

        struct FnPrint;
        impl JsMethod<Point> for FnPrint {
          const NAME: &'static str = "pprint\0";
          const LEN: u8 = 0;

          fn call(_: &mut Context, this_val: &mut Point, _argv: &[JsValue]) ->
JsValue {
            println!("rust-> pprint: {:?}", this_val);
            JsValue::Int(1)
          }
        }

        p.add_getter_setter(X);
        p.add_getter_setter(Y);
        p.add_function(FnPrint);
      }
    }

    struct PointModule;
    impl ModuleInit for PointModule {
      fn init_module(ctx: &mut Context, m: &mut JsModuleDef) {
        m.add_export("Point\0", PointDef::class_value(ctx));
      }
    }

    pub fn init_point_module(ctx: &mut Context) {
      ctx.register_class(PointDef);
      ctx.register_module("point\0", PointModule, &["Point\0"]);
    }
}
```

In the interpreter implementation, we call `point::init_point_module` first to register the Rust module with the JavaScript context, and then we can run a JavaScript program that simply use the `point` object.

```
use wasmedge_quickjs::*;
fn main() {
  let mut ctx = Context::new();
  point::init_point_module(&mut ctx);

  let code = r#"
    import('point').then((point)=>{
    let p0 = new point.Point(1,2)
    print("js->",p0.x,p0.y)
    p0.pprint()
    try{
      let p = new point.Point()
      print("js-> p:",p)
      print("js->",p.x,p.y)
      p.x=2
      p.pprint()
    } catch(e) {
      print("An error has been caught");
      print(e)
    }
    })
  "#;

  ctx.eval_global_str(code);
  ctx.promise_loop_poll();
}
```

The execution result from the above application is as follows.

```
rust-> new Point [Int(1), Int(2)]
rust-> get x
rust-> get y
js-> 1 2
rust-> pprint: Point(1, 2)
rust-> new Point []
js-> p: undefined
An error has been caught
TypeError: cannot read property 'x' of undefined
```

Code reuse

Using the Rust API, we could create JavaScript classes that inherit (or extend) from existing classes. That allows developers to create complex JavaScript APIs using Rust by building on existing solutions. You can see an example here.

Next, you can see the Rust code in the internal_module folder for more examples on how to

implement common JavaScript built-in functions including Node.js APIs.

Go

The best way to run Go programs in WasmEdge is to compile Go source code to WebAssembly using TinyGo. In this article, we will show you how.

Install TinyGo

You must have Go already installed on your machine before installing TinyGo. Go v1.17 or above is recommended. For Ubuntu or other Debian-based Linux systems on x86 processors, you could use the following command line to install TinyGo. For other platforms, please refer to TinyGo docs.

```
wget https://github.com/tinygo-org/tinygo/releases/download/v0.21.0
/tinygo_0.21.0_amd64.deb
sudo dpkg -i tinygo_0.21.0_amd64.deb`
```

Next, run the following command line to check out if the installation is successful.

```
$ tinygo version
tinygo version 0.21.0 linux/amd64 (using go version go1.16.7 and LLVM version
11.0.0)
```

Hello world

The simple Go app has a `main()` function to print a message to the console. The source code in `main.go` file is as follows.

```
package main

func main() {
  println("Hello TinyGo from WasmEdge!")
}
```

Inside the `main()` function, you can use Go standard API to read / write files, and access command line arguments and `env` variables.

Hello world: Compile and build

Next, compile the `main.go` program to WebAssembly using TinyGo.

```
tinygo build -o hello.wasm -target wasi main.go
```

You will see a file named `hello.wasm` in the same directory. This is a WebAssembly bytecode file.

Hello world: Run

You can run it with the WasmEdge CLI.

```
$ wasmedge hello.wasm
Hello TinyGo from WasmEdge!
```

A simple function

The second example is a Go function that takes a call parameter to compute a fibonacci number. However, in order for the Go application to set up proper access to the OS (e.g., to access the command line arguments), you must include an empty `main()` function in the source code.

```
package main

func main(){
}

//export fibArray
func fibArray(n int32) int32{
  arr := make([]int32, n)
  for i := int32(0); i < n; i++ {
    switch {
    case i < 2:
      arr[i] = i
    default:
      arr[i] = arr[i-1] + arr[i-2]
    }
  }
  return arr[n-1]
}
```

A simple function: Compile and build

Next, compile the `main.go` program to WebAssembly using TinyGo.

```
tinygo build -o fib.wasm -target wasi main.go
```

You will see a file named `fib.wasm` in the same directory. This is a WebAssembly bytecode file.

A simple function: Run

You can run it with the WasmEdge CLI in its `--reactor` mode. The command line arguments that follow the `wasm` file are the function name and its call parameters.

```
$ wasmedge --reactor fib.wasm fibArray 10
34
```

Improve performance

To achieve native Go performance for those applications, you could use the `wasmedgec` command to AOT compile the `wasm` program, and then run it with the `wasmedge` command.

```
$ wasmedgec hello.wasm hello.wasm

$ wasmedge hello.wasm
Hello TinyGo from WasmEdge!
```

For the `--reactor` mode,

```
$ wasmedgec fib.wasm fib.wasm

$ wasmedge --reactor fib.wasm fibArray 10
34
```

Swift

The swiftwasm project compiles Swift source code to WebAssembly.

AssemblyScript

AssemblyScript is a TypeScript-like language designed for WebAssembly. AssemblyScript programs can be easily compiled into WebAssembly.

Kotlin

Check out how to compile Kotlin programs to WebAssembly

Grain

Grain is a strongly typed languages designed for WebAssembly. Checkout its Hello world example.

Python

There are already several different language implementations of the Python runtime, and some of them support WebAssembly. This document will describe how to run RustPython on WasmEdge to execute Python programs.

Compile RustPython

To compile RustPython, you should have the Rust toolchain installed on your machine. And `wasm32-wasi` platform support should be enabled.

```
rustup target add wasm32-wasi
```

Then you could use the following command to clone and compile RustPython:

```
git clone https://github.com/RustPython/RustPython.git
cd RustPython
cargo build --release --target wasm32-wasi --features="freeze-stdlib"
```

`freeze-stdlib` feature is enabled for including Python standard library inside the binary file. The output file should be able at `target/wasm32-wasi/release/rustpython.wasm`.

AOT Compile

WasmEdge supports compiling WebAssembly bytecode programs into native machine code for better performance. It is highly recommended to compile the RustPython to native machine code before running.

```
wasmedgec ./target/wasm32-wasi/release/rustpython.wasm ./target/wasm32-
wasi/release/rustpython.wasm
```

Run

```
wasmedge ./target/wasm32-wasi/release/rustpython.wasm
```

Then you could get a Python shell in WebAssembly!

Grant file system access

You can pre-open directories to let WASI programs have permission to read and write files stored on the real machine. The following command mounted the current working directory to the WASI virtual file system.

```
wasmedge --dir .:. ./target/wasm32-wasi/release/rustpython.wasm
```

Use WasmEdge Library in Programming Languages

Besides using the WasmEdge command line tools to executing the WebAssembly applications, WasmEdge also provides SDKs for various programming languages. The WasmEdge library allows developers to embed the WasmEdge into their host applications, so that the WebAssembly applications can be executed in the WasmEdge sandbox safely. Furthermore, developers can implement the host functions for the extensions with the WasmEdge library.

In this chapter, we will discuss how to use WasmEdge SDKs to embed WasmEdge into C, Rust, Go, Node.js, and Python host applications.

WasmEdge C SDK

The WasmEdge C API denotes an interface to embed the WasmEdge runtime into a C program. The following are the quick start guide for working with the C APIs of WasmEdge. For the details of the WasmEdge C API, please refer to the full documentation. Before programming with the WasmEdge C API, please install WasmEdge first.

The WasmEdge C API is also the fundamental API for other languages' SDK.

Quick Start Guide for the WasmEdge runner

The following is an example for running a WASM file. Assume that the WASM file fibonacci.wasm is copied into the current directory, and the C file `test_wasmedge.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int Argc, const char* Argv[]) {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(32) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(VMCxt, Argv[1], FuncName,
Params, 1, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 32th fibonacci number is 3524578 in 0-based index)

```
$ gcc test_wasmedge.c -lwasmedge -o test_wasmedge
$ ./test_wasmedge fibonacci.wasm
Get result: 3524578
```

Quick Start Guide for the WasmEdge AOT compiler

Assume that the WASM file fibonacci.wasm is copied into the current directory, and the C file `test_wasmedge_compiler.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int Argc, const char* Argv[]) {
  /* Create the configure context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* ... Adjust settings in the configure context. */
  /* Result. */
  WasmEdge_Result Res;

  /* Create the compiler context. The configure context can be NULL. */
  WasmEdge_CompilerContext *CompilerCxt = WasmEdge_CompilerCreate(ConfCxt);
  /* Compile the WASM file with input and output paths. */
  Res = WasmEdge_CompilerCompile(CompilerCxt, Argv[1], Argv[2]);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Compilation failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }

  WasmEdge_CompilerDelete(CompilerCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  return 0;
}
```

Then you can compile and run (the output file is `fibonacci_aot.wasm`):

```
$ gcc test_wasmedge_compiler.c -lwasmedge -o test_wasmedge_compiler
$ ./test_wasmedge_compiler fibonacci.wasm fibonacci_aot.wasm
[2021-07-02 11:08:08.651] [info] compile start
[2021-07-02 11:08:08.653] [info] verify start
[2021-07-02 11:08:08.653] [info] optimize start
[2021-07-02 11:08:08.670] [info] codegen start
[2021-07-02 11:08:08.706] [info] compile done
```

The compiled-WASM file can be used as a WASM input for the WasmEdge runner. The following is the comparison of the interpreter mode and the AOT mode:

```
$ time ./test_wasmedge fibonacci.wasm
Get result: 5702887

real 0m2.715s
user 0m2.700s
sys 0m0.008s

$ time ./test_wasmedge fibonacci_aot.wasm
Get result: 5702887

real 0m0.036s
user 0m0.022s
sys 0m0.011s
```

API References

- 0.11.1
- 0.10.1
    - Upgrade to 0.11.0
- 0.9.1
    - Upgrade to 0.10.0

Examples

- Link with the WasmEdge library
- Use the external reference of WebAssembly input and output in C/C++
- Implement the host functions in C/C++

Use the WasmEdge Library

When programming with WasmEdge C API, developers should include the required headers and link with the WasmEdge Library. Besides install WasmEdge with the WasmEdge shared library, developers can also build WasmEdge to generate the WasmEdge static library.

Assume the example `test.c`:

```
#include <stdio.h>
#include <wasmedge/wasmedge.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x07, 0x01,
                    /* function type {i32, i32} -> {i32} */
                    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
                    /* Import section */
                    0x02, 0x13, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "func-add" */
                    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x0A, 0x01,
                    /* export name: "addTwo" */
                    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
                    /* export desc: func 0 */
                    0x00, 0x01,
                    /* Code section */
                    0x0A, 0x0A, 0x01,
                    /* code body */
                    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B};

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
      WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                        WasmEdge_ValType_I32};
```

```
  enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
  WasmEdge_FunctionTypeContext *HostFType =
      WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
      WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = {WasmEdge_ValueGenI32(1234),
                              WasmEdge_ValueGenI32(5678)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
      VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

This example will execute a WASM which call into a host function to add 2 numbers.

Link with WasmEdge Shared Library

To link the executable with the WasmEdge shared library is easy. Just compile the example file after installation of WasmEdge.

```
$ gcc test.c -lwasmedge -o test
$ ./test
Host function "Add": 1234 + 5678
Get the result: 6912
```

Link with WasmEdge Static Library

For preparing the WasmEdge static library, developers should build WasmEdge from source with the options:

```
# Recommend to use the `wasmedge/wasmedge:latest` docker image. This will
provide the required packages.
# In the WasmEdge source directory
cmake -Bbuild -GNinja -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_LINK_LLVM_STATIC=ON
-DWASMEDGE_BUILD_SHARED_LIB=Off -DWASMEDGE_BUILD_STATIC_LIB=On
-DWASMEDGE_LINK_TOOLS_STATIC=On -DWASMEDGE_BUILD_PLUGINS=Off
cmake --build build
cmake --install build
```

The cmake option `-DWASMEDGE_LINK_LLVM_STATIC=ON` will turn on the static library building, and the `-DWASMEDGE_BUILD_SHARED_LIB=Off` will turn off the shared library building.

After installation, developers can compile the example file:

```
# Note: only the Linux platforms need the `-lrt`. The MacOS platforms not need
this linker flag.
$ gcc test.c -lwasmedge -lrt -ldl -pthread -lm -lstdc++ -o test
$ ./test
Host function "Add": 1234 + 5678
Get the result: 6912
```

Host Functions

Host functions are the functions outside WebAssembly and passed to WASM modules as imports. The following steps give an example of implementing host functions and registering a `host module` into the WasmEdge runtime.

Host Instances

WasmEdge supports registering `host function`, `memory`, `table`, and `global` instances as imports.

Functions

The host function body definition in WasmEdge is defined as follows:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
    void *Data, const WasmEdge_CallingFrameContext *CallFrameCxt,
    const WasmEdge_Value *Params, WasmEdge_Value *Returns);
```

A simple host function can be defined as follows:

```
#include <wasmedge/wasmedge.h>

/* This function can add 2 i32 values and return the result. */
WasmEdge_Result Add(void *, const WasmEdge_CallingFrameContext *,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /*
  * Params: {i32, i32}
  * Returns: {i32}
  */

  /* Retrieve the value 1. */
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  /* Retrieve the value 2. */
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  /* Output value 1 is Val1 + Val2. */
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Return the status of success. */
  return WasmEdge_Result_Success;
}
```

For adding the host function into a host module instance, developers should create the

function instance with the function type context first.

```
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I32};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
/* Create a function type: {i32, i32} -> {i32}. */
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
/*
  * Create a function context with the function type and host function body.
  * The `Cost` parameter can be 0 if developers do not need the cost
  * measuring.
  */
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
  * The third parameter is the pointer to the additional data.
  * Developers should guarantee the life cycle of the data, and it can be NULL
if the external data is not needed.
  */
WasmEdge_FunctionTypeDelete(HostType);
```

Tables, Memories, and Globals

To create a `host table`, `memory`, and `global` instance, developers can use similar APIs.

```
/* Create a host table exported as "table". */
WasmEdge_Limit TabLimit = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *HostTType =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TabLimit);
WasmEdge_TableInstanceContext *HostTable =
    WasmEdge_TableInstanceCreate(HostTType);
WasmEdge_TableTypeDelete(HostTType);

/* Create a host memory exported as "memory". */
WasmEdge_Limit MemLimit = {.HasMax = true, .Shared = false, .Min = 1, .Max =
2};
WasmEdge_MemoryTypeContext *HostMType = WasmEdge_MemoryTypeCreate(MemLimit);
WasmEdge_MemoryInstanceContext *HostMemory =
    WasmEdge_MemoryInstanceCreate(HostMType);
WasmEdge_MemoryTypeDelete(HostMType);

/* Create a host global exported as "global_i32" and initialized as `666`. */
WasmEdge_GlobalTypeContext *HostGType =
    WasmEdge_GlobalTypeCreate(WasmEdge_ValType_I32, WasmEdge_Mutability_Const);
WasmEdge_GlobalInstanceContext *HostGlobal =
    WasmEdge_GlobalInstanceCreate(HostGType, WasmEdge_ValueGenI32(666));
WasmEdge_GlobalTypeDelete(HostGType);
```

Host Modules

The host module is a module instance that contains `host functions`, `tables`, `memories`, and `globals`, the same as the WASM modules. Developers can use APIs to add the instances into a host module. After registering the host modules into a `VM` or `Store` context, the exported instances in that modules can be imported by WASM modules when instantiating.

Module Instance Creation

Module instance supplies exported module name.

```
WasmEdge_String HostName = WasmEdge_StringCreateByCString("test");
WasmEdge_ModuleInstanceContext *HostMod =
    WasmEdge_ModuleInstanceCreate(HostName);
WasmEdge_StringDelete(HostName);
```

Add Instances

Developers can add the `host functions`, `tables`, `memories`, and `globals` into the module instance with the export name. After adding to the module, the ownership of the instances is moved into the module. Developers should **NOT** access or destroy them.

```
/* Add the host function created above with the export name "add". */
HostName = WasmEdge_StringCreateByCString("add");
WasmEdge_ModuleInstanceAddFunction(HostMod, HostName, HostFunc);
WasmEdge_StringDelete(HostName);

/* Add the table created above with the export name "table". */
HostName = WasmEdge_StringCreateByCString("table");
WasmEdge_ModuleInstanceAddTable(HostMod, HostName, HostTable);
WasmEdge_StringDelete(HostName);

/* Add the memory created above with the export name "memory". */
HostName = WasmEdge_StringCreateByCString("memory");
WasmEdge_ModuleInstanceAddMemory(HostMod, HostName, HostMemory);
WasmEdge_StringDelete(HostName);

/* Add the global created above with the export name "global_i32". */
HostName = WasmEdge_StringCreateByCString("global_i32");
WasmEdge_ModuleInstanceAddGlobal(HostMod, HostName, HostGlobal);
WasmEdge_StringDelete(HostName);
```

Register Host Modules to WasmEdge

For importing the host functions in WASM, developers can register the host modules into a `VM` or `Store` context.

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(NULL, NULL);

/* Register the module instance into the store. */
WasmEdge_Result Res =
    WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, HostModCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Host module registration failed: %s\n",
         WasmEdge_ResultGetMessage(Res));
  return -1;
}
/*
 * Developers can register the host module into a VM context by the
 * `WasmEdge_VMRegisterModuleFromImport()` API.
 */
/*
 * The owner of the host module will not be changed. Developers can register
 * the host module into several VMs or stores.
 */

/* Although being registered, the host module should be destroyed. */
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_ModuleInstanceDelete(HostModCxt);
```

Host Function Body Implementation Tips

There are some tips about implementing the host functions.

Calling Frame Context

The `WasmEdge_CallingFrameContext` is the context to provide developers to access the module instance of the frame on the top of the calling stack. According to the WASM spec, a frame with the module instance to which the caller function belonging is pushed into the stack when invoking a function. Therefore, the host functions can access the module instance of the top frame to retrieve the memory instances to read/write data.

```
/* Host function body definition. */
WasmEdge_Result LoadOffset(void *Data,
                           const WasmEdge_CallingFrameContext *CallFrameCxt,
                           const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {i32} -> {} */
  uint32_t Offset = (uint32_t)WasmEdge_ValueGetI32(In[0]);
  uint32_t Num = 0;

  /* Get the 0th memory instance of the module of the top frame on the stack.
*/
  /*
   * Noticed that the `MemCxt` will be `NULL` if there's no memory instance in
   * the module instance on the top frame.
   */
  WasmEdge_MemoryInstanceContext *MemCxt =
      WasmEdge_CallingFrameGetMemoryInstance(CallFrameCxt, 0);
  WasmEdge_Result Res =
      WasmEdge_MemoryInstanceGetData(MemCxt, (uint8_t *)(&Num), Offset, 4);
  if (WasmEdge_ResultOK(Res)) {
    printf("u32 at memory[%u]: %u\n", Offset, Num);
  } else {
    return Res;
  }
  return WasmEdge_Result_Success;
}
```

The `WasmEdge_CallingFrameGetModuleInstance()` API can help developers to get the module instance of the top frame on the stack. With the module instance context, developers can use the module instance-related APIs to get its contents. The `WasmEdge_CallingFrameGetExecutor()` API can help developers to get the currently used executor context. Therefore developers can use the executor to recursively invoke other WASM functions without creating a new executor context.

Return Error Codes

Usually, the host function in WasmEdge can return the `WasmEdge_Result_Success` to present the successful execution. For presenting the host function execution failed, one way is to return a trap with the error code. Then the WasmEdge runtime will cause the trap in WASM and return that error.

Note: We don't recommend using system calls such as `exit()`. That will shut down the whole WasmEdge runtime.

For simply generating the trap, developers can return the `WasmEdge_Result_Fail`. If developers call the `WasmEdge_ResultOK()` with the returned result, they will get `false`. If

developers call the `WasmEdge_ResultGetCode()` with the returned result, they will always get `2`.

For the versions after `0.11.0`, developers can specify the error code within 24-bit (smaller than `16777216`) size.

```
/* Host function body definition. */
WasmEdge_Result FaildFunc(void *Data,
                          const WasmEdge_CallingFrameContext *CallFrameCxt,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* This will create a trap in WASM with the error code. */
  return WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, 12345678);
}
```

Therefore when developers call the `WasmEdge_ResultGetCode()` with the returned result, they will get the error code `12345678`. Noticed that if developers call the `WasmEdge_ResultGetMessage()`, they will always get the C string `"user defined error code"`.

Host Data

The third parameter of the `WasmEdge_FunctionInstanceCreate()` API is for the host data as the type `void *`. Developers can pass the data into the host functions when creating. Then in the host function body, developers can access the data from the first argument. Developers should guarantee that the availability of the host data should be longer than the host functions.

```
/* Host function body definition. */
WasmEdge_Result PrintData(void *Data,
                          const WasmEdge_CallingFrameContext *,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {} -> {} */
  printf("Data: %lf\n", *(double *)Data);
  return WasmEdge_Result_Success;
}

/* The host data. */
double Number = 0.0f;

/* Create a function type: {} -> {}. */
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(NULL, 0, NULL, 0);
/* Create a function context with the function type and host function body. */
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, (void *)(&Number), NULL, 0);
WasmEdge_FunctionTypeDelete(HostType);
```

Forcing Termination

Sometimes developers may want to terminate the WASM execution with the success status. WasmEdge provides a method for terminating WASM execution in host functions. Developers can return `WasmEdge_Result_Terminate` to trigger the forcing termination of the current execution. If developers call the `WasmEdge_ResultOK()` with the returned result, they will get `true`. If developers call the `WasmEdge_ResultGetCode()` with the returned result, they will always get `1`.

Customized External References

External References denotes an opaque and unforgettable reference to a host object. A new `externref` type can be passed into a Wasm module or returned from it. The Wasm module cannot reveal an `externref` value's bit pattern, nor create a fake host reference by an integer value.

Tutorial

The following tutorial is the summary of the `externref` example in WasmEdge.

Prepare Your Wasm File

The Wasm file should contain importing host functions that would take the `externref`. Take the test WASM file (this WAT is the corresponding text format) as an example:

```
(module
  (type $t0 (func (param externref i32) (result i32)))
  (type $t1 (func (param externref i32 i32) (result i32)))
  (type $t2 (func (param externref externref i32 i32) (result i32)))
  (import "extern_module" "functor_square" (func $functor_square (type $t0)))
  (import "extern_module" "class_add" (func $class_add (type $t1)))
  (import "extern_module" "func_mul" (func $func_mul (type $t1)))
  (func $call_add (export "call_add") (type $t1) (param $p0 externref) (param
$p1 i32) (param $p2 i32) (result i32)
    (call $class_add
      (local.get $p0)
      (local.get $p1)
      (local.get $p2)))
  (func $call_mul (export "call_mul") (type $t1) (param $p0 externref) (param
$p1 i32) (param $p2 i32) (result i32)
    (call $func_mul
      (local.get $p0)
      (local.get $p1)
      (local.get $p2)))
  (func $call_square (export "call_square") (type $t0) (param $p0 externref)
(param $p1 i32) (result i32)
    (call $functor_square
      (local.get $p0)
      (local.get $p1)))
  (func $call_add_square (export "call_add_square") (type $t2) (param $p0
externref) (param $p1 externref) (param $p2 i32) (param $p3 i32) (result i32)
    (call $functor_square
      (local.get $p1)
      (call $class_add
        (local.get $p0)
        (local.get $p2)
        (local.get $p3))))
  (memory $memory (export "memory") 1))
```

Users can convert `wat` to `wasm` through wat2wasm live tool. Noted that `reference types` checkbox should be checked on this page.

Implement Host Module and Register into WasmEdge

The host module should be implemented and registered into WasmEdge before executing Wasm. Assume that the following code is saved as `main.c` :

```
#include <wasmedge/wasmedge.h>

#include <stdio.h>

uint32_t SquareFunc(uint32_t A) { return A * A; }
uint32_t AddFunc(uint32_t A, uint32_t B) { return A + B; }
uint32_t MulFunc(uint32_t A, uint32_t B) { return A * B; }

// Host function to call `SquareFunc` by external reference
WasmEdge_Result ExternSquare(void *Data,
                             const WasmEdge_CallingFrameContext *CallFrameCxt,
                             const WasmEdge_Value *In, WasmEdge_Value *Out) {
  // Function type: {externref, i32} -> {i32}
  uint32_t (*Func)(uint32_t) = WasmEdge_ValueGetExternRef(In[0]);
  uint32_t C = Func(WasmEdge_ValueGetI32(In[1]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}

// Host function to call `AddFunc` by external reference
WasmEdge_Result ExternAdd(void *Data,
                          const WasmEdge_CallingFrameContext *CallFrameCxt,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  // Function type: {externref, i32, i32} -> {i32}
  uint32_t (*Func)(uint32_t, uint32_t) = WasmEdge_ValueGetExternRef(In[0]);
  uint32_t C = Func(WasmEdge_ValueGetI32(In[1]), WasmEdge_ValueGetI32(In[2]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}

// Host function to call `ExternMul` by external reference
WasmEdge_Result ExternMul(void *Data,
                          const WasmEdge_CallingFrameContext *CallFrameCxt,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  // Function type: {externref, i32, i32} -> {i32}
  uint32_t (*Func)(uint32_t, uint32_t) = WasmEdge_ValueGetExternRef(In[0]);
  uint32_t C = Func(WasmEdge_ValueGetI32(In[1]), WasmEdge_ValueGetI32(In[2]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}

// Helper function to create the "extern_module" module instance.
WasmEdge_ModuleInstanceContext *CreateExternModule() {
  WasmEdge_String HostName;
  WasmEdge_FunctionTypeContext *HostFType = NULL;
  WasmEdge_FunctionInstanceContext *HostFunc = NULL;
  enum WasmEdge_ValType P[3], R[1];

  HostName = WasmEdge_StringCreateByCString("extern_module");
  WasmEdge_ModuleInstanceContext *HostMod =
      WasmEdge_ModuleInstanceCreate(HostName);
  WasmEdge_StringDelete(HostName);
```

```
  // Add host function "functor_square": {externref, i32} -> {i32}
  P[0] = WasmEdge_ValType_ExternRef;
  P[1] = WasmEdge_ValType_I32;
  R[0] = WasmEdge_ValType_I32;
  HostFType = WasmEdge_FunctionTypeCreate(P, 2, R, 1);
  HostFunc = WasmEdge_FunctionInstanceCreate(HostFType, ExternSquare, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  HostName = WasmEdge_StringCreateByCString("functor_square");
  WasmEdge_ModuleInstanceAddFunction(HostMod, HostName, HostFunc);
  WasmEdge_StringDelete(HostName);

  // Add host function "class_add": {externref, i32, i32} -> {i32}
  P[2] = WasmEdge_ValType_I32;
  HostFType = WasmEdge_FunctionTypeCreate(P, 3, R, 1);
  HostFunc = WasmEdge_FunctionInstanceCreate(HostFType, ExternAdd, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  HostName = WasmEdge_StringCreateByCString("class_add");
  WasmEdge_ModuleInstanceAddFunction(HostMod, HostName, HostFunc);
  WasmEdge_StringDelete(HostName);

  // Add host function "func_mul": {externref, i32, i32} -> {i32}
  HostFType = WasmEdge_FunctionTypeCreate(P, 3, R, 1);
  HostFunc = WasmEdge_FunctionInstanceCreate(HostFType, ExternMul, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  HostName = WasmEdge_StringCreateByCString("func_mul");
  WasmEdge_ModuleInstanceAddFunction(HostMod, HostName, HostFunc);
  WasmEdge_StringDelete(HostName);

  return HostMod;
}

int main() {
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
  WasmEdge_ModuleInstanceContext *HostMod = CreateExternModule();
  WasmEdge_Value P[3], R[1];
  WasmEdge_String FuncName;
  WasmEdge_Result Res;

  Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, HostMod);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Host module instance registration failed\n");
    return EXIT_FAILURE;
  }
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "funcs.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM file loading failed\n");
    return EXIT_FAILURE;
  }
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM validation failed\n");
    return EXIT_FAILURE;
```

```
  }
  Res = WasmEdge_VMInstantiate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM instantiation failed\n");
    return EXIT_FAILURE;
  }

  // Test 1: call add -- 1234 + 5678
  P[0] = WasmEdge_ValueGenExternRef(AddFunc);
  P[1] = WasmEdge_ValueGenI32(1234);
  P[2] = WasmEdge_ValueGenI32(5678);
  FuncName = WasmEdge_StringCreateByCString("call_add");
  Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 3, R, 1);
  WasmEdge_StringDelete(FuncName);
  if (WasmEdge_ResultOK(Res)) {
    printf("Test 1 -- `call_add` -- 1234 + 5678 = %d\n",
           WasmEdge_ValueGetI32(R[0]));
  } else {
    printf("Test 1 -- `call_add` -- 1234 + 5678 -- failed\n");
    return EXIT_FAILURE;
  }

  // Test 2: call mul -- 789 * 4321
  P[0] = WasmEdge_ValueGenExternRef(MulFunc);
  P[1] = WasmEdge_ValueGenI32(789);
  P[2] = WasmEdge_ValueGenI32(4321);
  FuncName = WasmEdge_StringCreateByCString("call_mul");
  Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 3, R, 1);
  WasmEdge_StringDelete(FuncName);
  if (WasmEdge_ResultOK(Res)) {
    printf("Test 2 -- `call_mul` -- 789 * 4321 = %d\n",
           WasmEdge_ValueGetI32(R[0]));
  } else {
    printf("Test 2 -- `call_mul` -- 789 * 4321 -- failed\n");
    return EXIT_FAILURE;
  }

  // Test 3: call square -- 8256^2
  P[0] = WasmEdge_ValueGenExternRef(SquareFunc);
  P[1] = WasmEdge_ValueGenI32(8256);
  FuncName = WasmEdge_StringCreateByCString("call_square");
  Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 2, R, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Test 3 -- `call_mul` -- 8256 ^ 2 = %d\n",
           WasmEdge_ValueGetI32(R[0]));
  } else {
    printf("Test 3 -- `call_mul` -- 8256 ^ 2 -- failed\n");
    return EXIT_FAILURE;
  }

  return EXIT_SUCCESS;
}
```

Setup the Environment And Compile

1. Install the WasmEdge shared library.

   Please refer to the Installation for details.

2. Prepare the WASM file and the `main.c` source file as above.

3. Compile

   ```
   gcc main.c -lwasmedge
   # Or you can use g++ for the C++ case, or use the clang.
   ```

4. Run the Test

   ```
   $ ./a.out
   Test 1 -- `call_add` -- 1234 + 5678 = 6912
   Test 2 -- `call_mul` -- 789 * 4321 = 3409269
   Test 3 -- `call_mul` -- 8256 ^ 2 = 68161536
   ```

Wasm module with External References

Take the following `wat` for example:

```
(module
  (type $t0 (func (param externref i32) (result i32)))
  ;; Import a host function which type is {externref i32} -> {i32}
  (import "extern_module" "functor_square" (func $functor_square (type $t0)))
  ;; Wasm function which type is {externref i32} -> {i32} and exported as
"call_square"
  (func $call_square (export "call_square") (type $t0) (param $p0 externref)
(param $p1 i32) (result i32)
    (call $functor_square (local.get $p0) (local.get $p1))
  )
  (memory $memory (export "memory") 1))
```

The Wasm function " `call_square` " takes an `externref` parameter, and calls the imported host function `functor_square` with that `externref` . Therefore, the `functor_square` host function can get the object reference when users call " `call_square` " Wasm function and pass the object's reference.

WasmEdge ExternRef Example

The following examples are how to use `externref` in Wasm with WasmEdge C API.

Wasm Code

The Wasm code must pass the `externref` to host functions that want to access it. Take the following `wat` for example, which is a part of the test WASM file:

```
(module
  (type $t0 (func (param externref i32 i32) (result i32)))
  (import "extern_module" "func_mul" (func $func_mul (type $t0)))
  (func $call_mul (export "call_mul") (type $t0) (param $p0 externref) (param
$p1 i32) (param $p2 i32) (result i32)
    (call $func_mul (local.get $p0) (local.get $p1) (local.get $p2))
  )
  (memory $memory (export "memory") 1))
```

The host function " `extern_module::func_mul` " takes `externref` as a function pointer to multiply parameters 1 and 2 and then returns the result. The exported Wasm function " `call_mul` " calls " `func_mul` " and passes the `externref` and 2 numbers as arguments.

Host Functions

To instantiate the above example Wasm, the host functions must be registered into WasmEdge. See Host Functions for more details. The host functions which take `externref` s must know the original objects' types. We take the function pointer case for example.

```
/* Function to pass as function pointer. */
uint32_t MulFunc(uint32_t A, uint32_t B) { return A * B; }

/* Host function to call the function by external reference as a function
pointer */
WasmEdge_Result ExternMul(void *, const WasmEdge_CallingFrameContext *,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {externref, i32, i32} -> {i32} */
  void *Ptr = WasmEdge_ValueGetExternRef(In[0]);
  uint32_t (*Obj)(uint32_t, uint32_t) = Ptr;
  /*
   * For C++, the `reinterpret_cast` is needed:
   * uint32_t (*Obj)(uint32_t, uint32_t) =
   *   *reinterpret_cast<uint32_t (*)(uint32_t, uint32_t)>(Ptr);
   */
  uint32_t C = Obj(WasmEdge_ValueGetI32(In[1]), WasmEdge_ValueGetI32(In[2]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}
```

" `MulFunc` " is a function that will be passed into Wasm as `externref`. In the " `func_mul` " host function, users can use " `WasmEdge_ValueGetExternRef` " API to get the pointer from the `WasmEdge_Value` which contains a `externref`.

Developers can add the host functions with names into a module instance.

```
/* Create a module instance. */
WasmEdge_String HostName = WasmEdge_StringCreateByCString("extern_module");
WasmEdge_ModuleInstanceContext *HostMod =
    WasmEdge_ModuleInstanceCreate(HostName);
WasmEdge_StringDelete(HostName);

/* Create a function instance and add into the module instance. */
enum WasmEdge_ValType P[3], R[1];
P[0] = WasmEdge_ValType_ExternRef;
P[1] = WasmEdge_ValType_I32;
P[2] = WasmEdge_ValType_I32;
R[0] = WasmEdge_ValType_I32;
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(P, 3, R, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, ExternFuncMul, NULL, 0);
WasmEdge_FunctionTypeDelete(HostFType);
HostName = WasmEdge_StringCreateByCString("func_mul");
WasmEdge_ModuleInstanceAddFunction(HostMod, HostName, HostFunc);
WasmEdge_StringDelete(HostName);

...
```

Execution

Take the test WASM file (this WAT is the corresponding text format) for example. Assume that the `funcs.wasm` is copied into the current directory. The following is the example to execute WASM with `externref` through the WasmEdge C API.

```
/* Create the VM context. */
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
/* Create the module instance context that contains the host functions. */
WasmEdge_ModuleInstanceContext *HostMod = /* Ignored ... */;
/* Assume that the host functions are added to the module instance above. */
WasmEdge_Value P[3], R[1];
WasmEdge_String FuncName;
WasmEdge_Result Res;

/* Register the module instance into VM. */
Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, HostMod);
if (!WasmEdge_ResultOK(Res)) {
  printf("Import object registration failed\n");
  return EXIT_FAILURE;
}
/* Load WASM from the file. */
Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "funcs.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM file loading failed\n");
  return EXIT_FAILURE;
}
/* Validate WASM. */
Res = WasmEdge_VMValidate(VMCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM validation failed\n");
  return EXIT_FAILURE;
}
/* Instantiate the WASM module. */
Res = WasmEdge_VMInstantiate(VMCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed\n");
  return EXIT_FAILURE;
}

/* Run a WASM function. */
P[0] = WasmEdge_ValueGenExternRef(AddFunc);
P[1] = WasmEdge_ValueGenI32(1234);
P[2] = WasmEdge_ValueGenI32(5678);
/* Run the `call_add` function. */
FuncName = WasmEdge_StringCreateByCString("call_add");
Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 3, R, 1);
WasmEdge_StringDelete(FuncName);
if (WasmEdge_ResultOK(Res)) {
  printf("Run -- `call_add` -- 1234 + 5678 = %d\n",
         WasmEdge_ValueGetI32(R[0]));
} else {
  printf("Run -- `call_add` -- 1234 + 5678 -- failed\n");
  return EXIT_FAILURE;
}
```

Passing Objects

The above example is passing a function reference as `externref`. The following examples are about how to pass an object reference into WASM as `externref` in C++.

Passing a Class

To pass a class as `externref`, the object instance is needed.

```
class AddClass {
public:
  uint32_t add(uint32_t A, uint32_t B) const { return A + B; }
};

AddClass AC;
```

Then users can pass the object into WasmEdge by using `WasmEdge_ValueGenExternRef()` API.

```
WasmEdge_Value P[3], R[1];
P[0] = WasmEdge_ValueGenExternRef(&AC);
P[1] = WasmEdge_ValueGenI32(1234);
P[2] = WasmEdge_ValueGenI32(5678);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("call_add");
WasmEdge_Result Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 3, R, 1);
WasmEdge_StringDelete(FuncName);
if (WasmEdge_ResultOK(Res)) {
  std::cout << "Result : " << WasmEdge_ValueGetI32(R[0]) std::endl;
  // Will print `6912`.
} else {
  return EXIT_FAILURE;
}
```

In the host function which would access the object by reference, users can use the `WasmEdge_ValueGetExternRef()` API to retrieve the reference to the object.

```
// Modify the `ExternAdd` in the above tutorial.
WasmEdge_Result ExternAdd(void *, const WasmEdge_CallingFrameContext *,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  // Function type: {externref, i32, i32} -> {i32}
  void *Ptr = WasmEdge_ValueGetExternRef(In[0]);
  AddClass &Obj = *reinterpret_cast<AddClass *>(Ptr);
  uint32_t C =
      Obj.add(WasmEdge_ValueGetI32(In[1]), WasmEdge_ValueGetI32(In[2]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}
```

Passing an Object As Functor

As the same as passing a class instance, the functor object instance is needed.

```
struct SquareStruct {
  uint32_t operator()(uint32_t Val) const { return Val * Val; }
};

SquareStruct SS;
```

Then users can pass the object into WasmEdge by using the `WasmEdge_ValueGenExternRef()` API.

```
WasmEdge_Value P[2], R[1];
P[0] = WasmEdge_ValueGenExternRef(&SS);
P[1] = WasmEdge_ValueGenI32(1024);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("call_square");
WasmEdge_Result Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 2, R, 1);
WasmEdge_StringDelete(FuncName);
if (WasmEdge_ResultOK(Res)) {
  std::cout << "Result : " << WasmEdge_ValueGetI32(R[0]) std::endl;
  // Will print `1048576`.
} else {
  return EXIT_FAILURE;
}
```

In the host function which would access the object by reference, users can use the `WasmEdge_ValueGetExternRef` API to retrieve the reference to the object, and the reference is a functor.

```
// Modify the `ExternSquare` in the above tutorial.
WasmEdge_Result ExternSquare(void *, const WasmEdge_CallingFrameContext *,
                             const WasmEdge_Value *In, WasmEdge_Value *Out) {
  // Function type: {externref, i32, i32} -> {i32}
  void *Ptr = WasmEdge_ValueGetExternRef(In[0]);
  SquareStruct &Obj = *reinterpret_cast<SquareStruct *>(Ptr);
  uint32_t C = Obj(WasmEdge_ValueGetI32(In[1]));
  Out[0] = WasmEdge_ValueGenI32(C);
  return WasmEdge_Result_Success;
}
```

Passing STL Objects

The example Wasm binary (this WAT is the corresponding text format) provides functions to interact with host functions which can access C++ STL objects. Assume that the WASM file `stl.wasm` is copied into the current directory.

Take the `std::ostream` and `std::string` objects for example. Assume that there's a host function accesses to a `std::ostream` and a `std::string` through `externref` s:

```
// Host function to output std::string through std::ostream
WasmEdge_Result ExternSTLOStreamStr(void *,
                                    const WasmEdge_CallingFrameContext *,
                                    const WasmEdge_Value *In,
                                    WasmEdge_Value *) {
  // Function type: {externref, externref} -> {}
  void *Ptr0 = WasmEdge_ValueGetExternRef(In[0]);
  void *Ptr1 = WasmEdge_ValueGetExternRef(In[1]);
  std::ostream &RefOS = *reinterpret_cast<std::ostream *>(Ptr0);
  std::string &RefStr = *reinterpret_cast<std::string *>(Ptr1);
  RefOS << RefStr;
  return WasmEdge_Result_Success;
}
```

Assume that the above host function is added to the module instance `HostMod` , and the `HostMod` is registered into a VM context `VMCxt` . Then users can instantiate the Wasm module:

```
WasmEdge_Result Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "stl.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM file loading failed\n");
  return EXIT_FAILURE;
}
Res = WasmEdge_VMValidate(VMCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM validation failed\n");
  return EXIT_FAILURE;
}
Res = WasmEdge_VMInstantiate(VMCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed\n");
  return EXIT_FAILURE;
}
```

Last, pass the `std::cout` and a `std::string` object by external references.

```
std::string PrintStr("Hello world!");
WasmEdge_Value P[2], R[1];
P[0] = WasmEdge_ValueGenExternRef(&std::cout);
P[1] = WasmEdge_ValueGenExternRef(&PrintStr);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("call_ostream_str");
WasmEdge_Result Res = WasmEdge_VMExecute(VMCxt, FuncName, P, 2, R, 1);
// Will print "Hello world!" to stdout.
WasmEdge_StringDelete(FuncName);
if (!WasmEdge_ResultOK(Res)) {
  return EXIT_FAILURE;
}
```

For other C++ STL objects cases, such as `std::vector<T>`, `std::map<T, U>`, or `std::set<T>`, the object can be accessed correctly in host functions if the type in `reinterpret_cast` is correct.

WasmEdge C 0.12.0 API Documentation

WasmEdge C API denotes an interface to access the WasmEdge runtime. The following are the guides to working with the C APIs of WasmEdge.

This document is for the `0.12.0` version. For the older `0.12.0` version, please refer to the document here.

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WasmEdge Installation

Download And Install

The easiest way to install WasmEdge is to run the following command. Your system should have `git` and `wget` as prerequisites.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.12.0
```

For more details, please refer to the Installation Guide for the WasmEdge installation.

Compile Sources

After the installation of WasmEdge, the following guide can help you to test for the availability of the WasmEdge C API.

1. Prepare the test C file (and assumed saved as `test.c`):

    ```
    #include <wasmedge/wasmedge.h>
    #include <stdio.h>
    int main() {
      printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
      return 0;
    }
    ```

2. Compile the file with `gcc` or `clang`.

```
gcc test.c -lwasmedge
```

3. Run and get the expected output.

```
$ ./a.out
WasmEdge version: 0.12.0
```

ABI Compatibility

WasmEdge C API introduces SONAME and SOVERSION since the 0.11.0 release to present the compatibility between different C API versions.

The releases before 0.11.0 are all unversioned. Please make sure the library version is the same as the corresponding C API version you used.

WasmEdge Version	WasmEdge C API Library Name	WasmEdge C API SONAME	WasmEdge C API SOVERSION
< 0.11.0	libwasmedge_c.so	Unversioned	Unversioned
0.11.0 to 0.11.1	libwasmedge.so	libwasmedge.so.0	libwasmedge.so.0.0.0
0.11.2	libwasmedge.so	libwasmedge.so.0	libwasmedge.so.0.0.1
Since 0.12.0	libwasmedge.so	libwasmedge.so.0	libwasmedge.so.0.0.2

WasmEdge Basics

In this part, we will introduce the utilities and concepts of WasmEdge shared library.

Version

The `Version` related APIs provide developers to check for the WasmEdge shared library version.

```
#include <wasmedge/wasmedge.h>
printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
printf("WasmEdge version major: %u\n", WasmEdge_VersionGetMajor());
printf("WasmEdge version minor: %u\n", WasmEdge_VersionGetMinor());
printf("WasmEdge version patch: %u\n", WasmEdge_VersionGetPatch());
```

Logging Settings

The `WasmEdge_LogSetErrorLevel()` and `WasmEdge_LogSetDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Developers can also use the `WasmEdge_LogOff()` API to disable all logging.

Value Types

In WasmEdge, developers should convert the values to `WasmEdge_Value` objects through APIs for matching to the WASM value types.

1. Number types: `i32`, `i64`, `f32`, `f64`, and `v128` for the `SIMD` proposal

```
WasmEdge_Value Val;
Val = WasmEdge_ValueGenI32(123456);
printf("%d\n", WasmEdge_ValueGetI32(Val));
/* Will print "123456" */
Val = WasmEdge_ValueGenI64(1234567890123LL);
printf("%ld\n", WasmEdge_ValueGetI64(Val));
/* Will print "1234567890123" */
Val = WasmEdge_ValueGenF32(123.456f);
printf("%f\n", WasmEdge_ValueGetF32(Val));
/* Will print "123.456001" */
Val = WasmEdge_ValueGenF64(123456.123456789);
printf("%.10f\n", WasmEdge_ValueGetF64(Val));
/* Will print "123456.1234567890" */
```

2. Reference types: `funcref` and `externref` for the `Reference-Types` proposal

```
WasmEdge_Value Val;
void *Ptr;
bool IsNull;
uint32_t Num = 10;
/* Generate a externref to NULL. */
Val = WasmEdge_ValueGenNullRef(WasmEdge_RefType_ExternRef);
IsNull = WasmEdge_ValueIsNullRef(Val);
/* The `IsNull` will be `TRUE`. */
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `NULL`. */

/* Get the function instance by creation or from module instance. */
const WasmEdge_FunctionInstanceContext *FuncCxt = ...;
/* Generate a funcref with the given function instance context. */
Val = WasmEdge_ValueGenFuncRef(FuncCxt);
const WasmEdge_FunctionInstanceContext *GotFuncCxt =
    WasmEdge_ValueGetFuncRef(Val);
/* The `GotFuncCxt` will be the same as `FuncCxt`. */

/* Generate a externref to `Num`. */
Val = WasmEdge_ValueGenExternRef(&Num);
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `&Num`. */
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "10" */
Num += 55;
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "65" */
```

Strings

The `WasmEdge_String` object is for the instance names when invoking a WASM function or finding the contexts of instances.

1. Create a `WasmEdge_String` from a C string (`const char *` with NULL termination) or a buffer with length.

   The content of the C string or buffer will be copied into the `WasmEdge_String` object.

```
char Buf[4] = {50, 55, 60, 65};
WasmEdge_String Str1 = WasmEdge_StringCreateByCString("test");
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
/* The objects should be deleted by `WasmEdge_StringDelete()`. */
WasmEdge_StringDelete(Str1);
WasmEdge_StringDelete(Str2);
```

2. Wrap a `WasmEdge_String` to a buffer with length.

   The content will not be copied, and the caller should guarantee the life cycle of the input buffer.

```
const char CStr[] = "test";
WasmEdge_String Str = WasmEdge_StringWrap(CStr, 4);
/* The object should __NOT__ be deleted by `WasmEdge_StringDelete()`. */
```

3. String comparison

```
const char CStr[] = "abcd";
char Buf[4] = {0x61, 0x62, 0x63, 0x64};
WasmEdge_String Str1 = WasmEdge_StringWrap(CStr, 4);
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
bool IsEq = WasmEdge_StringIsEqual(Str1, Str2);
/* The `IsEq` will be `TRUE`. */
WasmEdge_StringDelete(Str2);
```

4. Convert to C string

```
char Buf[256];
WasmEdge_String Str =
    WasmEdge_StringCreateByCString("test_wasmedge_string");
uint32_t StrLength = WasmEdge_StringCopy(Str, Buf, sizeof(Buf));
/* StrLength will be 20 */
printf("String: %s\n", Buf);
/* Will print "test_wasmedge_string". */
```

Results

The `WasmEdge_Result` object specifies the execution status. APIs about WASM execution will

return the `WasmEdge_Result` to denote the status.

```
WasmEdge_Result Res = WasmEdge_Result_Success;
bool IsSucceeded = WasmEdge_ResultOK(Res);
/* The `IsSucceeded` will be `TRUE`. */
uint32_t Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 0. */
const char *Msg = WasmEdge_ResultGetMessage(Res);
/* The `Msg` will be "success". */
enum WasmEdge_ErrCategory Category = WasmEdge_ResultGetCategory(Res);
/* The `Category` will be WasmEdge_ErrCategory_WASM. */

Res = WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, 123);
/* Generate the user-defined result with code. */
Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 123. */
Category = WasmEdge_ResultGetCategory(Res);
/* The `Category` will be WasmEdge_ErrCategory_UserLevelError. */
```

Contexts

The objects, such as `VM`, `Store`, and `Function`, are composed of `Context`s. All of the contexts can be created by calling the corresponding creation APIs and should be destroyed by calling the corresponding deletion APIs. Developers have responsibilities to manage the contexts for memory management.

```
/* Create the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Delete the configure context. */
WasmEdge_ConfigureDelete(ConfCxt);
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `WasmEdge_Limit` struct is defined in the header:

```
/// Struct of WASM limit.
typedef struct WasmEdge_Limit {
  /// Boolean to describe has max value or not.
  bool HasMax;
  /// Boolean to describe is shared memory or not.
  bool Shared;
  /// Minimum value.
  uint32_t Min;
  /// Maximum value. Will be ignored if the `HasMax` is false.
  uint32_t Max;
} WasmEdge_Limit;
```

Developers can initialize the struct by assigning it's value, and the `Max` value is needed to be larger or equal to the `Min` value. The API `WasmEdge_LimitIsEqual()` is provided to compare with 2 `WasmEdge_Limit` structs.

2. Function type context

   The `Function Type` context is used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `Function Type` context APIs to get the parameter or return value types information.

```
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I64};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_FuncRef};
WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);

enum WasmEdge_ValType Buf[16];
uint32_t ParamLen = WasmEdge_FunctionTypeGetParametersLength(FuncTypeCxt);
/* `ParamLen` will be 2. */
uint32_t GotParamLen =
    WasmEdge_FunctionTypeGetParameters(FuncTypeCxt, Buf, 16);
/* `GotParamLen` will be 2, and `Buf[0]` and `Buf[1]` will be the same as
 * `ParamList`. */
uint32_t ReturnLen = WasmEdge_FunctionTypeGetReturnsLength(FuncTypeCxt);
/* `ReturnLen` will be 1. */
uint32_t GotReturnLen =
    WasmEdge_FunctionTypeGetReturns(FuncTypeCxt, Buf, 16);
/* `GotReturnLen` will be 1, and `Buf[0]` will be the same as `ReturnList`.
 */

WasmEdge_FunctionTypeDelete(FuncTypeCxt);
```

3. Table type context

   The `Table Type` context is used for `Table` instance creation or getting information from `Table` instances.

```
WasmEdge_Limit TabLim = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_ExternRef, TabLim);

enum WasmEdge_RefType GotRefType =
WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `GotRefType` will be WasmEdge_RefType_ExternRef. */
WasmEdge_Limit GotTabLim = WasmEdge_TableTypeGetLimit(TabTypeCxt);
/* `GotTabLim` will be the same value as `TabLim`. */

WasmEdge_TableTypeDelete(TabTypeCxt);
```

4. Memory type context

   The `Memory Type` context is used for `Memory` instance creation or getting information from `Memory` instances.

```
WasmEdge_Limit MemLim = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_MemoryTypeContext *MemTypeCxt = WasmEdge_MemoryTypeCreate(MemLim);

WasmEdge_Limit GotMemLim = WasmEdge_MemoryTypeGetLimit(MemTypeCxt);
/* `GotMemLim` will be the same value as `MemLim`. */

WasmEdge_MemoryTypeDelete(MemTypeCxt)
```

5. Global type context

   The `Global Type` context is used for `Global` instance creation or getting information from `Global` instances.

```
WasmEdge_GlobalTypeContext *GlobTypeCxt = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_F64, WasmEdge_Mutability_Var);

WasmEdge_ValType GotValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `GotValType` will be WasmEdge_ValType_F64. */
WasmEdge_Mutability GotValMut =
    WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `GotValMut` will be WasmEdge_Mutability_Var. */

WasmEdge_GlobalTypeDelete(GlobTypeCxt);
```

6. Import type context

   The `Import Type` context is used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `Import Type` context. The details about querying `Import Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/*
 * Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
 * result of loading a WASM file.
 */
const WasmEdge_ImportTypeContext *ImpType = ...;
/* Assume that `ImpType` is queried from the `ASTCxt` for the import. */

enum WasmEdge_ExternalType ExtType =
    WasmEdge_ImportTypeGetExternalType(ImpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
 * `WasmEdge_ExternalType_Table`, `WasmEdge_ExternalType_Memory`, or
 * `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ModName = WasmEdge_ImportTypeGetModuleName(ImpType);
WasmEdge_String ExtName = WasmEdge_ImportTypeGetExternalName(ImpType);
/*
 * The `ModName` and `ExtName` should not be destroyed and the string
 * buffers are binded into the `ASTCxt`.
 */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_ImportTypeGetFunctionType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
 * `FuncTypeCxt` will be NULL.
 */
const WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_ImportTypeGetTableType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
 * will be NULL.
 */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_ImportTypeGetMemoryType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
 * will be NULL.
 */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
```

```
    WasmEdge_ImportTypeGetGlobalType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt`
 * will be NULL.
 */
```

7. Export type context

   The `Export Type` context is used for getting the exports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`) and external name from an `Export Type` context. The details about querying `Export Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/*
 * Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
 * result of loading a WASM file.
 */
const WasmEdge_ExportTypeContext *ExpType = ...;
/* Assume that `ExpType` is queried from the `ASTCxt` for the export. */

enum WasmEdge_ExternalType ExtType =
    WasmEdge_ExportTypeGetExternalType(ExpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
 * `WasmEdge_ExternalType_Table`, `WasmEdge_ExternalType_Memory`, or
 * `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ExtName = WasmEdge_ExportTypeGetExternalName(ExpType);
/*
 * The `ExtName` should not be destroyed and the string buffer is binded
 * into the `ASTCxt`.
 */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_ExportTypeGetFunctionType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
 * `FuncTypeCxt` will be NULL.
 */
const WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_ExportTypeGetTableType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
 * will be NULL.
 */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_ExportTypeGetMemoryType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
 * will be NULL.
 */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
    WasmEdge_ExportTypeGetGlobalType(ASTCxt, ExpType);
```

```
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt`
 * will be NULL.
 */
```

Async

After calling the asynchronous execution APIs, developers will get the `WasmEdge_Async` object. Developers own the object and should call the `WasmEdge_AsyncDelete()` API to destroy it.

1. Wait for the asynchronous execution

   Developers can wait the execution until finished:

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution. */
   WasmEdge_AsyncWait(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   Or developers can wait for a time limit. If the time limit exceeded, developers can choose to cancel the execution. For the interruptible execution in AOT mode, developers should set `TRUE` through the `WasmEdge_ConfigureCompilerSetInterruptible()` API into the configure context for the AOT compiler.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution for 1 second. */
bool IsEnd = WasmEdge_AsyncWaitFor(Async, 1000);
if (IsEnd) {
  /* The execution finished. Developers can get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(/* ... Ignored */);
} else {
  /*
   * The time limit exceeded. Developers can keep waiting or cancel the
   * execution.
   */
  WasmEdge_AsyncCancel(Async);
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, 0, NULL);
  /* The result error code will be `WasmEdge_ErrCode_Interrupted`. */
}
WasmEdge_AsyncDelete(Async);
```

2. Get the execution result of the asynchronous execution

   Developers can use the `WasmEdge_AsyncGetReturnsLength()` API to get the return value list length. This function will block and wait for the execution. If the execution has finished, this function will return the length immediately. If the execution failed, this function will return `0`. This function can help the developers to create the buffer to get the return values. If developers have already known the buffer length, they can skip this function and use the `WasmEdge_AsyncGet()` API to get the result.

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /*
    * Blocking and waiting for the execution and get the return value list
    * length.
    */
   uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   The `WasmEdge_AsyncGet()` API will block and wait for the execution. If the execution has finished, this function will fill the return values into the buffer and return the execution result immediately.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return values. */
const uint32_t BUF_LEN = 256;
WasmEdge_Value Buf[BUF_LEN];
WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Buf, BUF_LEN);
WasmEdge_AsyncDelete(Async);
```

Configurations

The configuration context, `WasmEdge_ConfigureContext`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` context to create other runtime contexts.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` context.

   ```
   enum WasmEdge_Proposal {
     WasmEdge_Proposal_ImportExportMutGlobals = 0,
     WasmEdge_Proposal_NonTrapFloatToIntConversions,
     WasmEdge_Proposal_SignExtensionOperators,
     WasmEdge_Proposal_MultiValue,
     WasmEdge_Proposal_BulkMemoryOperations,
     WasmEdge_Proposal_ReferenceTypes,
     WasmEdge_Proposal_SIMD,
     WasmEdge_Proposal_TailCall,
     WasmEdge_Proposal_MultiMemories,
     WasmEdge_Proposal_Annotations,
     WasmEdge_Proposal_Memory64,
     WasmEdge_Proposal_ExceptionHandling,
     WasmEdge_Proposal_ExtendedConst,
     WasmEdge_Proposal_Threads,
     WasmEdge_Proposal_FunctionReferences
   };
   ```

   Developers can add or remove the proposals into the `Configure` context.

```
/*
 * By default, the following proposals have turned on initially:
 * * Import/Export of mutable globals
 * * Non-trapping float-to-int conversions
 * * Sign-extension operators
 * * Multi-value returns
 * * Bulk memory operations
 * * Reference types
 * * Fixed-width SIMD
 *
 * For the current WasmEdge version, the following proposals are supported
 * (turned off by default) additionally:
 * * Tail-call
 * * Multiple memories
 * * Extended-const
 * * Threads
 */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddProposal(ConfCxt, WasmEdge_Proposal_MultiMemories);
WasmEdge_ConfigureRemoveProposal(ConfCxt,
WasmEdge_Proposal_ReferenceTypes);
bool IsBulkMem = WasmEdge_ConfigureHasProposal(
    ConfCxt, WasmEdge_Proposal_BulkMemoryOperations);
/* The `IsBulkMem` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

2. Host registrations

This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` contexts.

```
enum WasmEdge_HostRegistration {
  WasmEdge_HostRegistration_Wasi = 0,
  WasmEdge_HostRegistration_WasmEdge_Process
};
```

The details will be introduced in the preregistrations of VM context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsHostWasi = WasmEdge_ConfigureHasHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `FALSE`. */
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_Wasi);
IsHostWasi = WasmEdge_ConfigureHasHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
uint32_t PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* By default, the maximum memory page size is 65536. */
WasmEdge_ConfigureSetMaxMemoryPage(ConfCxt, 1024);
/*
 * Limit the memory size of each memory instance with not larger than 1024
 * pages (64 MiB).
 */
PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* The `PageSize` will be 1024. */
WasmEdge_ConfigureDelete(ConfCxt);
```

4. Forcibly interpreter mode

   If developers want to execute the WASM file or the AOT compiled WASM in interpreter mode forcibly, they can turn on the configuration.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsForceInterp = WasmEdge_ConfigureIsForceInterpreter(ConfCxt);
/* By default, The `IsForceInterp` will be `FALSE`. */
WasmEdge_ConfigureSetForceInterpreter(ConfCxt, TRUE);
IsForceInterp = WasmEdge_ConfigureIsForceInterpreter(ConfCxt);
/* The `IsForceInterp` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

5. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
enum WasmEdge_CompilerOptimizationLevel {
  // Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  // Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  // Optimize for fast execution as much as possible without triggering
  // significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  // Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  // Optimize for small code size as much as possible without triggering
  // significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  // Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

enum WasmEdge_CompilerOutputFormat {
  // Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  // WebAssembly with AOT compiled codes in custom section.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

   These configurations are only effective in `Compiler` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the optimization level is O3. */
WasmEdge_ConfigureCompilerSetOptimizationLevel(
    ConfCxt, WasmEdge_CompilerOptimizationLevel_O2);
/* By default, the output format is universal WASM. */
WasmEdge_ConfigureCompilerSetOutputFormat(
    ConfCxt, WasmEdge_CompilerOutputFormat_Native);
/* By default, the dump IR is `FALSE`. */
WasmEdge_ConfigureCompilerSetDumpIR(ConfCxt, TRUE);
/* By default, the generic binary is `FALSE`. */
WasmEdge_ConfigureCompilerSetGenericBinary(ConfCxt, TRUE);
/* By default, the interruptible is `FALSE`.
/* Set this option to `TRUE` to support the interruptible execution in AOT
mode. */
WasmEdge_ConfigureCompilerSetInterruptible(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

6. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/*
 * By default, the instruction counting is `FALSE` when running a
 * compiled-WASM or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetInstructionCounting(ConfCxt, TRUE);
/*
 * By default, the cost measurement is `FALSE` when running a compiled-WASM
 * or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetCostMeasuring(ConfCxt, TRUE);
/*
 * By default, the time measurement is `FALSE` when running a compiled-WASM
 * or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetTimeMeasuring(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

Statistics

The statistics context, `WasmEdge_StatisticsContext`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` context from the `VM` context, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
   /*
    * ...
    * After running the WASM functions with the `Statistics` context
    */
   uint32_t Count = WasmEdge_StatisticsGetInstrCount(StatCxt);
   double IPS = WasmEdge_StatisticsGetInstrPerSecond(StatCxt);
   WasmEdge_StatisticsDelete(StatCxt);
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` context. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
uint64_t CostTable[16] = {
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0
};
/*
 * Developers can set the costs of each instruction. The value not
 * covered will be 0.
 */
WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
WasmEdge_StatisticsSetCostLimit(StatCxt, 5000000);
/*
 * ...
 * After running the WASM functions with the `Statistics` context
 */
uint64_t Cost = WasmEdge_StatisticsGetTotalCost(StatCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

Tools Driver

Besides executing the `wasmedge` and `wasmedgec` CLI tools, developers can trigger the WasmEdge CLI tools by WasmEdge C API. The API arguments are the same as the command line arguments of the CLI tools.

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge AOT compiler. */
  return WasmEdge_Driver_Compiler(argc, argv);
}
```

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge runtime tool. */
  return WasmEdge_Driver_Tool(argc, argv);
}
```

WasmEdge VM

In this partition, we will introduce the functions of `WasmEdge_VMContext` object and show examples of executing WASM functions.

WASM Execution Example With VM Context

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s (get_local $n)(i32.const 2))
      (return (i32.const 1))
    )
    (return
      (i32.add
        (call $fib (i32.sub (get_local $n)(i32.const 2)))
        (call $fib (i32.sub (get_local $n)(i32.const 1)))
      )
    )
  )
)
```

1. Run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <stdio.h>
#include <wasmedge/wasmedge.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                        WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(5)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(
      VMCxt, "fibonacci.wasm", FuncName, Params, 1, Returns, 1);
  /*
   * Developers can run the WASM binary from buffer with the
   * `WasmEdge_VMRunWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMRunWasmFromASTModule()` API.
   */

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 5th Fibonacci number is 8 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 8
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need the WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                        WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(10)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
   * `WasmEdge_VMLoadWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
```

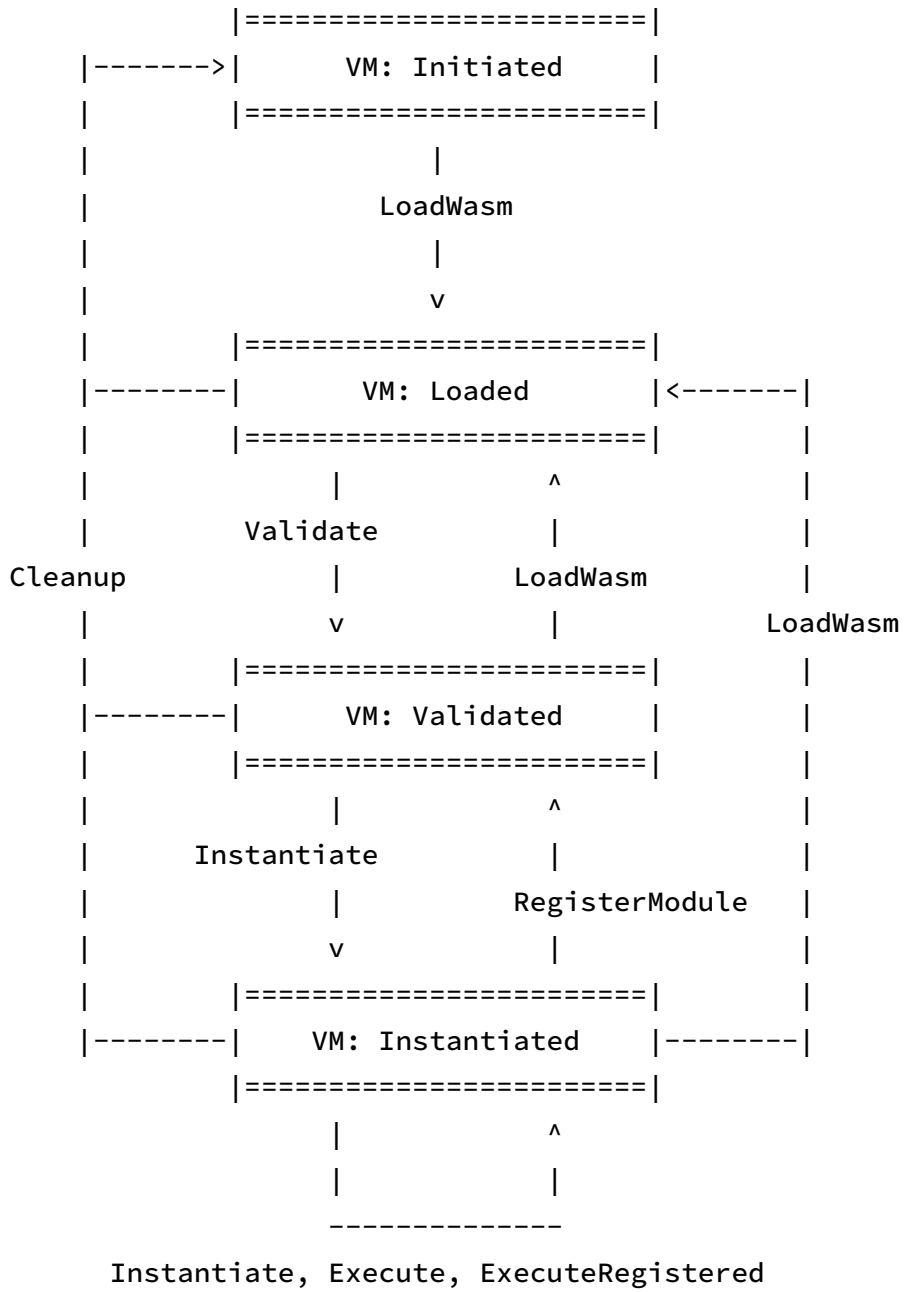
```
  /*
   * Developers can load, validate, and instantiate another WASM module to
   * replace the instantiated one. In this case, the old module will be
   * cleared, but the registered modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
   * Step 4: Execute WASM functions. You can execute functions repeatedly
   * after instantiation.
   */
  Res = WasmEdge_VMExecute(VMCxt, FuncName, Params, 1, Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 10th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 89
```

The following graph explains the status of the `VM` context.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or module instances in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation API accepts the `Configure` context and the `Store` context. If developers only need the default settings, just pass `NULL` to the creation API. The details of the `Store` context will be introduced in Store.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, StoreCxt);
/* The caller should guarantee the life cycle if the store context. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_VMGetStatisticsContext(VMCxt);
/*
 * The VM context already contains the statistics context and can be retrieved
 * by this API.
 */
/*
 * Note that the retrieved store and statistics contexts from the VM contexts
by
 * VM APIs should __NOT__ be destroyed and owned by the VM contexts.
 */
WasmEdge_VMDelete(VMCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_Wasi);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration.
 */
WasmEdge_ModuleInstanceContext *WasiModule =
    WasmEdge_VMGetImportModuleContext(VMCxt,
                                      WasmEdge_HostRegistration_Wasi);
/* Initialize the WASI. */
WasmEdge_ModuleInstanceInitWASI(WasiModule, /* ... ignored */);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

   This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` plugin.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasmEdge_Process);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
 */
WasmEdge_ModuleInstanceContext *ProcModule =
    WasmEdge_VMGetImportModuleContext(
        VMCxt, WasmEdge_HostRegistration_WasmEdge_Process);
/* Initialize the WasmEdge_Process. */
WasmEdge_ModuleInstanceInitWasmEdgeProcess(ProcModule, /* ... ignored */);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WasmEdge_Process module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

3. WASI-NN proposal

   Developers can turn on the WASI-NN proposal support for VM in the `Configure` context.

> Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
 */
WasmEdge_ModuleInstanceContext *NNModule =
    WasmEdge_VMGetImportModuleContext(VMCxt,
                                      WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-NN module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

4. WASI-Crypto proposal

   Developers can turn on the WASI-Crypto proposal support for VM in the `Configure` context.

Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* The WASI-Crypto related configures are suggested to turn on together. */
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_AsymmetricCommon);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Kx);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Signatures);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Symmetric);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
  */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
  */
WasmEdge_ModuleInstanceContext *CryptoCommonModule =
    WasmEdge_VMGetImportModuleContext(
        VMCxt, WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-Crypto module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, the host functions are composed into host modules as `WasmEdge_ModuleInstanceContext` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` context.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_ModuleInstanceContext *WasiModule =
    WasmEdge_ModuleInstanceCreateWASI(/* ... ignored ... */);
/* You can also create and register the WASI host modules by this API. */
WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModule);
/* The result status should be checked. */

/* ... */

WasmEdge_ModuleInstanceDelete(WasiModule);
/*
 * The created module instances should be deleted by the developers when the VM
 * deallocation.
 */
WasmEdge_VMDelete(VMCxt);
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM modules.

1. Register the WASM modules with exported module names

   Unless the module instances have already contained the module names, every WASM module should be named uniquely when registering. Assume that the WASM file `fibonacci.wasm` is copied into the current directory.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
WasmEdge_Result Res =
    WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName, "fibonacci.wasm");
/*
 * Developers can register the WASM module from buffer with the
 * `WasmEdge_VMRegisterModuleFromBuffer()` API, or from
 * `WasmEdge_ASTModuleContext` object with the
 * `WasmEdge_VMRegisterModuleFromASTModule()` API.
 */
/*
 * The result status should be checked.
 * The error will occur if the WASM module instantiation failed or the
 * module name conflicts.
 */
WasmEdge_StringDelete(ModName);
WasmEdge_VMDelete(VMCxt);
```

2. Execute the functions in registered WASM modules

   Assume that the C file `test.c` is as follows:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(20)};
  WasmEdge_Value Returns[1];
  /* Names. */
  WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Register the WASM module into VM. */
  Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
"fibonacci.wasm");
  /*
   * Developers can register the WASM module from buffer with the
   * `WasmEdge_VMRegisterModuleFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMRegisterModuleFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM registration failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
   * The function "fib" in the "fibonacci.wasm" was exported with the
module
   * name "mod". As the same as host functions, other modules can import
the
   * function `"mod" "fib"`.
   */

  /*
   * Execute WASM functions in registered modules.
   * Unlike the execution of functions, the registered functions can be
   * invoked without `WasmEdge_VMInstantiate()` because the WASM module was
```

```
     * instantiated when registering. Developers can also invoke the host
     * functions directly with this API.
     */
    Res = WasmEdge_VMExecuteRegistered(VMCxt, ModName, FuncName, Params, 1,
                                       Returns, 1);
    if (WasmEdge_ResultOK(Res)) {
      printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
    } else {
      printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    }
    WasmEdge_StringDelete(ModName);
    WasmEdge_StringDelete(FuncName);
    WasmEdge_VMDelete(VMCxt);
    return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 10946
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(20)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Asynchronously run the WASM function from file and get the
   * `WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncRunWasmFromFile(
      VMCxt, "fibonacci.wasm", FuncName, Params, 1);
  /*
   * Developers can run the WASM binary from buffer with the
   * `WasmEdge_VMAsyncRunWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMAsyncRunWasmFromASTModule()` API.
   */

  /* Wait for the execution. */
  WasmEdge_AsyncWait(Async);
  /*
   * Developers can also use the `WasmEdge_AsyncGetReturnsLength()` or
   * `WasmEdge_AsyncGet()` APIs to wait for the asynchronous execution.
   * These APIs will wait until the execution finished.
   */

  /* Check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
   * known the return arity. */

  /* Get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Returns, Arity);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
```

```
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(25)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
   * `WasmEdge_VMLoadWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
  /*
   * Developers can load, validate, and instantiate another WASM module to
   * replace the instantiated one. In this case, the old module will be
   * cleared, but the registered modules are still kept.
   */
```

```
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Asynchronously execute the WASM function and get the
   * `WasmEdge_Async` object. */
  WasmEdge_Async *Async =
      WasmEdge_VMAsyncExecute(VMCxt, FuncName, Params, 1);
  /*
   * Developers can execute functions repeatedly after instantiation.
   * For invoking the registered functions, you can use the
   * `WasmEdge_VMAsyncExecuteRegistered()` API.
   */

  /* Wait and check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
   * known the return arity. */

  /* Get the result. */
  Res = WasmEdge_AsyncGet(Async, Returns, Arity);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
}
```

Then you can compile and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` context supplies the APIs to retrieve the instances.

1. Store

   If the `VM` context is created without assigning a `Store` context, the `VM` context will allocate and own a `Store` context.

   ```
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
   WasmEdge_StoreContext *StoreCxt = WasmEdge_VMGetStoreContext(VMCxt);
   /* The object should __NOT__ be deleted by `WasmEdge_StoreDelete()`. */
   WasmEdge_VMDelete(VMCxt);
   ```

   Developers can also create the `VM` context with a `Store` context. In this case, developers should guarantee the life cycle of the `Store` context. Please refer to the Store Contexts for the details about the `Store` context APIs.

   ```
   WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);
   WasmEdge_StoreContext *StoreCxtMock = WasmEdge_VMGetStoreContext(VMCxt);
   /* The `StoreCxt` and the `StoreCxtMock` are the same. */
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_StoreDelete(StoreCxt);
   ```

2. List exported functions

   After the WASM module instantiation, developers can use the `WasmEdge_VMExecute()` API to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);

  WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  WasmEdge_VMValidate(VMCxt);
  WasmEdge_VMInstantiate(VMCxt);

  /* List the exported functions. */
  /* Get the number of exported functions. */
  uint32_t FuncNum = WasmEdge_VMGetFunctionListLength(VMCxt);
  /* Create the name buffers and the function type buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  WasmEdge_FunctionTypeContext *FuncTypes[BUF_LEN];
  /*
   * Get the export function list.
   * If the function list length is larger than the buffer length, the
   * overflowed data will be discarded. The `FuncNames` and `FuncTypes` can
   * be NULL if developers don't need them.
   */
  uint32_t RealFuncNum =
      WasmEdge_VMGetFunctionList(VMCxt, FuncNames, FuncTypes, BUF_LEN);

  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size,
           Buf);
    /*
     * The function names should be __NOT__ destroyed.
     * The returned function type contexts should __NOT__ be destroyed.
     */
  }
  WasmEdge_StoreDelete(StoreCxt);
  WasmEdge_VMDelete(VMCxt);
  return 0;
}
```

Then you can compile and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get exported function string length: 3, name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` context from the `VM` context and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

The `VM` context provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
const WasmEdge_FunctionTypeContext *FuncType =
    WasmEdge_VMGetFunctionType(VMCxt, FuncName);
/*
 * Developers can get the function types of functions in the registered
 * modules via the `WasmEdge_VMGetFunctionTypeRegistered()` API with the
 * module name. If the function is not found, these APIs will return
`NULL`.
 * The returned function type contexts should __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

4. Get the active module

After the WASM module instantiation, an anonymous module is instantiated and owned by the `VM` context. Developers may need to retrieve it to get the instances beyond the module. Then developers can use the `WasmEdge_VMGetActiveModule()` API to get that anonymous module instance. Please refer to the Module instance for the details about the module instance APIs.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
const WasmEdge_ModuleInstanceContext *ModCxt =
    WasmEdge_VMGetActiveModule(VMCxt);
/*
 * If there's no WASM module instantiated, this API will return `NULL`.
 * The returned module instance context should __NOT__ be destroyed.
 */
```

5. Get the components

   The `VM` context is composed by the `Loader`, `Validator`, and `Executor` contexts. For the developers who want to use these contexts without creating another instances, these APIs can help developers to get them from the `VM` context. The get contexts are owned by the `VM` context, and developers should not call their delete functions.

```
WasmEdge_LoaderContext *LoadCxt = WasmEdge_VMGetLoaderContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_LoaderDelete()`. */
WasmEdge_ValidatorContext *ValidCxt =
WasmEdge_VMGetValidatorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ValidatorDelete()`. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_VMGetExecutorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ExecutorDelete()`. */
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` context, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` contexts. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /*
   * Create the configure context. This step is not necessary because we didn't
   * adjust any setting.
   */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /*
   * Create the statistics context. This step is not necessary if the
statistics
   * in runtime is not needed.
   */
  WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
  /*
   * Create the store context. The store context is the object to link the
   * modules for imports and exports.
   */
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  /* Result. */
  WasmEdge_Result Res;

  /* Create the loader context. The configure context can be NULL. */
  WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);
  /* Create the validator context. The configure context can be NULL. */
  WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
  /*
   * Create the executor context. The configure context and the statistics
   * context can be NULL.
   */
  WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);

  /*
   * Load the WASM file or the compiled-WASM file and convert into the AST
   * module context.
   */
  WasmEdge_ASTModuleContext *ASTCxt = NULL;
  Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Validate the WASM module. */
  Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Instantiate the WASM module into store context. */
  WasmEdge_ModuleInstanceContext *ModCxt = NULL;
  Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
```

```
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return 1;
}

/* Try to list the exported functions of the instantiated WASM module. */
uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
 * will be discarded.
 */
uint32_t RealFuncNum =
    WasmEdge_ModuleInstanceListFunction(ModCxt, FuncNames, BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  char Buf[BUF_LEN];
  uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
  printf("Get exported function string length: %u, name: %s\n", Size, Buf);
  /* The function names should __NOT__ be destroyed. */
}

/* The parameters and returns arrays. */
WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(18)};
WasmEdge_Value Returns[1];
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
/* Find the exported function by function name. */
WasmEdge_FunctionInstanceContext *FuncCxt =
    WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
if (FuncCxt == NULL) {
  printf("Function `fib` not found.\n");
  return 1;
}
/* Invoke the WASM fnction. */
Res = WasmEdge_ExecutorInvoke(ExecCxt, FuncCxt, Params, 1, Returns, 1);
if (WasmEdge_ResultOK(Res)) {
  printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
} else {
  printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}

/* Resources deallocations. */
WasmEdge_StringDelete(FuncName);
WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_ConfigureDelete(ConfCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

```
  return 0;
}
```

Then you can compile and run: (the 18th Fibonacci number is 4181 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get exported function string length: 3, name: fib
Get the result: 4181
```

Loader

The `Loader` context loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
uint8_t Buf[4096];
/* ... Read the WASM code to the buffer. */
uint32_t FileSize = ...;
/* The `FileSize` is the length of the WASM code. */

/* Developers can adjust settings in the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);

WasmEdge_ASTModuleContext *ASTCxt = NULL;
WasmEdge_Result Res;

/* Load WASM or compiled-WASM from the file. */
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

/* Load WASM or compiled-WASM from the buffer. */
Res = WasmEdge_LoaderParseFromBuffer(LoadCxt, &ASTCxt, Buf, FileSize);
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Validator

The `Validator` context can validate the WASM module. Every WASM module should be validated before instantiation.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the loader
 * context.
 * Assume that the `ConfCxt` is the configure context.
 */
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
WasmEdge_Result Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
WasmEdge_ValidatorDelete(ValidCxt);
```

Executor

The `Executor` context is the executor for both WASM and compiled-WASM. This object should work base on the `Store` context. For the details of the `Store` context, please refer to the next chapter.

1. Instantiate and register an `AST module` as a named `Module` instance

   As the same of registering host modules or importing WASM modules in `VM` contexts, developers can instantiate and register an `AST module` contexts into the `Store` context as a named `Module` instance by the `Executor` APIs. After the registration, the result `Module` instance is exported with the given module name and can be linked when instantiating another module. For the details about the `Module` instances APIs, please refer to the Instances.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/*
 * Register the WASM module into the store with the export module name
 * "mod".
 */
Res =
    WasmEdge_ExecutorRegister(ExecCxt, &ModCxt, StoreCxt, ASTCxt, ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
WasmEdge_StringDelete(ModName);

/* ... */
```

```
/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

2. Register an existing `Module` instance and export the module name

   Besides instantiating and registering an `AST module` contexts, developers can register an existing `Module` instance into the store with exporting the module name (which is in the `Module` instance already). This case occurs when developers create a `Module` instance for the host functions and want to register it for linking. For the details about the construction of host functions in `Module` instances, please refer to the Host Functions.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create a module instance for host functions. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("host-module");
WasmEdge_ModuleInstanceContext *HostModCxt =
    WasmEdge_ModuleInstanceCreate(ModName);
WasmEdge_StringDelete(ModName);
/*
 * ...
 * Create and add the host functions, tables, memories, and globals into
the
 * module instance.
 */

/* Register the module instance into store with the exported module name.
*/
/* The export module name is in the module instance already. */
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, HostModCxt);
if (!WasmEdge_ResultOK(Res)) {
```

```
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

3. Instantiate an `AST module` to an anonymous `Module` instance

   WASM or compiled-WASM modules should be instantiated before the function invocation. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` context for linking.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/* Instantiate the WASM module. */
WasmEdge_Result Res =
    WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed: %s\n",
WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

4. Invoke functions

   After registering or instantiating and get the result `Module` instance, developers can retrieve the exported `Function` instances from the `Module` instance for invocation. For the details about the `Module` instances APIs, please refer to the Instances. Please refer to the example above for the `Function` instance invocation with the `WasmEdge_ExecutorInvoke()` API.

AST Module

The `AST Module` context presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST Module` context.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that a WASM is loaded into an AST module context. */

/* Create the import type context buffers. */
const uint32_t BUF_LEN = 256;
const WasmEdge_ImportTypeContext *ImpTypes[BUF_LEN];
uint32_t ImportNum = WasmEdge_ASTModuleListImportsLength(ASTCxt);
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealImportNum =
    WasmEdge_ASTModuleListImports(ASTCxt, ImpTypes, BUF_LEN);
for (uint32_t I = 0; I < RealImportNum && I < BUF_LEN; I++) {
  /* Working with the import type `ImpTypes[I]` ... */
}

/* Create the export type context buffers. */
const WasmEdge_ExportTypeContext *ExpTypes[BUF_LEN];
uint32_t ExportNum = WasmEdge_ASTModuleListExportsLength(ASTCxt);
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealExportNum =
    WasmEdge_ASTModuleListExports(ASTCxt, ExpTypes, BUF_LEN);
for (uint32_t I = 0; I < RealExportNum && I < BUF_LEN; I++) {
  /* Working with the export type `ExpTypes[I]` ... */
}

WasmEdge_ASTModuleDelete(ASTCxt);
/*
 * After deletion of `ASTCxt`, all data queried from the `ASTCxt` should not be
 * accessed.
 */
```

Store

Store is the runtime structure for the representation of all global state that can be manipulated by WebAssembly programs. The `Store` context in WasmEdge is an object to provide the instance exporting and importing when instantiating WASM modules. Developers can retrieve the named modules from the `Store` context.

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/*
 * ...
 * Register a WASM module via the executor context.
 */

/* Try to list the registered WASM modules. */
uint32_t ModNum = WasmEdge_StoreListModuleLength(StoreCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String ModNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealModNum = WasmEdge_StoreListModule(StoreCxt, ModNames, BUF_LEN);
for (uint32_t I = 0; I < RealModNum && I < BUF_LEN; I++) {
  /* Working with the module name `ModNames[I]` ... */
  /* The module names should __NOT__ be destroyed. */
}

/* Find named module by name. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module");
const WasmEdge_ModuleInstanceContext *ModCxt =
    WasmEdge_StoreFindModule(StoreCxt, ModName);
/* If the module with name not found, the `ModCxt` will be NULL. */
WasmEdge_StringDelete(ModName);
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the `Module` instances from the `Store` contexts, and retrieve the other instances from the `Module` instances. A single instance can be allocated by its creation function. Developers can construct instances into an `Module` instance for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed by developers, EXCEPT they are added into an `Module` instance.

1. Module instance

   After instantiating or registering an `AST module` context, developers will get a `Module` instance as the result, and have the responsibility to destroy it when not in use. A `Module` instance can also be created for the host module. Please refer to the host function for the details. `Module` instance provides APIs to list and find the exported instances in the module.

```
/*
 * ...
 * Instantiate a WASM module via the executor context and get the `ModCxt`
 * as the output module instance.
 */

/* Try to list the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
 * will be discarded.
 */
uint32_t RealFuncNum =
    WasmEdge_ModuleInstanceListFunction(ModCxt, FuncNames, BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  /* Working with the function name `FuncNames[I]` ... */
  /* The function names should __NOT__ be destroyed. */
}

/* Try to find the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FuncCxt =
    WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
/* `FuncCxt` will be `NULL` if the function not found. */
/*
 * The returned instance is owned by the module instance context and should
 * __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

2. Function instance

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` contexts for host functions and add them into an `Module` instance context for registering into a `VM` or a

`Store`. Developers can retrieve the `Function Type` from the `Function` contexts through the API. For the details of the `Host Function` guide, please refer to the next chapter.

```
/* Retrieve the function instance from the module instance context. */
WasmEdge_FunctionInstanceContext *FuncCxt = ...;
WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_FunctionInstanceGetFunctionType(FuncCxt);
/*
 * The `FuncTypeCxt` is owned by the `FuncCxt` and should __NOT__ be
 * destroyed.
 */

/*
 * For the function instance creation, please refer to the `Host Function`
 * guide.
 */
```

3. Table instance

In WasmEdge, developers can create the `Table` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Table` contexts supply APIs to control the data in table instances.

```
WasmEdge_Limit TabLimit = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
/* Create the table type with limit and the `FuncRef` element type. */
WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TabLimit);
/* Create the table instance with table type. */
WasmEdge_TableInstanceContext *HostTable =
    WasmEdge_TableInstanceCreate(TabTypeCxt);
/* Delete the table type. */
WasmEdge_TableTypeDelete(TabTypeCxt);
WasmEdge_Result Res;
WasmEdge_Value Data;

TabTypeCxt = WasmEdge_TableInstanceGetTableType(HostTable);
/*
 * The `TabTypeCxt` got from table instance is owned by the `HostTable` and
 * should __NOT__ be destroyed.
 */
enum WasmEdge_RefType RefType = WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `RefType` will be `WasmEdge_RefType_FuncRef`. */
Data = WasmEdge_ValueGenFuncRef(5);
Res = WasmEdge_TableInstanceSetData(HostTable, Data, 3);
/* Set the function index 5 to the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceSetData(HostTable, Data, 13);
 */
Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 3);
/* Get the FuncRef value of the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 13);
 */

uint32_t Size = WasmEdge_TableInstanceGetSize(HostTable);
/* `Size` will be 10. */
Res = WasmEdge_TableInstanceGrow(HostTable, 6);
/* Grow the table size of 6, the table size will be 16. */
```

```
/*
 * This will get an "out of bounds table access" error because
 * the size (16 + 6) will reach the table limit(20):
 *   Res = WasmEdge_TableInstanceGrow(HostTable, 6);
 */

WasmEdge_TableInstanceDelete(HostTable);
```

4. Memory instance

   In WasmEdge, developers can create the `Memory` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Memory` contexts supply APIs to control the data in memory instances.

```
WasmEdge_Limit MemLimit = {
    .HasMax = true, .Shared = false, .Min = 1, .Max = 5};
/* Create the memory type with limit. The memory page size is 64KiB. */
WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_MemoryTypeCreate(MemLimit);
/* Create the memory instance with memory type. */
WasmEdge_MemoryInstanceContext *HostMemory =
    WasmEdge_MemoryInstanceCreate(MemTypeCxt);
/* Delete the memory type. */
WasmEdge_MemoryTypeDelete(MemTypeCxt);
WasmEdge_Result Res;
uint8_t Buf[256];

Buf[0] = 0xAA;
Buf[1] = 0xBB;
Buf[2] = 0xCC;
Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0x1000, 3);
/* Set the data[0:2] to the memory[4096:4098]. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */
Buf[0] = 0;
Buf[1] = 0;
Buf[2] = 0;
Res = WasmEdge_MemoryInstanceGetData(HostMemory, Buf, 0x1000, 3);
/* Get the memory[4096:4098]. Buf[0:2] will be `{0xAA, 0xBB, 0xCC}`. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */

uint32_t PageSize = WasmEdge_MemoryInstanceGetPageSize(HostMemory);
/* `PageSize` will be 1. */
Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 2);
/* Grow the page size of 2, the page size of the memory instance will be 3.
 */
/*
```

```
  * This will get an "out of bounds memory access" error because
  * the page size (3 + 3) will reach the memory limit(5):
  *   Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 3);
  */

 WasmEdge_MemoryInstanceDelete(HostMemory);
```

5. Global instance

   In WasmEdge, developers can create the `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Global` contexts supply APIs to control the value in global instances.

```
WasmEdge_Value Val = WasmEdge_ValueGenI64(1000);
/* Create the global type with value type and mutation. */
WasmEdge_GlobalTypeContext *GlobTypeCxt = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_I64, WasmEdge_Mutability_Var);
/* Create the global instance with value and global type. */
WasmEdge_GlobalInstanceContext *HostGlobal =
    WasmEdge_GlobalInstanceCreate(GlobTypeCxt, Val);
/* Delete the global type. */
WasmEdge_GlobalTypeDelete(GlobTypeCxt);
WasmEdge_Result Res;

GlobTypeCxt = WasmEdge_GlobalInstanceGetGlobalType(HostGlobal);
/* The `GlobTypeCxt` got from global instance is owned by the `HostGlobal`
 * and should __NOT__ be destroyed. */
enum WasmEdge_ValType ValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `ValType` will be `WasmEdge_ValType_I64`. */
enum WasmEdge_Mutability ValMut =
    WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `ValMut` will be `WasmEdge_Mutability_Var`. */

WasmEdge_GlobalInstanceSetValue(HostGlobal, WasmEdge_ValueGenI64(888));
/*
 * Set the value u64(888) to the global.
 * This function will do nothing if the value type mismatched or
 * the global mutability is `WasmEdge_Mutability_Const`.
 */
WasmEdge_Value GlobVal = WasmEdge_GlobalInstanceGetValue(HostGlobal);
/* Get the value (888 now) of the global context. */

WasmEdge_GlobalInstanceDelete(HostGlobal);
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function`, `Memory`, `Table`, and `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`.

1. Host function allocation

Developers can define C functions with the following function signature as the host function body:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
    void *Data, const WasmEdge_CallingFrameContext *CallFrameCxt,
    const WasmEdge_Value *Params, WasmEdge_Value *Returns);
```

The example of an `add` host function to add 2 `i32` values:

```
WasmEdge_Result Add(void *, const WasmEdge_CallingFrameContext *,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /*
  * Params: {i32, i32}
  * Returns: {i32}
  * Developers should take care about the function type.
  */
  /* Retrieve the value 1. */
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  /* Retrieve the value 2. */
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  /* Output value 1 is Val1 + Val2. */
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Return the status of success. */
  return WasmEdge_Result_Success;
}
```

Then developers can create `Function` context with the host function body and the function type:

```
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I32};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
/* Create a function type: {i32, i32} -> {i32}. */
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
/*
 * Create a function context with the function type and host function body.
 * The `Cost` parameter can be 0 if developers do not need the cost
 * measuring.
 */
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostType);

/*
 * If the function instance is __NOT__ added into a module instance
context,
 * it should be deleted.
 */
WasmEdge_FunctionInstanceDelete(HostFunc);
```

2. Calling frame context

   The `WasmEdge_CallingFrameContext` is the context to provide developers to access the module instance of the frame on the top of the calling stack. According to the WASM spec, a frame with the module instance is pushed into the stack when invoking a function. Therefore, the host functions can access the module instance of the top frame to retrieve the memory instances to read/write data.

```
WasmEdge_Result LoadOffset(void *Data,
                           const WasmEdge_CallingFrameContext
*CallFrameCxt,
                           const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {i32} -> {} */
  uint32_t Offset = (uint32_t)WasmEdge_ValueGetI32(In[0]);
  uint32_t Num = 0;

  /*
   * Get the 0-th memory instance of the module instance of the top frame
on
   * stack.
   */
  WasmEdge_MemoryInstanceContext *MemCxt =
      WasmEdge_CallingFrameGetMemoryInstance(CallFrameCxt, 0);

  WasmEdge_Result Res =
      WasmEdge_MemoryInstanceGetData(MemCxt, (uint8_t *)(&Num), Offset, 4);
  if (WasmEdge_ResultOK(Res)) {
    printf("u32 at memory[%lu]: %lu\n", Offset, Num);
  } else {
    return Res;
  }
  return WasmEdge_Result_Success;
}
```

Besides using the `WasmEdge_CallingFrameGetMemoryInstance()` API to get the memory instance by index in the module instance, developers can use the `WasmEdge_CallingFrameGetModuleInstance()` to get the module instance directly. Therefore, developers can retrieve the exported contexts by the `WasmEdge_ModuleInstanceContext` APIs. And also, developers can use the `WasmEdge_CallingFrameGetExecutor()` API to get the currently used executor context.

3. User-defined error code of the host functions

   In host functions, WasmEdge provides `WasmEdge_Result_Success` to return success, `WasmEdge_Result_Terminate` to terminate the WASM execution, and `WasmEdge_Result_Fail` to return fail. WasmEdge also provides the usage of returning the user-specified codes. Developers can use the `WasmEdge_ResultGen()` API to generate the `WasmEdge_Result` with error code, and use the `WasmEdge_ResultGetCode()` API to get the error code.

Notice: The error code only supports 24-bit integer (0 ~ 16777216 in `uint32_t`). The values larger than 24-bit will be truncated.

Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32)))
  (import "extern" "trap" (func $f-trap (type $t0)))
  (func (export "trap") (param i32)
    local.get 0
    call $f-trap)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Trap(void *Data,
                     const WasmEdge_CallingFrameContext *CallFrameCxt,
                     const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val = WasmEdge_ValueGetI32(In[0]);
  /* Return the error code from the param[0]. */
  return WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, Val);
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x05, 0x01,
                    /* function type {i32} -> {} */
                    0x60, 0x01, 0x7F, 0x00,
                    /* Import section */
                    0x02, 0x0F, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "trap" */
                    0x04, 0x74, 0x72, 0x61, 0x70,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x08, 0x01,
                    /* export name: "trap" */
                    0x04, 0x74, 0x72, 0x61, 0x70,
                    /* export desc: func 0 */
                    0x00, 0x01,
                    /* Code section */
```

```
                        0x0A, 0x08, 0x01,
                        /* code body */
                        0x06, 0x00, 0x20, 0x00, 0x10, 0x00, 0x0B};

    /* Create the module instance. */
    WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
    WasmEdge_ModuleInstanceContext *HostModCxt =
        WasmEdge_ModuleInstanceCreate(ExportName);
    enum WasmEdge_ValType ParamList[1] = {WasmEdge_ValType_I32};
    WasmEdge_FunctionTypeContext *HostFType =
        WasmEdge_FunctionTypeCreate(ParamList, 1, NULL, 0);
    WasmEdge_FunctionInstanceContext *HostFunc =
        WasmEdge_FunctionInstanceCreate(HostFType, Trap, NULL, 0);
    WasmEdge_FunctionTypeDelete(HostFType);
    WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("trap");
    WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
    WasmEdge_StringDelete(HostFuncName);

    WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

    /* The parameters and returns arrays. */
    WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(5566)};
    /* Function name. */
    WasmEdge_String FuncName = WasmEdge_StringCreateByCString("trap");
    /* Run the WASM function from file. */
    WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
        VMCxt, WASM, sizeof(WASM), FuncName, Params, 1, NULL, 0);

    /* Get the result code and print. */
    printf("Get the error code: %u\n", WasmEdge_ResultGetCode(Res));

    /* Resources deallocations. */
    WasmEdge_VMDelete(VMCxt);
    WasmEdge_StringDelete(FuncName);
    WasmEdge_ModuleInstanceDelete(HostModCxt);
    return 0;
}
```

Then you can compile and run: (giving the expected error code `5566`)

```
$ gcc test.c -lwasmedge
$ ./a.out
[2022-08-26 15:06:40.384] [error] user defined failed: user defined error
code, Code: 0x15be
[2022-08-26 15:06:40.384] [error]     When executing function name: "trap"
Get the error code: 5566
```

4. Construct a module instance with host instances

   Besides creating a `Module` instance by registering or instantiating a WASM module, developers can create a `Module` instance with a module name and add the `Function`, `Memory`, `Table`, and `Global` instances into it with their exporting names.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create a module instance. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ModuleInstanceContext *HostModCxt =
    WasmEdge_ModuleInstanceCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the module instance. */
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I32};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ModuleInstanceAddFunction(HostModCxt, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/* Create and add a table instance into the import object. */
WasmEdge_Limit TableLimit = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *HostTType =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TableLimit);
WasmEdge_TableInstanceContext *HostTable =
```

```
    WasmEdge_TableInstanceCreate(HostTType);
WasmEdge_TableTypeDelete(HostTType);
WasmEdge_String TableName = WasmEdge_StringCreateByCString("table");
WasmEdge_ModuleInstanceAddTable(HostModCxt, TableName, HostTable);
WasmEdge_StringDelete(TableName);

/* Create and add a memory instance into the import object. */
WasmEdge_Limit MemoryLimit = {
    .HasMax = true, .Shared = false, .Min = 1, .Max = 2};
WasmEdge_MemoryTypeContext *HostMType =
    WasmEdge_MemoryTypeCreate(MemoryLimit);
WasmEdge_MemoryInstanceContext *HostMemory =
    WasmEdge_MemoryInstanceCreate(HostMType);
WasmEdge_MemoryTypeDelete(HostMType);
WasmEdge_String MemoryName = WasmEdge_StringCreateByCString("memory");
WasmEdge_ModuleInstanceAddMemory(HostModCxt, MemoryName, HostMemory);
WasmEdge_StringDelete(MemoryName);

/* Create and add a global instance into the module instance. */
WasmEdge_GlobalTypeContext *HostGType = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_I32, WasmEdge_Mutability_Var);
WasmEdge_GlobalInstanceContext *HostGlobal =
    WasmEdge_GlobalInstanceCreate(HostGType, WasmEdge_ValueGenI32(666));
WasmEdge_GlobalTypeDelete(HostGType);
WasmEdge_String GlobalName = WasmEdge_StringCreateByCString("global");
WasmEdge_ModuleInstanceAddGlobal(HostModCxt, GlobalName, HostGlobal);
WasmEdge_StringDelete(GlobalName);

/*
 * The module instance should be deleted.
 * Developers should __NOT__ destroy the instances added into the module
 * instance contexts.
 */
WasmEdge_ModuleInstanceDelete(HostModCxt);
```

5. Specified module instance

`WasmEdge_ModuleInstanceCreateWASI()` API can create and initialize the `WASI` module instance.

`WasmEdge_ModuleInstanceCreateWasiNN()` API can create and initialize the

`wasi_ephemeral_nn` module instance for `WASI-NN` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoCommon()` API can create and initialize the `wasi_ephemeral_crypto_common` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoAsymmetricCommon()` API can create and initialize the `wasi_ephemeral_crypto_asymmetric_common` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoKx()` API can create and initialize the `wasi_ephemeral_crypto_kx` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoSignatures()` API can create and initialize the `wasi_ephemeral_crypto_signatures` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoSymmetric()` API can create and initialize the `wasi_ephemeral_crypto_symmetric` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasmEdgeProcess()` API can create and initialize the `wasmedge_process` module instance for `wasmedge_process` plugin.

Developers can create these module instance contexts and register them into the `Store` or `VM` contexts rather than adjust the settings in the `Configure` contexts.

> Note: For the `WASI-NN` plugin, please check that the dependencies and prerequests are satisfied. Note: For the `WASI-Crypto` plugin, please check that the dependencies and prerequests are satisfied. And the 5 modules are recommended to all be created and registered together.

```
WasmEdge_ModuleInstanceContext *WasiModCxt =
    WasmEdge_ModuleInstanceCreateWASI(/* ... ignored */);
WasmEdge_ModuleInstanceContext *ProcModCxt =
    WasmEdge_ModuleInstanceCreateWasmEdgeProcess(/* ... ignored */);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
/* Register the WASI and WasmEdge_Process into the VM context. */
WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModCxt);
WasmEdge_VMRegisterModuleFromImport(VMCxt, ProcModCxt);
/* Get the WASI exit code. */
uint32_t ExitCode = WasmEdge_ModuleInstanceWASIGetExitCode(WasiModCxt);
/*
 * The `ExitCode` will be EXIT_SUCCESS if the execution has no error.
 * Otherwise, it will return with the related exit code.
 */
WasmEdge_VMDelete(VMCxt);
/* The module instances should be deleted. */
WasmEdge_ModuleInstanceDelete(WasiModCxt);
WasmEdge_ModuleInstanceDelete(ProcModCxt);
```

6. Example

Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x07, 0x01,
                    /* function type {i32, i32} -> {i32} */
                    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
                    /* Import section */
                    0x02, 0x13, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "func-add" */
                    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x0A, 0x01,
                    /* export name: "addTwo" */
                    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
                    /* export desc: func 0 */
```

```
                        0x00, 0x01,
                        /* Code section */
                        0x0A, 0x0A, 0x01,
                        /* code body */
                        0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B};

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
      WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                        WasmEdge_ValType_I32};
  enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
  WasmEdge_FunctionTypeContext *HostFType =
      WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
      WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = {WasmEdge_ValueGenI32(1234),
                              WasmEdge_ValueGenI32(5678)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
      VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
```

```
  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
```

7. Host Data Example

Developers can set a external data object to the `Function` context, and access to the object in the function body. Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Also set the result to the data. */
  int32_t *DataPtr = (int32_t *)Data;
  *DataPtr = Val1 + Val2;
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x07, 0x01,
                    /* function type {i32, i32} -> {i32} */
                    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
                    /* Import section */
                    0x02, 0x13, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "func-add" */
                    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x0A, 0x01,
```

```
                        /* export name: "addTwo" */
                        0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
                        /* export desc: func 0 */
                        0x00, 0x01,
                        /* Code section */
                        0x0A, 0x0A, 0x01,
                        /* code body */
                        0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B};

  /* The external data object: an integer. */
  int32_t Data;

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
      WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                        WasmEdge_ValType_I32};
  enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
  WasmEdge_FunctionTypeContext *HostFType =
      WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
      WasmEdge_FunctionInstanceCreate(HostFType, Add, &Data, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = {WasmEdge_ValueGenI32(1234),
                              WasmEdge_ValueGenI32(5678)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
      VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);
```

```
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  printf("Data value: %d\n", Data);

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options.

WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* ... Adjust settings in the configure context. */
  /* Result. */
  WasmEdge_Result Res;

  /* Create the compiler context. The configure context can be NULL. */
  WasmEdge_CompilerContext *CompilerCxt = WasmEdge_CompilerCreate(ConfCxt);
  /* Compile the WASM file with input and output paths. */
  Res = WasmEdge_CompilerCompile(CompilerCxt, "fibonacci.wasm",
                                 "fibonacci-aot.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Compilation failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }

  WasmEdge_CompilerDelete(CompilerCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  return 0;
}
```

Then you can compile and run (the output file is "fibonacci-aot.wasm"):

```
$ gcc test.c -lwasmedge
$ ./a.out
[2021-07-02 11:08:08.651] [info] compile start
[2021-07-02 11:08:08.653] [info] verify start
[2021-07-02 11:08:08.653] [info] optimize start
[2021-07-02 11:08:08.670] [info] codegen start
[2021-07-02 11:08:08.706] [info] compile done
```

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
/// AOT compiler optimization level enumeration.
enum WasmEdge_CompilerOptimizationLevel {
  /// Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  /// Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  /// Optimize for fast execution as much as possible without triggering
  /// significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  /// Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  /// Optimize for small code size as much as possible without triggering
  /// significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  /// Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

/// AOT compiler output binary format enumeration.
enum WasmEdge_CompilerOutputFormat {
  /// Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  /// WebAssembly with AOT compiled codes in custom sections.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

Please refer to the AOT compiler options configuration for details.

WasmEdge C 0.11.2 API Documentation

WasmEdge C API denotes an interface to access the WasmEdge runtime. The following are the guides to working with the C APIs of WasmEdge.

Please notice that the WasmEdge C API provides SONAME and SOVERSION after the `0.11.0` release.

Please notice that `libwasmedge_c.so` is renamed to `libwasmedge.so` after the `0.11.0` release. Please use `-lwasmedge` instead of `-lwasmedge_c` for the linker option.

This document is for the `0.11.2` version. For the older `0.10.1` version, please refer to the document here.

Developers can refer to here to upgrade to 0.11.0.

Table of Contents

WasmEdge Installation

Download And Install

The easiest way to install WasmEdge is to run the following command. Your system should have `git` and `wget` as prerequisites.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2
```

For more details, please refer to the Installation Guide for the WasmEdge installation.

Compile Sources

After the installation of WasmEdge, the following guide can help you to test for the availability of the WasmEdge C API.

1. Prepare the test C file (and assumed saved as `test.c`):

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
  return 0;
}
```

2. Compile the file with `gcc` or `clang`.

```
gcc test.c -lwasmedge
```

3. Run and get the expected output.

```
$ ./a.out
WasmEdge version: 0.11.2
```

ABI Compatibility

WasmEdge C API introduces SONAME and SOVERSION in the 0.11.0 release to present the compatibility between different C API versions.

The releases before 0.11.0 are all unversioned. Please make sure the library version is the same as the corresponding C API version you used.

WasmEdge Version	WasmEdge C API Library Name	WasmEdge C API SONAME	WasmEdge C API SOVERSION
< 0.11.0	libwasmedge_c.so	Unversioned	Unversioned
0.11.0 to 0.11.1	libwasmedge.so	libwasmedge.so.0	libwasmedge.so.0.0.0
since 0.11.2	libwasmedge.so	libwasmedge.so.0	libwasmedge.so.0.0.1

WasmEdge Basics

In this part, we will introduce the utilities and concepts of WasmEdge shared library.

Version

The `Version` related APIs provide developers to check for the WasmEdge shared library version.

```
#include <wasmedge/wasmedge.h>
printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
printf("WasmEdge version major: %u\n", WasmEdge_VersionGetMajor());
printf("WasmEdge version minor: %u\n", WasmEdge_VersionGetMinor());
printf("WasmEdge version patch: %u\n", WasmEdge_VersionGetPatch());
```

Logging Settings

The `WasmEdge_LogSetErrorLevel()` and `WasmEdge_LogSetDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Developers can also use the `WasmEdge_LogOff()` API to disable all logging. (`0.11.2` or upper only)

Value Types

In WasmEdge, developers should convert the values to `WasmEdge_Value` objects through APIs for matching to the WASM value types.

1. Number types: `i32` , `i64` , `f32` , `f64` , and `v128` for the `SIMD` proposal

```
WasmEdge_Value Val;
Val = WasmEdge_ValueGenI32(123456);
printf("%d\n", WasmEdge_ValueGetI32(Val));
/* Will print "123456" */
Val = WasmEdge_ValueGenI64(1234567890123LL);
printf("%ld\n", WasmEdge_ValueGetI64(Val));
/* Will print "1234567890123" */
Val = WasmEdge_ValueGenF32(123.456f);
printf("%f\n", WasmEdge_ValueGetF32(Val));
/* Will print "123.456001" */
Val = WasmEdge_ValueGenF64(123456.123456789);
printf("%.10f\n", WasmEdge_ValueGetF64(Val));
/* Will print "123456.1234567890" */
```

2. Reference types: `funcref` and `externref` for the `Reference-Types` proposal

```
WasmEdge_Value Val;
void *Ptr;
bool IsNull;
uint32_t Num = 10;
/* Generate a externref to NULL. */
Val = WasmEdge_ValueGenNullRef(WasmEdge_RefType_ExternRef);
IsNull = WasmEdge_ValueIsNullRef(Val);
/* The `IsNull` will be `TRUE`. */
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `NULL`. */

/* Get the function instance by creation or from module instance. */
const WasmEdge_FunctionInstanceContext *FuncCxt = ...;
/* Generate a funcref with the given function instance context. */
Val = WasmEdge_ValueGenFuncRef(FuncCxt);
const WasmEdge_FunctionInstanceContext *GotFuncCxt =
    WasmEdge_ValueGetFuncRef(Val);
/* The `GotFuncCxt` will be the same as `FuncCxt`. */

/* Generate a externref to `Num`. */
Val = WasmEdge_ValueGenExternRef(&Num);
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `&Num`. */
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "10" */
Num += 55;
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "65" */
```

Strings

The `WasmEdge_String` object is for the instance names when invoking a WASM function or finding the contexts of instances.

1. Create a `WasmEdge_String` from a C string (`const char *` with NULL termination) or a buffer with length.

   The content of the C string or buffer will be copied into the `WasmEdge_String` object.

```
char Buf[4] = {50, 55, 60, 65};
WasmEdge_String Str1 = WasmEdge_StringCreateByCString("test");
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
/* The objects should be deleted by `WasmEdge_StringDelete()`. */
WasmEdge_StringDelete(Str1);
WasmEdge_StringDelete(Str2);
```

2. Wrap a `WasmEdge_String` to a buffer with length.

   The content will not be copied, and the caller should guarantee the life cycle of the input buffer.

```
const char CStr[] = "test";
WasmEdge_String Str = WasmEdge_StringWrap(CStr, 4);
/* The object should __NOT__ be deleted by `WasmEdge_StringDelete()`. */
```

3. String comparison

```
const char CStr[] = "abcd";
char Buf[4] = {0x61, 0x62, 0x63, 0x64};
WasmEdge_String Str1 = WasmEdge_StringWrap(CStr, 4);
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
bool IsEq = WasmEdge_StringIsEqual(Str1, Str2);
/* The `IsEq` will be `TRUE`. */
WasmEdge_StringDelete(Str2);
```

4. Convert to C string

```
char Buf[256];
WasmEdge_String Str =
    WasmEdge_StringCreateByCString("test_wasmedge_string");
uint32_t StrLength = WasmEdge_StringCopy(Str, Buf, sizeof(Buf));
/* StrLength will be 20 */
printf("String: %s\n", Buf);
/* Will print "test_wasmedge_string". */
```

Results

The `WasmEdge_Result` object specifies the execution status. APIs about WASM execution will

return the `WasmEdge_Result` to denote the status.

```
WasmEdge_Result Res = WasmEdge_Result_Success;
bool IsSucceeded = WasmEdge_ResultOK(Res);
/* The `IsSucceeded` will be `TRUE`. */
uint32_t Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 0. */
const char *Msg = WasmEdge_ResultGetMessage(Res);
/* The `Msg` will be "success". */
enum WasmEdge_ErrCategory Category = WasmEdge_ResultGetCategory(Res);
/* The `Category` will be WasmEdge_ErrCategory_WASM. */

Res = WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, 123);
/* Generate the user-defined result with code. */
Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 123. */
Category = WasmEdge_ResultGetCategory(Res);
/* The `Category` will be WasmEdge_ErrCategory_UserLevelError. */
```

Contexts

The objects, such as `VM`, `Store`, and `Function`, are composed of `Context`s. All of the contexts can be created by calling the corresponding creation APIs and should be destroyed by calling the corresponding deletion APIs. Developers have responsibilities to manage the contexts for memory management.

```
/* Create the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Delete the configure context. */
WasmEdge_ConfigureDelete(ConfCxt);
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `WasmEdge_Limit` struct is defined in the header:

```
/// Struct of WASM limit.
typedef struct WasmEdge_Limit {
  /// Boolean to describe has max value or not.
  bool HasMax;
  /// Boolean to describe is shared memory or not.
  bool Shared;
  /// Minimum value.
  uint32_t Min;
  /// Maximum value. Will be ignored if the `HasMax` is false.
  uint32_t Max;
} WasmEdge_Limit;
```

Developers can initialize the struct by assigning it's value, and the `Max` value is needed to be larger or equal to the `Min` value. The API `WasmEdge_LimitIsEqual()` is provided to compare with 2 `WasmEdge_Limit` structs.

2. Function type context

   The `Function Type` context is used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `Function Type` context APIs to get the parameter or return value types information.

```
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I64};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_FuncRef};
WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);

enum WasmEdge_ValType Buf[16];
uint32_t ParamLen = WasmEdge_FunctionTypeGetParametersLength(FuncTypeCxt);
/* `ParamLen` will be 2. */
uint32_t GotParamLen =
    WasmEdge_FunctionTypeGetParameters(FuncTypeCxt, Buf, 16);
/* `GotParamLen` will be 2, and `Buf[0]` and `Buf[1]` will be the same as
 * `ParamList`. */
uint32_t ReturnLen = WasmEdge_FunctionTypeGetReturnsLength(FuncTypeCxt);
/* `ReturnLen` will be 1. */
uint32_t GotReturnLen =
    WasmEdge_FunctionTypeGetReturns(FuncTypeCxt, Buf, 16);
/* `GotReturnLen` will be 1, and `Buf[0]` will be the same as `ReturnList`.
 */

WasmEdge_FunctionTypeDelete(FuncTypeCxt);
```

3. Table type context

   The `Table Type` context is used for `Table` instance creation or getting information from `Table` instances.

```
WasmEdge_Limit TabLim = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_ExternRef, TabLim);

enum WasmEdge_RefType GotRefType =
WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `GotRefType` will be WasmEdge_RefType_ExternRef. */
WasmEdge_Limit GotTabLim = WasmEdge_TableTypeGetLimit(TabTypeCxt);
/* `GotTabLim` will be the same value as `TabLim`. */

WasmEdge_TableTypeDelete(TabTypeCxt);
```

4. Memory type context

   The `Memory Type` context is used for `Memory` instance creation or getting information from `Memory` instances.

```
WasmEdge_Limit MemLim = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_MemoryTypeContext *MemTypeCxt = WasmEdge_MemoryTypeCreate(MemLim);

WasmEdge_Limit GotMemLim = WasmEdge_MemoryTypeGetLimit(MemTypeCxt);
/* `GotMemLim` will be the same value as `MemLim`. */

WasmEdge_MemoryTypeDelete(MemTypeCxt)
```

5. Global type context

   The `Global Type` context is used for `Global` instance creation or getting information from `Global` instances.

```
WasmEdge_GlobalTypeContext *GlobTypeCxt = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_F64, WasmEdge_Mutability_Var);

WasmEdge_ValType GotValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `GotValType` will be WasmEdge_ValType_F64. */
WasmEdge_Mutability GotValMut =
    WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `GotValMut` will be WasmEdge_Mutability_Var. */

WasmEdge_GlobalTypeDelete(GlobTypeCxt);
```

6. Import type context

   The `Import Type` context is used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `Import Type` context. The details about querying `Import Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/*
 * Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
 * result of loading a WASM file.
 */
const WasmEdge_ImportTypeContext *ImpType = ...;
/* Assume that `ImpType` is queried from the `ASTCxt` for the import. */

enum WasmEdge_ExternalType ExtType =
    WasmEdge_ImportTypeGetExternalType(ImpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
 * `WasmEdge_ExternalType_Table`, `WasmEdge_ExternalType_Memory`, or
 * `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ModName = WasmEdge_ImportTypeGetModuleName(ImpType);
WasmEdge_String ExtName = WasmEdge_ImportTypeGetExternalName(ImpType);
/*
 * The `ModName` and `ExtName` should not be destroyed and the string
 * buffers are binded into the `ASTCxt`.
 */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_ImportTypeGetFunctionType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
 * `FuncTypeCxt` will be NULL.
 */
const WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_ImportTypeGetTableType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
 * will be NULL.
 */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_ImportTypeGetMemoryType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
 * will be NULL.
 */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
```

```
    WasmEdge_ImportTypeGetGlobalType(ASTCxt, ImpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt`
 * will be NULL.
 */
```

7. Export type context

   The `Export Type` context is used for getting the exports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`) and external name from an `Export Type` context. The details about querying `Export Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/*
 * Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
 * result of loading a WASM file.
 */
const WasmEdge_ExportTypeContext *ExpType = ...;
/* Assume that `ExpType` is queried from the `ASTCxt` for the export. */

enum WasmEdge_ExternalType ExtType =
    WasmEdge_ExportTypeGetExternalType(ExpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
 * `WasmEdge_ExternalType_Table`, `WasmEdge_ExternalType_Memory`, or
 * `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ExtName = WasmEdge_ExportTypeGetExternalName(ExpType);
/*
 * The `ExtName` should not be destroyed and the string buffer is binded
 * into the `ASTCxt`.
 */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_ExportTypeGetFunctionType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
 * `FuncTypeCxt` will be NULL.
 */
const WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_ExportTypeGetTableType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
 * will be NULL.
 */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_ExportTypeGetMemoryType(ASTCxt, ExpType);
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
 * will be NULL.
 */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
    WasmEdge_ExportTypeGetGlobalType(ASTCxt, ExpType);
```

```
/*
 * If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt`
 * will be NULL.
 */
```

Async

After calling the asynchronous execution APIs, developers will get the `WasmEdge_Async` object. Developers own the object and should call the `WasmEdge_AsyncDelete()` API to destroy it.

1. Wait for the asynchronous execution

   Developers can wait the execution until finished:

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution. */
   WasmEdge_AsyncWait(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   Or developers can wait for a time limit. If the time limit exceeded, developers can choose to cancel the execution. For the interruptible execution in AOT mode, developers should set `TRUE` through the `WasmEdge_ConfigureCompilerSetInterruptible()` API into the configure context for the AOT compiler.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution for 1 second. */
bool IsEnd = WasmEdge_AsyncWaitFor(Async, 1000);
if (IsEnd) {
  /* The execution finished. Developers can get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(/* ... Ignored */);
} else {
  /*
   * The time limit exceeded. Developers can keep waiting or cancel the
   * execution.
   */
  WasmEdge_AsyncCancel(Async);
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, 0, NULL);
  /* The result error code will be `WasmEdge_ErrCode_Interrupted`. */
}
WasmEdge_AsyncDelete(Async);
```

2. Get the execution result of the asynchronous execution

   Developers can use the `WasmEdge_AsyncGetReturnsLength()` API to get the return value list length. This function will block and wait for the execution. If the execution has finished, this function will return the length immediately. If the execution failed, this function will return `0`. This function can help the developers to create the buffer to get the return values. If developers have already known the buffer length, they can skip this function and use the `WasmEdge_AsyncGet()` API to get the result.

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /*
    * Blocking and waiting for the execution and get the return value list
    * length.
    */
   uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   The `WasmEdge_AsyncGet()` API will block and wait for the execution. If the execution has finished, this function will fill the return values into the buffer and return the execution result immediately.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return values. */
const uint32_t BUF_LEN = 256;
WasmEdge_Value Buf[BUF_LEN];
WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Buf, BUF_LEN);
WasmEdge_AsyncDelete(Async);
```

Configurations

The configuration context, `WasmEdge_ConfigureContext`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` context to create other runtime contexts.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` context.

   ```
   enum WasmEdge_Proposal {
     WasmEdge_Proposal_ImportExportMutGlobals = 0,
     WasmEdge_Proposal_NonTrapFloatToIntConversions,
     WasmEdge_Proposal_SignExtensionOperators,
     WasmEdge_Proposal_MultiValue,
     WasmEdge_Proposal_BulkMemoryOperations,
     WasmEdge_Proposal_ReferenceTypes,
     WasmEdge_Proposal_SIMD,
     WasmEdge_Proposal_TailCall,
     WasmEdge_Proposal_MultiMemories,
     WasmEdge_Proposal_Annotations,
     WasmEdge_Proposal_Memory64,
     WasmEdge_Proposal_ExceptionHandling,
     WasmEdge_Proposal_ExtendedConst,
     WasmEdge_Proposal_Threads,
     WasmEdge_Proposal_FunctionReferences
   };
   ```

   Developers can add or remove the proposals into the `Configure` context.

```
/*
 * By default, the following proposals have turned on initially:
 * * Import/Export of mutable globals
 * * Non-trapping float-to-int conversions
 * * Sign-extension operators
 * * Multi-value returns
 * * Bulk memory operations
 * * Reference types
 * * Fixed-width SIMD
 *
 * For the current WasmEdge version, the following proposals are supported
 * (turned off by default) additionally:
 * * Tail-call
 * * Multiple memories
 * * Extended-const
 * * Threads
 */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddProposal(ConfCxt, WasmEdge_Proposal_MultiMemories);
WasmEdge_ConfigureRemoveProposal(ConfCxt,
WasmEdge_Proposal_ReferenceTypes);
bool IsBulkMem = WasmEdge_ConfigureHasProposal(
    ConfCxt, WasmEdge_Proposal_BulkMemoryOperations);
/* The `IsBulkMem` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

2. Host registrations

This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` contexts.

```
enum WasmEdge_HostRegistration {
  WasmEdge_HostRegistration_Wasi = 0,
  WasmEdge_HostRegistration_WasmEdge_Process
};
```

The details will be introduced in the preregistrations of VM context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsHostWasi = WasmEdge_ConfigureHasHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `FALSE`. */
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_Wasi);
IsHostWasi = WasmEdge_ConfigureHasHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
uint32_t PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* By default, the maximum memory page size is 65536. */
WasmEdge_ConfigureSetMaxMemoryPage(ConfCxt, 1024);
/*
 * Limit the memory size of each memory instance with not larger than 1024
 * pages (64 MiB).
 */
PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* The `PageSize` will be 1024. */
WasmEdge_ConfigureDelete(ConfCxt);
```

4. Forcibly interpreter mode (`0.11.2` or upper only)

   If developers want to execute the WASM file or the AOT compiled WASM in interpreter mode forcibly, they can turn on the configuration.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsForceInterp = WasmEdge_ConfigureIsForceInterpreter(ConfCxt);
/* By default, The `IsForceInterp` will be `FALSE`. */
WasmEdge_ConfigureSetForceInterpreter(ConfCxt, TRUE);
IsForceInterp = WasmEdge_ConfigureIsForceInterpreter(ConfCxt);
/* The `IsForceInterp` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

5. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
enum WasmEdge_CompilerOptimizationLevel {
  // Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  // Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  // Optimize for fast execution as much as possible without triggering
  // significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  // Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  // Optimize for small code size as much as possible without triggering
  // significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  // Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

enum WasmEdge_CompilerOutputFormat {
  // Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  // WebAssembly with AOT compiled codes in custom section.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

   These configurations are only effective in `Compiler` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the optimization level is O3. */
WasmEdge_ConfigureCompilerSetOptimizationLevel(
    ConfCxt, WasmEdge_CompilerOptimizationLevel_O2);
/* By default, the output format is universal WASM. */
WasmEdge_ConfigureCompilerSetOutputFormat(
    ConfCxt, WasmEdge_CompilerOutputFormat_Native);
/* By default, the dump IR is `FALSE`. */
WasmEdge_ConfigureCompilerSetDumpIR(ConfCxt, TRUE);
/* By default, the generic binary is `FALSE`. */
WasmEdge_ConfigureCompilerSetGenericBinary(ConfCxt, TRUE);
/* By default, the interruptible is `FALSE`.
/* Set this option to `TRUE` to support the interruptible execution in AOT
mode. */
WasmEdge_ConfigureCompilerSetInterruptible(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

6. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/*
 * By default, the instruction counting is `FALSE` when running a
 * compiled-WASM or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetInstructionCounting(ConfCxt, TRUE);
/*
 * By default, the cost measurement is `FALSE` when running a compiled-WASM
 * or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetCostMeasuring(ConfCxt, TRUE);
/*
 * By default, the time measurement is `FALSE` when running a compiled-WASM
 * or a pure-WASM.
 */
WasmEdge_ConfigureStatisticsSetTimeMeasuring(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

Statistics

The statistics context, `WasmEdge_StatisticsContext`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` context from the `VM` context, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
   /*
    * ...
    * After running the WASM functions with the `Statistics` context
    */
   uint32_t Count = WasmEdge_StatisticsGetInstrCount(StatCxt);
   double IPS = WasmEdge_StatisticsGetInstrPerSecond(StatCxt);
   WasmEdge_StatisticsDelete(StatCxt);
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` context. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
uint64_t CostTable[16] = {
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0
};
/*
 * Developers can set the costs of each instruction. The value not
 * covered will be 0.
 */
WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
WasmEdge_StatisticsSetCostLimit(StatCxt, 5000000);
/*
 * ...
 * After running the WASM functions with the `Statistics` context
 */
uint64_t Cost = WasmEdge_StatisticsGetTotalCost(StatCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

Tools Driver

Besides executing the `wasmedge` and `wasmedgec` CLI tools, developers can trigger the WasmEdge CLI tools by WasmEdge C API. The API arguments are the same as the command line arguments of the CLI tools.

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge AOT compiler. */
  return WasmEdge_Driver_Compiler(argc, argv);
}
```

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge runtime tool. */
  return WasmEdge_Driver_Tool(argc, argv);
}
```

WasmEdge VM

In this partition, we will introduce the functions of `WasmEdge_VMContext` object and show examples of executing WASM functions.

WASM Execution Example With VM Context

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s (get_local $n)(i32.const 2))
      (return (i32.const 1))
    )
    (return
      (i32.add
        (call $fib (i32.sub (get_local $n)(i32.const 2)))
        (call $fib (i32.sub (get_local $n)(i32.const 1)))
      )
    )
  )
)
```

1. Run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <stdio.h>
#include <wasmedge/wasmedge.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                        WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(5)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(
      VMCxt, "fibonacci.wasm", FuncName, Params, 1, Returns, 1);
  /*
   * Developers can run the WASM binary from buffer with the
   * `WasmEdge_VMRunWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMRunWasmFromASTModule()` API.
   */

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 5th Fibonacci number is 8 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 8
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need the WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                        WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(10)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
   * `WasmEdge_VMLoadWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
```

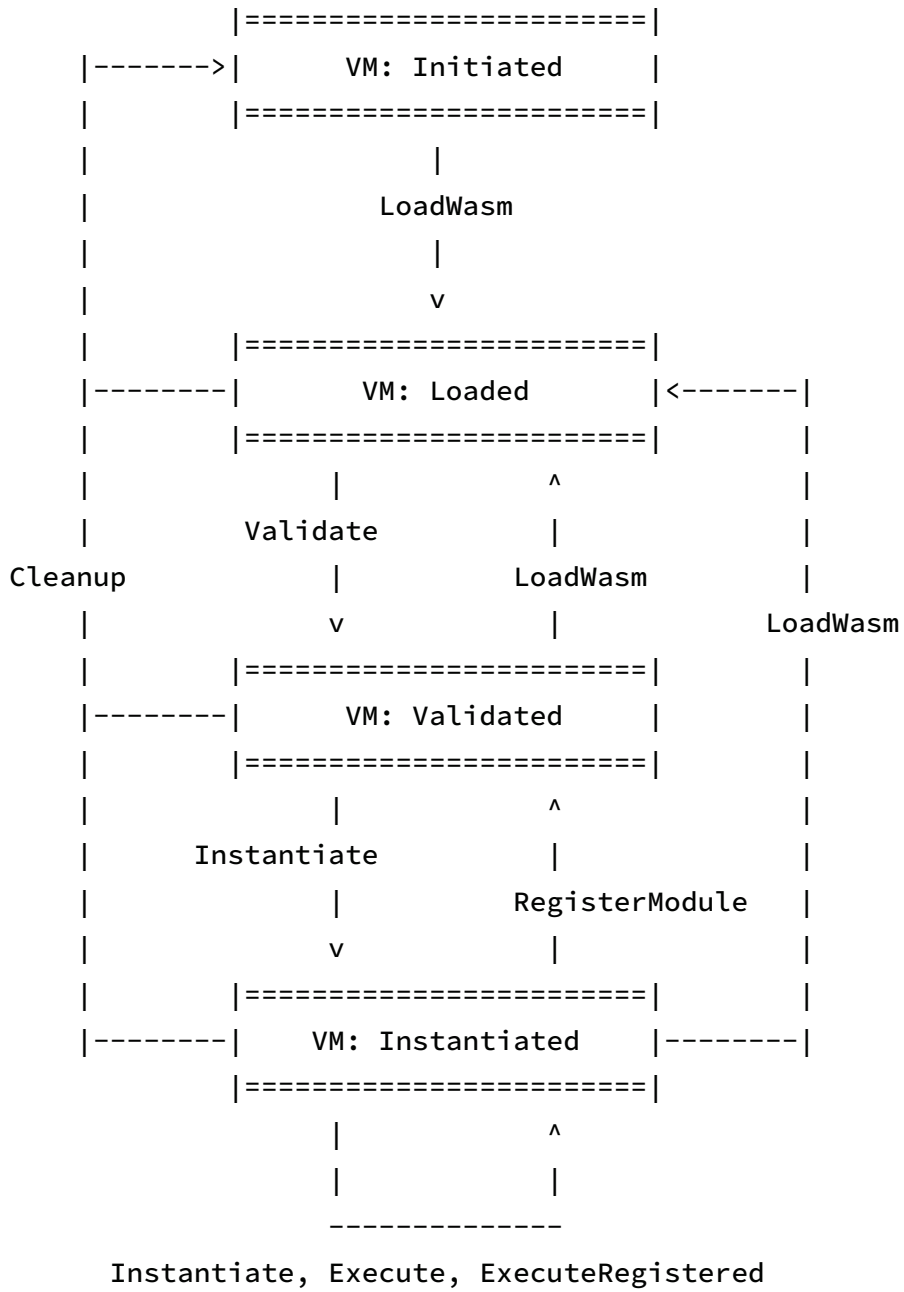
```
  /*
   * Developers can load, validate, and instantiate another WASM module to
   * replace the instantiated one. In this case, the old module will be
   * cleared, but the registered modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
   * Step 4: Execute WASM functions. You can execute functions repeatedly
   * after instantiation.
   */
  Res = WasmEdge_VMExecute(VMCxt, FuncName, Params, 1, Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 10th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 89
```

The following graph explains the status of the `VM` context.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or module instances in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation API accepts the `Configure` context and the `Store` context. If developers only need the default settings, just pass `NULL` to the creation API. The details of the `Store` context will be introduced in Store.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, StoreCxt);
/* The caller should guarantee the life cycle if the store context. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_VMGetStatisticsContext(VMCxt);
/*
 * The VM context already contains the statistics context and can be retrieved
 * by this API.
 */
/*
 * Note that the retrieved store and statistics contexts from the VM contexts
by
 * VM APIs should __NOT__ be destroyed and owned by the VM contexts.
 */
WasmEdge_VMDelete(VMCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_Wasi);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration.
 */
WasmEdge_ModuleInstanceContext *WasiModule =
    WasmEdge_VMGetImportModuleContext(VMCxt,
                                      WasmEdge_HostRegistration_Wasi);
/* Initialize the WASI. */
WasmEdge_ModuleInstanceInitWASI(WasiModule, /* ... ignored */);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

   This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` plugin.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasmEdge_Process);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
 */
WasmEdge_ModuleInstanceContext *ProcModule =
    WasmEdge_VMGetImportModuleContext(
        VMCxt, WasmEdge_HostRegistration_WasmEdge_Process);
/* Initialize the WasmEdge_Process. */
WasmEdge_ModuleInstanceInitWasmEdgeProcess(ProcModule, /* ... ignored */);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WasmEdge_Process module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

3. WASI-NN proposal

   Developers can turn on the WASI-NN proposal support for VM in the `Configure` context.

> Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
                                      WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
 */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
 */
WasmEdge_ModuleInstanceContext *NNModule =
    WasmEdge_VMGetImportModuleContext(VMCxt,
                                      WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-NN module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

4. WASI-Crypto proposal

   Developers can turn on the WASI-Crypto proposal support for VM in the `Configure` context.

Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* The WASI-Crypto related configures are suggested to turn on together. */
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_AsymmetricCommon);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Kx);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Signatures);
WasmEdge_ConfigureAddHostRegistration(
    ConfCxt, WasmEdge_HostRegistration_WasiCrypto_Symmetric);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/*
 * The following API can retrieve the pre-registration module instances
from
 * the VM context.
  */
/*
 * This API will return `NULL` if the corresponding pre-registration is not
 * set into the configuration or the plugin load failed.
  */
WasmEdge_ModuleInstanceContext *CryptoCommonModule =
    WasmEdge_VMGetImportModuleContext(
        VMCxt, WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-Crypto module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, the host functions are composed into host modules as `WasmEdge_ModuleInstanceContext` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` context.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_ModuleInstanceContext *WasiModule =
    WasmEdge_ModuleInstanceCreateWASI(/* ... ignored ... */);
/* You can also create and register the WASI host modules by this API. */
WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModule);
/* The result status should be checked. */

/* ... */

WasmEdge_ModuleInstanceDelete(WasiModule);
/*
 * The created module instances should be deleted by the developers when the VM
 * deallocation.
 */
WasmEdge_VMDelete(VMCxt);
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM modules.

1. Register the WASM modules with exported module names

   Unless the module instances have already contained the module names, every WASM module should be named uniquely when registering. Assume that the WASM file `fibonacci.wasm` is copied into the current directory.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
WasmEdge_Result Res =
    WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName, "fibonacci.wasm");
/*
 * Developers can register the WASM module from buffer with the
 * `WasmEdge_VMRegisterModuleFromBuffer()` API, or from
 * `WasmEdge_ASTModuleContext` object with the
 * `WasmEdge_VMRegisterModuleFromASTModule()` API.
 */
/*
 * The result status should be checked.
 * The error will occur if the WASM module instantiation failed or the
 * module name conflicts.
 */
WasmEdge_StringDelete(ModName);
WasmEdge_VMDelete(VMCxt);
```

2. Execute the functions in registered WASM modules

   Assume that the C file `test.c` is as follows:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(20)};
  WasmEdge_Value Returns[1];
  /* Names. */
  WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Register the WASM module into VM. */
  Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
"fibonacci.wasm");
  /*
   * Developers can register the WASM module from buffer with the
   * `WasmEdge_VMRegisterModuleFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMRegisterModuleFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM registration failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
   * The function "fib" in the "fibonacci.wasm" was exported with the
module
   * name "mod". As the same as host functions, other modules can import
the
   * function `"mod" "fib"`.
   */

  /*
   * Execute WASM functions in registered modules.
   * Unlike the execution of functions, the registered functions can be
   * invoked without `WasmEdge_VMInstantiate()` because the WASM module was
```

```
     * instantiated when registering. Developers can also invoke the host
     * functions directly with this API.
     */
    Res = WasmEdge_VMExecuteRegistered(VMCxt, ModName, FuncName, Params, 1,
                                       Returns, 1);
    if (WasmEdge_ResultOK(Res)) {
      printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
    } else {
      printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    }
    WasmEdge_StringDelete(ModName);
    WasmEdge_StringDelete(FuncName);
    WasmEdge_VMDelete(VMCxt);
    return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 10946
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(20)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Asynchronously run the WASM function from file and get the
   * `WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncRunWasmFromFile(
      VMCxt, "fibonacci.wasm", FuncName, Params, 1);
  /*
   * Developers can run the WASM binary from buffer with the
   * `WasmEdge_VMAsyncRunWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMAsyncRunWasmFromASTModule()` API.
   */

  /* Wait for the execution. */
  WasmEdge_AsyncWait(Async);
  /*
   * Developers can also use the `WasmEdge_AsyncGetReturnsLength()` or
   * `WasmEdge_AsyncGet()` APIs to wait for the asynchronous execution.
   * These APIs will wait until the execution finished.
   */

  /* Check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
   * known the return arity. */

  /* Get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Returns, Arity);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
```

```
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(25)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
   * `WasmEdge_VMLoadWasmFromBuffer()` API, or from
   * `WasmEdge_ASTModuleContext` object with the
   * `WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
  /*
   * Developers can load, validate, and instantiate another WASM module to
   * replace the instantiated one. In this case, the old module will be
   * cleared, but the registered modules are still kept.
   */
```

```
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
           WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Asynchronously execute the WASM function and get the
   * `WasmEdge_Async` object. */
  WasmEdge_Async *Async =
      WasmEdge_VMAsyncExecute(VMCxt, FuncName, Params, 1);
  /*
   * Developers can execute functions repeatedly after instantiation.
   * For invoking the registered functions, you can use the
   * `WasmEdge_VMAsyncExecuteRegistered()` API.
   */

  /* Wait and check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
   * known the return arity. */

  /* Get the result. */
  Res = WasmEdge_AsyncGet(Async, Returns, Arity);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
}
```

Then you can compile and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` context supplies the APIs to retrieve the instances.

1. Store

   If the `VM` context is created without assigning a `Store` context, the `VM` context will allocate and own a `Store` context.

   ```
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
   WasmEdge_StoreContext *StoreCxt = WasmEdge_VMGetStoreContext(VMCxt);
   /* The object should __NOT__ be deleted by `WasmEdge_StoreDelete()`. */
   WasmEdge_VMDelete(VMCxt);
   ```

   Developers can also create the `VM` context with a `Store` context. In this case, developers should guarantee the life cycle of the `Store` context. Please refer to the Store Contexts for the details about the `Store` context APIs.

   ```
   WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);
   WasmEdge_StoreContext *StoreCxtMock = WasmEdge_VMGetStoreContext(VMCxt);
   /* The `StoreCxt` and the `StoreCxtMock` are the same. */
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_StoreDelete(StoreCxt);
   ```

2. List exported functions

   After the WASM module instantiation, developers can use the `WasmEdge_VMExecute()` API to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);

  WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  WasmEdge_VMValidate(VMCxt);
  WasmEdge_VMInstantiate(VMCxt);

  /* List the exported functions. */
  /* Get the number of exported functions. */
  uint32_t FuncNum = WasmEdge_VMGetFunctionListLength(VMCxt);
  /* Create the name buffers and the function type buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  WasmEdge_FunctionTypeContext *FuncTypes[BUF_LEN];
  /*
   * Get the export function list.
   * If the function list length is larger than the buffer length, the
   * overflowed data will be discarded. The `FuncNames` and `FuncTypes` can
   * be NULL if developers don't need them.
   */
  uint32_t RealFuncNum =
      WasmEdge_VMGetFunctionList(VMCxt, FuncNames, FuncTypes, BUF_LEN);

  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size,
           Buf);
    /*
     * The function names should be __NOT__ destroyed.
     * The returned function type contexts should __NOT__ be destroyed.
     */
  }
  WasmEdge_StoreDelete(StoreCxt);
  WasmEdge_VMDelete(VMCxt);
  return 0;
}
```

Then you can compile and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get exported function string length: 3, name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` context from the `VM` context and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

   The `VM` context provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
const WasmEdge_FunctionTypeContext *FuncType =
    WasmEdge_VMGetFunctionType(VMCxt, FuncName);
/*
 * Developers can get the function types of functions in the registered
 * modules via the `WasmEdge_VMGetFunctionTypeRegistered()` API with the
 * module name. If the function is not found, these APIs will return
`NULL`.
 * The returned function type contexts should __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

4. Get the active module

   After the WASM module instantiation, an anonymous module is instantiated and owned by the `VM` context. Developers may need to retrieve it to get the instances beyond the module. Then developers can use the `WasmEdge_VMGetActiveModule()` API to get that anonymous module instance. Please refer to the Module instance for the details about the module instance APIs.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
const WasmEdge_ModuleInstanceContext *ModCxt =
    WasmEdge_VMGetActiveModule(VMCxt);
/*
 * If there's no WASM module instantiated, this API will return `NULL`.
 * The returned module instance context should __NOT__ be destroyed.
 */
```

5. Get the components

   The `VM` context is composed by the `Loader`, `Validator`, and `Executor` contexts. For the developers who want to use these contexts without creating another instances, these APIs can help developers to get them from the `VM` context. The get contexts are owned by the `VM` context, and developers should not call their delete functions.

```
WasmEdge_LoaderContext *LoadCxt = WasmEdge_VMGetLoaderContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_LoaderDelete()`. */
WasmEdge_ValidatorContext *ValidCxt =
WasmEdge_VMGetValidatorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ValidatorDelete()`. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_VMGetExecutorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ExecutorDelete()`. */
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` context, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` contexts. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /*
   * Create the configure context. This step is not necessary because we didn't
   * adjust any setting.
   */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /*
   * Create the statistics context. This step is not necessary if the
statistics
   * in runtime is not needed.
   */
  WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
  /*
   * Create the store context. The store context is the object to link the
   * modules for imports and exports.
   */
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  /* Result. */
  WasmEdge_Result Res;

  /* Create the loader context. The configure context can be NULL. */
  WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);
  /* Create the validator context. The configure context can be NULL. */
  WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
  /*
   * Create the executor context. The configure context and the statistics
   * context can be NULL.
   */
  WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);

  /*
   * Load the WASM file or the compiled-WASM file and convert into the AST
   * module context.
   */
  WasmEdge_ASTModuleContext *ASTCxt = NULL;
  Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Validate the WASM module. */
  Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Instantiate the WASM module into store context. */
  WasmEdge_ModuleInstanceContext *ModCxt = NULL;
  Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
```

```
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return 1;
}

/* Try to list the exported functions of the instantiated WASM module. */
uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
 * will be discarded.
 */
uint32_t RealFuncNum =
    WasmEdge_ModuleInstanceListFunction(ModCxt, FuncNames, BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  char Buf[BUF_LEN];
  uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
  printf("Get exported function string length: %u, name: %s\n", Size, Buf);
  /* The function names should __NOT__ be destroyed. */
}

/* The parameters and returns arrays. */
WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(18)};
WasmEdge_Value Returns[1];
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
/* Find the exported function by function name. */
WasmEdge_FunctionInstanceContext *FuncCxt =
    WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
if (FuncCxt == NULL) {
  printf("Function `fib` not found.\n");
  return 1;
}
/* Invoke the WASM fnction. */
Res = WasmEdge_ExecutorInvoke(ExecCxt, FuncCxt, Params, 1, Returns, 1);
if (WasmEdge_ResultOK(Res)) {
  printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
} else {
  printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}

/* Resources deallocations. */
WasmEdge_StringDelete(FuncName);
WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_ConfigureDelete(ConfCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

```
  return 0;
}
```

Then you can compile and run: (the 18th Fibonacci number is 4181 in 0-based index)

```
$ gcc test.c -lwasmedge
$ ./a.out
Get exported function string length: 3, name: fib
Get the result: 4181
```

Loader

The `Loader` context loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
uint8_t Buf[4096];
/* ... Read the WASM code to the buffer. */
uint32_t FileSize = ...;
/* The `FileSize` is the length of the WASM code. */

/* Developers can adjust settings in the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);

WasmEdge_ASTModuleContext *ASTCxt = NULL;
WasmEdge_Result Res;

/* Load WASM or compiled-WASM from the file. */
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

/* Load WASM or compiled-WASM from the buffer. */
Res = WasmEdge_LoaderParseFromBuffer(LoadCxt, &ASTCxt, Buf, FileSize);
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Validator

The `Validator` context can validate the WASM module. Every WASM module should be validated before instantiation.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the loader
 * context.
 * Assume that the `ConfCxt` is the configure context.
 */
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
WasmEdge_Result Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
WasmEdge_ValidatorDelete(ValidCxt);
```

Executor

The `Executor` context is the executor for both WASM and compiled-WASM. This object should work base on the `Store` context. For the details of the `Store` context, please refer to the next chapter.

1. Instantiate and register an `AST module` as a named `Module` instance

   As the same of registering host modules or importing WASM modules in `VM` contexts, developers can instantiate and register an `AST module` contexts into the `Store` context as a named `Module` instance by the `Executor` APIs. After the registration, the result `Module` instance is exported with the given module name and can be linked when instantiating another module. For the details about the `Module` instances APIs, please refer to the Instances.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/*
 * Register the WASM module into the store with the export module name
 * "mod".
 */
Res =
    WasmEdge_ExecutorRegister(ExecCxt, &ModCxt, StoreCxt, ASTCxt, ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
WasmEdge_StringDelete(ModName);

/* ... */
```

```
/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

2. Register an existing `Module` instance and export the module name

   Besides instantiating and registering an `AST module` contexts, developers can register an existing `Module` instance into the store with exporting the module name (which is in the `Module` instance already). This case occurs when developers create a `Module` instance for the host functions and want to register it for linking. For the details about the construction of host functions in `Module` instances, please refer to the Host Functions.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create a module instance for host functions. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("host-module");
WasmEdge_ModuleInstanceContext *HostModCxt =
    WasmEdge_ModuleInstanceCreate(ModName);
WasmEdge_StringDelete(ModName);
/*
 * ...
 * Create and add the host functions, tables, memories, and globals into
the
 * module instance.
 */

/* Register the module instance into store with the exported module name.
*/
/* The export module name is in the module instance already. */
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, HostModCxt);
if (!WasmEdge_ResultOK(Res)) {
```

```
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

3. Instantiate an `AST module` to an anonymous `Module` instance

   WASM or compiled-WASM modules should be instantiated before the function invocation. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` context for linking.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the
loader
 * context and has passed the validation. Assume that the `ConfCxt` is the
 * configure context.
 */
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/*
 * Create the executor context. The configure and the statistics contexts
 * can be NULL.
 */
WasmEdge_ExecutorContext *ExecCxt =
    WasmEdge_ExecutorCreate(ConfCxt, StatCxt);
/*
 * Create the store context. The store context is the object to link the
 * modules for imports and exports.
 */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/* Instantiate the WASM module. */
WasmEdge_Result Res =
    WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed: %s\n",
WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

4. Invoke functions

   After registering or instantiating and get the result `Module` instance, developers can retrieve the exported `Function` instances from the `Module` instance for invocation. For the details about the `Module` instances APIs, please refer to the Instances. Please refer to the example above for the `Function` instance invocation with the `WasmEdge_ExecutorInvoke()` API.

AST Module

The `AST Module` context presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST Module` context.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that a WASM is loaded into an AST module context. */

/* Create the import type context buffers. */
const uint32_t BUF_LEN = 256;
const WasmEdge_ImportTypeContext *ImpTypes[BUF_LEN];
uint32_t ImportNum = WasmEdge_ASTModuleListImportsLength(ASTCxt);
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealImportNum =
    WasmEdge_ASTModuleListImports(ASTCxt, ImpTypes, BUF_LEN);
for (uint32_t I = 0; I < RealImportNum && I < BUF_LEN; I++) {
  /* Working with the import type `ImpTypes[I]` ... */
}

/* Create the export type context buffers. */
const WasmEdge_ExportTypeContext *ExpTypes[BUF_LEN];
uint32_t ExportNum = WasmEdge_ASTModuleListExportsLength(ASTCxt);
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealExportNum =
    WasmEdge_ASTModuleListExports(ASTCxt, ExpTypes, BUF_LEN);
for (uint32_t I = 0; I < RealExportNum && I < BUF_LEN; I++) {
  /* Working with the export type `ExpTypes[I]` ... */
}

WasmEdge_ASTModuleDelete(ASTCxt);
/*
 * After deletion of `ASTCxt`, all data queried from the `ASTCxt` should not be
 * accessed.
 */
```

Store

Store is the runtime structure for the representation of all global state that can be manipulated by WebAssembly programs. The `Store` context in WasmEdge is an object to provide the instance exporting and importing when instantiating WASM modules. Developers can retrieve the named modules from the `Store` context.

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/*
 * ...
 * Register a WASM module via the executor context.
 */

/* Try to list the registered WASM modules. */
uint32_t ModNum = WasmEdge_StoreListModuleLength(StoreCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String ModNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
will
 * be discarded.
 */
uint32_t RealModNum = WasmEdge_StoreListModule(StoreCxt, ModNames, BUF_LEN);
for (uint32_t I = 0; I < RealModNum && I < BUF_LEN; I++) {
  /* Working with the module name `ModNames[I]` ... */
  /* The module names should __NOT__ be destroyed. */
}

/* Find named module by name. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module");
const WasmEdge_ModuleInstanceContext *ModCxt =
    WasmEdge_StoreFindModule(StoreCxt, ModName);
/* If the module with name not found, the `ModCxt` will be NULL. */
WasmEdge_StringDelete(ModName);
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the `Module` instances from the `Store` contexts, and retrieve the other instances from the `Module` instances. A single instance can be allocated by its creation function. Developers can construct instances into an `Module` instance for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed by developers, EXCEPT they are added into an `Module` instance.

1. Module instance

   After instantiating or registering an `AST module` context, developers will get a `Module` instance as the result, and have the responsibility to destroy it when not in use. A `Module` instance can also be created for the host module. Please refer to the host function for the details. `Module` instance provides APIs to list and find the exported instances in the module.

```
/*
 * ...
 * Instantiate a WASM module via the executor context and get the `ModCxt`
 * as the output module instance.
 */

/* Try to list the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/*
 * If the list length is larger than the buffer length, the overflowed data
 * will be discarded.
 */
uint32_t RealFuncNum =
    WasmEdge_ModuleInstanceListFunction(ModCxt, FuncNames, BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  /* Working with the function name `FuncNames[I]` ... */
  /* The function names should __NOT__ be destroyed. */
}

/* Try to find the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FuncCxt =
    WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
/* `FuncCxt` will be `NULL` if the function not found. */
/*
 * The returned instance is owned by the module instance context and should
 * __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

2. Function instance

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` contexts for host functions and add them into an `Module` instance context for registering into a `VM` or a

`Store`. Developers can retrieve the `Function Type` from the `Function` contexts through the API. For the details of the `Host Function` guide, please refer to the next chapter.

```
/* Retrieve the function instance from the module instance context. */
WasmEdge_FunctionInstanceContext *FuncCxt = ...;
WasmEdge_FunctionTypeContext *FuncTypeCxt =
    WasmEdge_FunctionInstanceGetFunctionType(FuncCxt);
/*
 * The `FuncTypeCxt` is owned by the `FuncCxt` and should __NOT__ be
 * destroyed.
 */

/*
 * For the function instance creation, please refer to the `Host Function`
 * guide.
 */
```

3. Table instance

In WasmEdge, developers can create the `Table` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Table` contexts supply APIs to control the data in table instances.

```
WasmEdge_Limit TabLimit = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
/* Create the table type with limit and the `FuncRef` element type. */
WasmEdge_TableTypeContext *TabTypeCxt =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TabLimit);
/* Create the table instance with table type. */
WasmEdge_TableInstanceContext *HostTable =
    WasmEdge_TableInstanceCreate(TabTypeCxt);
/* Delete the table type. */
WasmEdge_TableTypeDelete(TabTypeCxt);
WasmEdge_Result Res;
WasmEdge_Value Data;

TabTypeCxt = WasmEdge_TableInstanceGetTableType(HostTable);
/*
 * The `TabTypeCxt` got from table instance is owned by the `HostTable` and
 * should __NOT__ be destroyed.
 */
enum WasmEdge_RefType RefType = WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `RefType` will be `WasmEdge_RefType_FuncRef`. */
Data = WasmEdge_ValueGenFuncRef(5);
Res = WasmEdge_TableInstanceSetData(HostTable, Data, 3);
/* Set the function index 5 to the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceSetData(HostTable, Data, 13);
 */
Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 3);
/* Get the FuncRef value of the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 13);
 */

uint32_t Size = WasmEdge_TableInstanceGetSize(HostTable);
/* `Size` will be 10. */
Res = WasmEdge_TableInstanceGrow(HostTable, 6);
/* Grow the table size of 6, the table size will be 16. */
```

```
/*
 * This will get an "out of bounds table access" error because
 * the size (16 + 6) will reach the table limit(20):
 *   Res = WasmEdge_TableInstanceGrow(HostTable, 6);
 */

WasmEdge_TableInstanceDelete(HostTable);
```

4. Memory instance

   In WasmEdge, developers can create the `Memory` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Memory` contexts supply APIs to control the data in memory instances.

```
WasmEdge_Limit MemLimit = {
    .HasMax = true, .Shared = false, .Min = 1, .Max = 5};
/* Create the memory type with limit. The memory page size is 64KiB. */
WasmEdge_MemoryTypeContext *MemTypeCxt =
    WasmEdge_MemoryTypeCreate(MemLimit);
/* Create the memory instance with memory type. */
WasmEdge_MemoryInstanceContext *HostMemory =
    WasmEdge_MemoryInstanceCreate(MemTypeCxt);
/* Delete the memory type. */
WasmEdge_MemoryTypeDelete(MemTypeCxt);
WasmEdge_Result Res;
uint8_t Buf[256];

Buf[0] = 0xAA;
Buf[1] = 0xBB;
Buf[2] = 0xCC;
Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0x1000, 3);
/* Set the data[0:2] to the memory[4096:4098]. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */
Buf[0] = 0;
Buf[1] = 0;
Buf[2] = 0;
Res = WasmEdge_MemoryInstanceGetData(HostMemory, Buf, 0x1000, 3);
/* Get the memory[4096:4098]. Buf[0:2] will be `{0xAA, 0xBB, 0xCC}`. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */

uint32_t PageSize = WasmEdge_MemoryInstanceGetPageSize(HostMemory);
/* `PageSize` will be 1. */
Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 2);
/* Grow the page size of 2, the page size of the memory instance will be 3.
 */
/*
```

```
  * This will get an "out of bounds memory access" error because
  * the page size (3 + 3) will reach the memory limit(5):
  *   Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 3);
  */

 WasmEdge_MemoryInstanceDelete(HostMemory);
```

5. Global instance

   In WasmEdge, developers can create the `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Global` contexts supply APIs to control the value in global instances.

```
WasmEdge_Value Val = WasmEdge_ValueGenI64(1000);
/* Create the global type with value type and mutation. */
WasmEdge_GlobalTypeContext *GlobTypeCxt = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_I64, WasmEdge_Mutability_Var);
/* Create the global instance with value and global type. */
WasmEdge_GlobalInstanceContext *HostGlobal =
    WasmEdge_GlobalInstanceCreate(GlobTypeCxt, Val);
/* Delete the global type. */
WasmEdge_GlobalTypeDelete(GlobTypeCxt);
WasmEdge_Result Res;

GlobTypeCxt = WasmEdge_GlobalInstanceGetGlobalType(HostGlobal);
/* The `GlobTypeCxt` got from global instance is owned by the `HostGlobal`
 * and should __NOT__ be destroyed. */
enum WasmEdge_ValType ValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `ValType` will be `WasmEdge_ValType_I64`. */
enum WasmEdge_Mutability ValMut =
    WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `ValMut` will be `WasmEdge_Mutability_Var`. */

WasmEdge_GlobalInstanceSetValue(HostGlobal, WasmEdge_ValueGenI64(888));
/*
 * Set the value u64(888) to the global.
 * This function will do nothing if the value type mismatched or
 * the global mutability is `WasmEdge_Mutability_Const`.
 */
WasmEdge_Value GlobVal = WasmEdge_GlobalInstanceGetValue(HostGlobal);
/* Get the value (888 now) of the global context. */

WasmEdge_GlobalInstanceDelete(HostGlobal);
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function`, `Memory`, `Table`, and `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`.

1. Host function allocation

Developers can define C functions with the following function signature as the host function body:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
    void *Data, const WasmEdge_CallingFrameContext *CallFrameCxt,
    const WasmEdge_Value *Params, WasmEdge_Value *Returns);
```

The example of an `add` host function to add 2 `i32` values:

```
WasmEdge_Result Add(void *, const WasmEdge_CallingFrameContext *,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /*
  * Params: {i32, i32}
  * Returns: {i32}
  * Developers should take care about the function type.
  */
  /* Retrieve the value 1. */
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  /* Retrieve the value 2. */
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  /* Output value 1 is Val1 + Val2. */
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Return the status of success. */
  return WasmEdge_Result_Success;
}
```

Then developers can create `Function` context with the host function body and the function type:

```
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I32};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
/* Create a function type: {i32, i32} -> {i32}. */
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
/*
 * Create a function context with the function type and host function body.
 * The `Cost` parameter can be 0 if developers do not need the cost
 * measuring.
 */
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostType);

/*
 * If the function instance is __NOT__ added into a module instance
context,
 * it should be deleted.
 */
WasmEdge_FunctionInstanceDelete(HostFunc);
```

2. Calling frame context

   The `WasmEdge_CallingFrameContext` is the context to provide developers to access the module instance of the frame on the top of the calling stack. According to the WASM spec, a frame with the module instance is pushed into the stack when invoking a function. Therefore, the host functions can access the module instance of the top frame to retrieve the memory instances to read/write data.

```
WasmEdge_Result LoadOffset(void *Data,
                           const WasmEdge_CallingFrameContext
*CallFrameCxt,
                           const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {i32} -> {} */
  uint32_t Offset = (uint32_t)WasmEdge_ValueGetI32(In[0]);
  uint32_t Num = 0;

  /*
   * Get the 0-th memory instance of the module instance of the top frame
on
   * stack.
   */
  WasmEdge_MemoryInstanceContext *MemCxt =
      WasmEdge_CallingFrameGetMemoryInstance(CallFrameCxt, 0);

  WasmEdge_Result Res =
      WasmEdge_MemoryInstanceGetData(MemCxt, (uint8_t *)(&Num), Offset, 4);
  if (WasmEdge_ResultOK(Res)) {
    printf("u32 at memory[%lu]: %lu\n", Offset, Num);
  } else {
    return Res;
  }
  return WasmEdge_Result_Success;
}
```

Besides using the `WasmEdge_CallingFrameGetMemoryInstance()` API to get the memory instance by index in the module instance, developers can use the `WasmEdge_CallingFrameGetModuleInstance()` to get the module instance directly. Therefore, developers can retrieve the exported contexts by the `WasmEdge_ModuleInstanceContext` APIs. And also, developers can use the `WasmEdge_CallingFrameGetExecutor()` API to get the currently used executor context.

3. User-defined error code of the host functions

   In host functions, WasmEdge provides `WasmEdge_Result_Success` to return success, `WasmEdge_Result_Terminate` to terminate the WASM execution, and `WasmEdge_Result_Fail` to return fail. WasmEdge also provides the usage of returning the user-specified codes. Developers can use the `WasmEdge_ResultGen()` API to generate the `WasmEdge_Result` with error code, and use the `WasmEdge_ResultGetCode()` API to get the error code.

Notice: The error code only supports 24-bit integer (0 ~ 16777216 in `uint32_t`). The values larger than 24-bit will be truncated.

Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32)))
  (import "extern" "trap" (func $f-trap (type $t0)))
  (func (export "trap") (param i32)
    local.get 0
    call $f-trap)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Trap(void *Data,
                     const WasmEdge_CallingFrameContext *CallFrameCxt,
                     const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val = WasmEdge_ValueGetI32(In[0]);
  /* Return the error code from the param[0]. */
  return WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, Val);
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x05, 0x01,
                    /* function type {i32} -> {} */
                    0x60, 0x01, 0x7F, 0x00,
                    /* Import section */
                    0x02, 0x0F, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "trap" */
                    0x04, 0x74, 0x72, 0x61, 0x70,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x08, 0x01,
                    /* export name: "trap" */
                    0x04, 0x74, 0x72, 0x61, 0x70,
                    /* export desc: func 0 */
                    0x00, 0x01,
                    /* Code section */
```

```
                        0x0A, 0x08, 0x01,
                        /* code body */
                        0x06, 0x00, 0x20, 0x00, 0x10, 0x00, 0x0B};

    /* Create the module instance. */
    WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
    WasmEdge_ModuleInstanceContext *HostModCxt =
        WasmEdge_ModuleInstanceCreate(ExportName);
    enum WasmEdge_ValType ParamList[1] = {WasmEdge_ValType_I32};
    WasmEdge_FunctionTypeContext *HostFType =
        WasmEdge_FunctionTypeCreate(ParamList, 1, NULL, 0);
    WasmEdge_FunctionInstanceContext *HostFunc =
        WasmEdge_FunctionInstanceCreate(HostFType, Trap, NULL, 0);
    WasmEdge_FunctionTypeDelete(HostFType);
    WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("trap");
    WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
    WasmEdge_StringDelete(HostFuncName);

    WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

    /* The parameters and returns arrays. */
    WasmEdge_Value Params[1] = {WasmEdge_ValueGenI32(5566)};
    /* Function name. */
    WasmEdge_String FuncName = WasmEdge_StringCreateByCString("trap");
    /* Run the WASM function from file. */
    WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
        VMCxt, WASM, sizeof(WASM), FuncName, Params, 1, NULL, 0);

    /* Get the result code and print. */
    printf("Get the error code: %u\n", WasmEdge_ResultGetCode(Res));

    /* Resources deallocations. */
    WasmEdge_VMDelete(VMCxt);
    WasmEdge_StringDelete(FuncName);
    WasmEdge_ModuleInstanceDelete(HostModCxt);
    return 0;
}
```

Then you can compile and run: (giving the expected error code `5566`)

```
$ gcc test.c -lwasmedge
$ ./a.out
[2022-08-26 15:06:40.384] [error] user defined failed: user defined error
code, Code: 0x15be
[2022-08-26 15:06:40.384] [error]     When executing function name: "trap"
Get the error code: 5566
```

4. Construct a module instance with host instances

   Besides creating a `Module` instance by registering or instantiating a WASM module, developers can create a `Module` instance with a module name and add the `Function`, `Memory`, `Table`, and `Global` instances into it with their exporting names.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create a module instance. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ModuleInstanceContext *HostModCxt =
    WasmEdge_ModuleInstanceCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the module instance. */
enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                      WasmEdge_ValType_I32};
enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ModuleInstanceAddFunction(HostModCxt, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/* Create and add a table instance into the import object. */
WasmEdge_Limit TableLimit = {
    .HasMax = true, .Shared = false, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *HostTType =
    WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TableLimit);
WasmEdge_TableInstanceContext *HostTable =
```

```
    WasmEdge_TableInstanceCreate(HostTType);
WasmEdge_TableTypeDelete(HostTType);
WasmEdge_String TableName = WasmEdge_StringCreateByCString("table");
WasmEdge_ModuleInstanceAddTable(HostModCxt, TableName, HostTable);
WasmEdge_StringDelete(TableName);

/* Create and add a memory instance into the import object. */
WasmEdge_Limit MemoryLimit = {
    .HasMax = true, .Shared = false, .Min = 1, .Max = 2};
WasmEdge_MemoryTypeContext *HostMType =
    WasmEdge_MemoryTypeCreate(MemoryLimit);
WasmEdge_MemoryInstanceContext *HostMemory =
    WasmEdge_MemoryInstanceCreate(HostMType);
WasmEdge_MemoryTypeDelete(HostMType);
WasmEdge_String MemoryName = WasmEdge_StringCreateByCString("memory");
WasmEdge_ModuleInstanceAddMemory(HostModCxt, MemoryName, HostMemory);
WasmEdge_StringDelete(MemoryName);

/* Create and add a global instance into the module instance. */
WasmEdge_GlobalTypeContext *HostGType = WasmEdge_GlobalTypeCreate(
    WasmEdge_ValType_I32, WasmEdge_Mutability_Var);
WasmEdge_GlobalInstanceContext *HostGlobal =
    WasmEdge_GlobalInstanceCreate(HostGType, WasmEdge_ValueGenI32(666));
WasmEdge_GlobalTypeDelete(HostGType);
WasmEdge_String GlobalName = WasmEdge_StringCreateByCString("global");
WasmEdge_ModuleInstanceAddGlobal(HostModCxt, GlobalName, HostGlobal);
WasmEdge_StringDelete(GlobalName);

/*
 * The module instance should be deleted.
 * Developers should __NOT__ destroy the instances added into the module
 * instance contexts.
 */
WasmEdge_ModuleInstanceDelete(HostModCxt);
```

5. Specified module instance

`WasmEdge_ModuleInstanceCreateWASI()` API can create and initialize the `WASI` module instance.

`WasmEdge_ModuleInstanceCreateWasiNN()` API can create and initialize the

`wasi_ephemeral_nn` module instance for `WASI-NN` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoCommon()` API can create and initialize the `wasi_ephemeral_crypto_common` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoAsymmetricCommon()` API can create and initialize the `wasi_ephemeral_crypto_asymmetric_common` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoKx()` API can create and initialize the `wasi_ephemeral_crypto_kx` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoSignatures()` API can create and initialize the `wasi_ephemeral_crypto_signatures` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasiCryptoSymmetric()` API can create and initialize the `wasi_ephemeral_crypto_symmetric` module instance for `WASI-Crypto` plugin.

`WasmEdge_ModuleInstanceCreateWasmEdgeProcess()` API can create and initialize the `wasmedge_process` module instance for `wasmedge_process` plugin.

Developers can create these module instance contexts and register them into the `Store` or `VM` contexts rather than adjust the settings in the `Configure` contexts.

> Note: For the `WASI-NN` plugin, please check that the dependencies and prerequests are satisfied. Note: For the `WASI-Crypto` plugin, please check that the dependencies and prerequests are satisfied. And the 5 modules are recommended to all be created and registered together.

```
WasmEdge_ModuleInstanceContext *WasiModCxt =
    WasmEdge_ModuleInstanceCreateWASI(/* ... ignored */);
WasmEdge_ModuleInstanceContext *ProcModCxt =
    WasmEdge_ModuleInstanceCreateWasmEdgeProcess(/* ... ignored */);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
/* Register the WASI and WasmEdge_Process into the VM context. */
WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModCxt);
WasmEdge_VMRegisterModuleFromImport(VMCxt, ProcModCxt);
/* Get the WASI exit code. */
uint32_t ExitCode = WasmEdge_ModuleInstanceWASIGetExitCode(WasiModCxt);
/*
 * The `ExitCode` will be EXIT_SUCCESS if the execution has no error.
 * Otherwise, it will return with the related exit code.
 */
WasmEdge_VMDelete(VMCxt);
/* The module instances should be deleted. */
WasmEdge_ModuleInstanceDelete(WasiModCxt);
WasmEdge_ModuleInstanceDelete(ProcModCxt);
```

6. Example

Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x07, 0x01,
                    /* function type {i32, i32} -> {i32} */
                    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
                    /* Import section */
                    0x02, 0x13, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "func-add" */
                    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x0A, 0x01,
                    /* export name: "addTwo" */
                    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
                    /* export desc: func 0 */
```

```
                        0x00, 0x01,
                        /* Code section */
                        0x0A, 0x0A, 0x01,
                        /* code body */
                        0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B};

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
      WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                        WasmEdge_ValType_I32};
  enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
  WasmEdge_FunctionTypeContext *HostFType =
      WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
      WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = {WasmEdge_ValueGenI32(1234),
                              WasmEdge_ValueGenI32(5678)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
      VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
```

```
  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
```

7. Host Data Example

Developers can set a external data object to the `Function` context, and access to the object in the function body. Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

And the `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data,
                    const WasmEdge_CallingFrameContext *CallFrameCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Also set the result to the data. */
  int32_t *DataPtr = (int32_t *)Data;
  *DataPtr = Val1 + Val2;
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {/* WASM header */
                    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
                    /* Type section */
                    0x01, 0x07, 0x01,
                    /* function type {i32, i32} -> {i32} */
                    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
                    /* Import section */
                    0x02, 0x13, 0x01,
                    /* module name: "extern" */
                    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
                    /* extern name: "func-add" */
                    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
                    /* import desc: func 0 */
                    0x00, 0x00,
                    /* Function section */
                    0x03, 0x02, 0x01, 0x00,
                    /* Export section */
                    0x07, 0x0A, 0x01,
```

```
                        /* export name: "addTwo" */
                        0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
                        /* export desc: func 0 */
                        0x00, 0x01,
                        /* Code section */
                        0x0A, 0x0A, 0x01,
                        /* code body */
                        0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B};

  /* The external data object: an integer. */
  int32_t Data;

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
      WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = {WasmEdge_ValType_I32,
                                        WasmEdge_ValType_I32};
  enum WasmEdge_ValType ReturnList[1] = {WasmEdge_ValType_I32};
  WasmEdge_FunctionTypeContext *HostFType =
      WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
      WasmEdge_FunctionInstanceCreate(HostFType, Add, &Data, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = {WasmEdge_ValueGenI32(1234),
                              WasmEdge_ValueGenI32(5678)};
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
      VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);
```

```
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  printf("Data value: %d\n", Data);

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options.

WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* ... Adjust settings in the configure context. */
  /* Result. */
  WasmEdge_Result Res;

  /* Create the compiler context. The configure context can be NULL. */
  WasmEdge_CompilerContext *CompilerCxt = WasmEdge_CompilerCreate(ConfCxt);
  /* Compile the WASM file with input and output paths. */
  Res = WasmEdge_CompilerCompile(CompilerCxt, "fibonacci.wasm",
                                 "fibonacci-aot.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Compilation failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }

  WasmEdge_CompilerDelete(CompilerCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  return 0;
}
```

Then you can compile and run (the output file is "fibonacci-aot.wasm"):

```
$ gcc test.c -lwasmedge
$ ./a.out
[2021-07-02 11:08:08.651] [info] compile start
[2021-07-02 11:08:08.653] [info] verify start
[2021-07-02 11:08:08.653] [info] optimize start
[2021-07-02 11:08:08.670] [info] codegen start
[2021-07-02 11:08:08.706] [info] compile done
```

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
/// AOT compiler optimization level enumeration.
enum WasmEdge_CompilerOptimizationLevel {
  /// Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  /// Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  /// Optimize for fast execution as much as possible without triggering
  /// significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  /// Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  /// Optimize for small code size as much as possible without triggering
  /// significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  /// Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

/// AOT compiler output binary format enumeration.
enum WasmEdge_CompilerOutputFormat {
  /// Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  /// WebAssembly with AOT compiled codes in custom sections.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

Please refer to the AOT compiler options configuration for details.

WasmEdge 0.10.1 C API Documentation

WasmEdge C API denotes an interface to access the WasmEdge runtime at version `0.10.1`. The following are the guides to working with the C APIs of WasmEdge.

Developers can refer to here to upgrade to 0.11.0.

Table of Contents

WasmEdge Installation

Download And Install

The easiest way to install WasmEdge is to run the following command. Your system should have `git` and `wget` as prerequisites.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.10.1
```

For more details, please refer to the Installation Guide for the WasmEdge installation.

Compile Sources

After the installation of WasmEdge, the following guide can help you to test for the availability of the WasmEdge C API.

1. Prepare the test C file (and assumed saved as `test.c`):

    ```
    #include <wasmedge/wasmedge.h>
    #include <stdio.h>
    int main() {
      printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
      return 0;
    }
    ```

2. Compile the file with `gcc` or `clang`.

    ```
    gcc test.c -lwasmedge_c
    ```

3. Run and get the expected output.

```
$ ./a.out
WasmEdge version: 0.10.1
```

WasmEdge Basics

In this part, we will introduce the utilities and concepts of WasmEdge shared library.

Version

The `Version` related APIs provide developers to check for the WasmEdge shared library version.

```
#include <wasmedge/wasmedge.h>
printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
printf("WasmEdge version major: %u\n", WasmEdge_VersionGetMajor());
printf("WasmEdge version minor: %u\n", WasmEdge_VersionGetMinor());
printf("WasmEdge version patch: %u\n", WasmEdge_VersionGetPatch());
```

Logging Settings

The `WasmEdge_LogSetErrorLevel()` and `WasmEdge_LogSetDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Value Types

In WasmEdge, developers should convert the values to `WasmEdge_Value` objects through APIs for matching to the WASM value types.

1. Number types: `i32`, `i64`, `f32`, `f64`, and `v128` for the `SIMD` proposal

```
WasmEdge_Value Val;
Val = WasmEdge_ValueGenI32(123456);
printf("%d\n", WasmEdge_ValueGetI32(Val));
/* Will print "123456" */
Val = WasmEdge_ValueGenI64(1234567890123LL);
printf("%ld\n", WasmEdge_ValueGetI64(Val));
/* Will print "1234567890123" */
Val = WasmEdge_ValueGenF32(123.456f);
printf("%f\n", WasmEdge_ValueGetF32(Val));
/* Will print "123.456001" */
Val = WasmEdge_ValueGenF64(123456.123456789);
printf("%.10f\n", WasmEdge_ValueGetF64(Val));
/* Will print "123456.1234567890" */
```

2. Reference types: `funcref` and `externref` for the `Reference-Types` proposal

```
WasmEdge_Value Val;
void *Ptr;
bool IsNull;
uint32_t Num = 10;
/* Generate a externref to NULL. */
Val = WasmEdge_ValueGenNullRef(WasmEdge_RefType_ExternRef);
IsNull = WasmEdge_ValueIsNullRef(Val);
/* The `IsNull` will be `TRUE`. */
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `NULL`. */

/* Get the function instance by creation or from module instance. */
const WasmEdge_FunctionInstanceContext *FuncCxt = ...;
/* Generate a funcref with the given function instance context. */
Val = WasmEdge_ValueGenFuncRef(FuncCxt);
const WasmEdge_FunctionInstanceContext *GotFuncCxt =
WasmEdge_ValueGetFuncRef(Val);
/* The `GotFuncCxt` will be the same as `FuncCxt`. */

/* Generate a externref to `Num`. */
Val = WasmEdge_ValueGenExternRef(&Num);
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `&Num`. */
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "10" */
Num += 55;
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "65" */
```

Strings

The `WasmEdge_String` object is for the instance names when invoking a WASM function or finding the contexts of instances.

1. Create a `WasmEdge_String` from a C string (`const char *` with NULL termination) or a buffer with length.

   The content of the C string or buffer will be copied into the `WasmEdge_String` object.

```
char Buf[4] = {50, 55, 60, 65};
WasmEdge_String Str1 = WasmEdge_StringCreateByCString("test");
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
/* The objects should be deleted by `WasmEdge_StringDelete()`. */
WasmEdge_StringDelete(Str1);
WasmEdge_StringDelete(Str2);
```

2. Wrap a `WasmEdge_String` to a buffer with length.

   The content will not be copied, and the caller should guarantee the life cycle of the input buffer.

```
const char CStr[] = "test";
WasmEdge_String Str = WasmEdge_StringWrap(CStr, 4);
/* The object should __NOT__ be deleted by `WasmEdge_StringDelete()`. */
```

3. String comparison

```
const char CStr[] = "abcd";
char Buf[4] = {0x61, 0x62, 0x63, 0x64};
WasmEdge_String Str1 = WasmEdge_StringWrap(CStr, 4);
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
bool IsEq = WasmEdge_StringIsEqual(Str1, Str2);
/* The `IsEq` will be `TRUE`. */
WasmEdge_StringDelete(Str2);
```

4. Convert to C string

```
char Buf[256];
WasmEdge_String Str =
WasmEdge_StringCreateByCString("test_wasmedge_string");
uint32_t StrLength = WasmEdge_StringCopy(Str, Buf, sizeof(Buf));
/* StrLength will be 20 */
printf("String: %s\n", Buf);
/* Will print "test_wasmedge_string". */
```

Results

The `WasmEdge_Result` object specifies the execution status. APIs about WASM execution will

return the `WasmEdge_Result` to denote the status.

```
WasmEdge_Result Res = WasmEdge_Result_Success;
bool IsSucceeded = WasmEdge_ResultOK(Res);
/* The `IsSucceeded` will be `TRUE`. */
uint32_t Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 0. */
const char *Msg = WasmEdge_ResultGetMessage(Res);
/* The `Msg` will be "success". */
```

Contexts

The objects, such as `VM`, `Store`, and `Function`, are composed of `Context`s. All of the contexts can be created by calling the corresponding creation APIs and should be destroyed by calling the corresponding deletion APIs. Developers have responsibilities to manage the contexts for memory management.

```
/* Create the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Delete the configure context. */
WasmEdge_ConfigureDelete(ConfCxt);
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `WasmEdge_Limit` struct is defined in the header:

```
/// Struct of WASM limit.
typedef struct WasmEdge_Limit {
  /// Boolean to describe has max value or not.
  bool HasMax;
  /// Boolean to describe is shared memory or not.
  bool Shared;
  /// Minimum value.
  uint32_t Min;
  /// Maximum value. Will be ignored if the `HasMax` is false.
  uint32_t Max;
} WasmEdge_Limit;
```

Developers can initialize the struct by assigning it's value, and the `Max` value is needed to be larger or equal to the `Min` value. The API `WasmEdge_LimitIsEqual()` is provided to compare with 2 `WasmEdge_Limit` structs.

2. Function type context

   The `Function Type` context is used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `Function Type` context APIs to get the parameter or return value types information.

```
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I64 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_FuncRef };
WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);

enum WasmEdge_ValType Buf[16];
uint32_t ParamLen = WasmEdge_FunctionTypeGetParametersLength(FuncTypeCxt);
/* `ParamLen` will be 2. */
uint32_t GotParamLen = WasmEdge_FunctionTypeGetParameters(FuncTypeCxt, Buf,
16);
/* `GotParamLen` will be 2, and `Buf[0]` and `Buf[1]` will be the same as
`ParamList`. */
uint32_t ReturnLen = WasmEdge_FunctionTypeGetReturnsLength(FuncTypeCxt);
/* `ReturnLen` will be 1. */
uint32_t GotReturnLen = WasmEdge_FunctionTypeGetReturns(FuncTypeCxt, Buf,
16);
/* `GotReturnLen` will be 1, and `Buf[0]` will be the same as `ReturnList`.
*/

WasmEdge_FunctionTypeDelete(FuncTypeCxt);
```

3. Table type context

   The `Table Type` context is used for `Table` instance creation or getting information from `Table` instances.

```
WasmEdge_Limit TabLim = {.HasMax = true, .Shared = false, .Min = 10, .Max =
20};
WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_TableTypeCreate(WasmEdge_RefType_ExternRef, TabLim);

enum WasmEdge_RefType GotRefType =
WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `GotRefType` will be WasmEdge_RefType_ExternRef. */
WasmEdge_Limit GotTabLim = WasmEdge_TableTypeGetLimit(TabTypeCxt);
/* `GotTabLim` will be the same value as `TabLim`. */

WasmEdge_TableTypeDelete(TabTypeCxt);
```

4. Memory type context

   The `Memory Type` context is used for `Memory` instance creation or getting information from `Memory` instances.

   ```
   WasmEdge_Limit MemLim = {.HasMax = true, .Shared = false, .Min = 10, .Max = 20};
   WasmEdge_MemoryTypeContext *MemTypeCxt = WasmEdge_MemoryTypeCreate(MemLim);

   WasmEdge_Limit GotMemLim = WasmEdge_MemoryTypeGetLimit(MemTypeCxt);
   /* `GotMemLim` will be the same value as `MemLim`. */

   WasmEdge_MemoryTypeDelete(MemTypeCxt)
   ```

5. Global type context

   The `Global Type` context is used for `Global` instance creation or getting information from `Global` instances.

   ```
   WasmEdge_GlobalTypeContext *GlobTypeCxt =
   WasmEdge_GlobalTypeCreate(WasmEdge_ValType_F64, WasmEdge_Mutability_Var);

   WasmEdge_ValType GotValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
   /* `GotValType` will be WasmEdge_ValType_F64. */
   WasmEdge_Mutability GotValMut =
   WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
   /* `GotValMut` will be WasmEdge_Mutability_Var. */

   WasmEdge_GlobalTypeDelete(GlobTypeCxt);
   ```

6. Import type context

   The `Import Type` context is used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `Import Type` context. The details about querying `Import Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
result of loading a WASM file. */
const WasmEdge_ImportTypeContext *ImpType = ...;
/* Assume that `ImpType` is queried from the `ASTCxt` for the import. */

enum WasmEdge_ExternalType ExtType =
WasmEdge_ImportTypeGetExternalType(ImpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
`WasmEdge_ExternalType_Table`,
 * `WasmEdge_ExternalType_Memory`, or `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ModName = WasmEdge_ImportTypeGetModuleName(ImpType);
WasmEdge_String ExtName = WasmEdge_ImportTypeGetExternalName(ImpType);
/* The `ModName` and `ExtName` should not be destroyed and the string
buffers are binded into the `ASTCxt`. */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_ImportTypeGetFunctionType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
`FuncTypeCxt` will be NULL. */
const WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_ImportTypeGetTableType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
will be NULL. */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_ImportTypeGetMemoryType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
will be NULL. */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_ImportTypeGetGlobalType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt` will be NULL. */
```

7. Export type context

   The `Export Type` context is used for getting the exports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`) and external name from an `Export Type` context. The details about querying `Export Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
result of loading a WASM file. */
const WasmEdge_ExportTypeContext *ExpType = ...;
/* Assume that `ExpType` is queried from the `ASTCxt` for the export. */

enum WasmEdge_ExternalType ExtType =
WasmEdge_ExportTypeGetExternalType(ExpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
`WasmEdge_ExternalType_Table`,
 * `WasmEdge_ExternalType_Memory`, or `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ExtName = WasmEdge_ExportTypeGetExternalName(ExpType);
/* The `ExtName` should not be destroyed and the string buffer is binded
into the `ASTCxt`. */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_ExportTypeGetFunctionType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
`FuncTypeCxt` will be NULL. */
const WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_ExportTypeGetTableType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
will be NULL. */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_ExportTypeGetMemoryType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
will be NULL. */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_ExportTypeGetGlobalType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt` will be NULL. */
```

Async

After calling the asynchronous execution APIs, developers will get the `WasmEdge_Async` object. Developers own the object and should call the `WasmEdge_AsyncDelete()` API to destroy it.

1. Wait for the asynchronous execution

   Developers can wait the execution until finished:

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution. */
   WasmEdge_AsyncWait(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   Or developers can wait for a time limit. If the time limit exceeded, developers can choose to cancel the execution. For the interruptible execution in AOT mode, developers should set `TRUE` through the `WasmEdge_ConfigureCompilerSetInterruptible()` API into the configure context for the AOT compiler.

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution for 1 second. */
   bool IsEnd = WasmEdge_AsyncWaitFor(Async, 1000);
   if (IsEnd) {
     /* The execution finished. Developers can get the result. */
     WasmEdge_Result Res = WasmEdge_AsyncGet(/* ... Ignored */);
   } else {
     /* The time limit exceeded. Developers can keep waiting or cancel the
   execution. */
     WasmEdge_AsyncCancel(Async);
     WasmEdge_Result Res = WasmEdge_AsyncGet(Async, 0, NULL);
     /* The result error code will be `WasmEdge_ErrCode_Interrupted`. */
   }
   WasmEdge_AsyncDelete(Async);
   ```

2. Get the execution result of the asynchronous execution

   Developers can use the `WasmEdge_AsyncGetReturnsLength()` API to get the return value list length. This function will block and wait for the execution. If the execution has finished, this function will return the length immediately. If the execution failed, this function will return `0`. This function can help the developers to create the buffer to get the return values. If developers have already known the buffer length, they can skip this function and use the `WasmEdge_AsyncGet()` API to get the result.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return value list
length. */
uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
WasmEdge_AsyncDelete(Async);
```

The `WasmEdge_AsyncGet()` API will block and wait for the execution. If the execution has finished, this function will fill the return values into the buffer and return the execution result immediately.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return values. */
const uint32_t BUF_LEN = 256;
WasmEdge_Value Buf[BUF_LEN];
WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Buf, BUF_LEN);
WasmEdge_AsyncDelete(Async);
```

Configurations

The configuration context, `WasmEdge_ConfigureContext`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` context to create other runtime contexts.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` context.

```
enum WasmEdge_Proposal {
  WasmEdge_Proposal_ImportExportMutGlobals = 0,
  WasmEdge_Proposal_NonTrapFloatToIntConversions,
  WasmEdge_Proposal_SignExtensionOperators,
  WasmEdge_Proposal_MultiValue,
  WasmEdge_Proposal_BulkMemoryOperations,
  WasmEdge_Proposal_ReferenceTypes,
  WasmEdge_Proposal_SIMD,
  WasmEdge_Proposal_TailCall,
  WasmEdge_Proposal_MultiMemories,
  WasmEdge_Proposal_Annotations,
  WasmEdge_Proposal_Memory64,
  WasmEdge_Proposal_ExceptionHandling,
  WasmEdge_Proposal_ExtendedConst,
  WasmEdge_Proposal_Threads,
  WasmEdge_Proposal_FunctionReferences
};
```

Developers can add or remove the proposals into the `Configure` context.

```
/*
 * By default, the following proposals have turned on initially:
 * * Import/Export of mutable globals
 * * Non-trapping float-to-int conversions
 * * Sign-extension operators
 * * Multi-value returns
 * * Bulk memory operations
 * * Reference types
 * * Fixed-width SIMD
 *
 * For the current WasmEdge version, the following proposals are supported
 * (turned of by default) additionally:
 * * Tail-call
 * * Multiple memories
 * * Extended-const
 * * Threads
 */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddProposal(ConfCxt, WasmEdge_Proposal_MultiMemories);
WasmEdge_ConfigureRemoveProposal(ConfCxt,
WasmEdge_Proposal_ReferenceTypes);
bool IsBulkMem = WasmEdge_ConfigureHasProposal(ConfCxt,
WasmEdge_Proposal_BulkMemoryOperations);
/* The `IsBulkMem` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

2. Host registrations

This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` contexts.

```
enum WasmEdge_HostRegistration {
  WasmEdge_HostRegistration_Wasi = 0,
  WasmEdge_HostRegistration_WasmEdge_Process
};
```

The details will be introduced in the preregistrations of VM context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsHostWasi = WasmEdge_ConfigureHasHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `FALSE`. */
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
IsHostWasi = WasmEdge_ConfigureHasHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
uint32_t PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* By default, the maximum memory page size is 65536. */
WasmEdge_ConfigureSetMaxMemoryPage(ConfCxt, 1024);
/* Limit the memory size of each memory instance with not larger than 1024
pages (64 MiB). */
PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* The `PageSize` will be 1024. */
WasmEdge_ConfigureDelete(ConfCxt);
```

4. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
enum WasmEdge_CompilerOptimizationLevel {
  // Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  // Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  // Optimize for fast execution as much as possible without triggering
  // significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  // Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  // Optimize for small code size as much as possible without triggering
  // significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  // Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

enum WasmEdge_CompilerOutputFormat {
  // Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  // WebAssembly with AOT compiled codes in custom section.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

These configurations are only effective in `Compiler` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the optimization level is O3. */
WasmEdge_ConfigureCompilerSetOptimizationLevel(ConfCxt,
WasmEdge_CompilerOptimizationLevel_O2);
/* By default, the output format is universal WASM. */
WasmEdge_ConfigureCompilerSetOutputFormat(ConfCxt,
WasmEdge_CompilerOutputFormat_Native);
/* By default, the dump IR is `FALSE`. */
WasmEdge_ConfigureCompilerSetDumpIR(ConfCxt, TRUE);
/* By default, the generic binary is `FALSE`. */
WasmEdge_ConfigureCompilerSetGenericBinary(ConfCxt, TRUE);
/* By default, the interruptible is `FALSE`.
/* Set this option to `TRUE` to support the interruptible execution in AOT
mode. */
WasmEdge_ConfigureCompilerSetInterruptible(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

5. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the instruction counting is `FALSE` when running a compiled-
WASM or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetInstructionCounting(ConfCxt, TRUE);
/* By default, the cost measurement is `FALSE` when running a compiled-WASM
or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetCostMeasuring(ConfCxt, TRUE);
/* By default, the time measurement is `FALSE` when running a compiled-WASM
or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetTimeMeasuring(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

Statistics

The statistics context, `WasmEdge_StatisticsContext`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` context from the `VM` context, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
   /*
    * ...
    * After running the WASM functions with the `Statistics` context
    */
   uint32_t Count = WasmEdge_StatisticsGetInstrCount(StatCxt);
   double IPS = WasmEdge_StatisticsGetInstrPerSecond(StatCxt);
   WasmEdge_StatisticsDelete(StatCxt);
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` context. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
uint64_t CostTable[16] = {
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0
};
/* Developers can set the costs of each instruction. The value not covered
will be 0. */
WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
WasmEdge_StatisticsSetCostLimit(StatCxt, 5000000);
/*
 * ...
 * After running the WASM functions with the `Statistics` context
 */
uint64_t Cost = WasmEdge_StatisticsGetTotalCost(StatCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

Tools Driver

Besides executing the `wasmedge` and `wasmedgec` CLI tools, developers can trigger the WasmEdge CLI tools by WasmEdge C API. The API arguments are the same as the command line arguments of the CLI tools.

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge AOT compiler. */
  return WasmEdge_Driver_Compiler(argc, argv);
}
```

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main(int argc, const char *argv[]) {
  /* Run the WasmEdge runtime tool. */
  return WasmEdge_Driver_Tool(argc, argv);
}
```

WasmEdge VM

In this partition, we will introduce the functions of `WasmEdge_VMContext` object and show examples of executing WASM functions.

WASM Execution Example With VM Context

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s (get_local $n)(i32.const 2))
      (return (i32.const 1))
    )
    (return
      (i32.add
        (call $fib (i32.sub (get_local $n)(i32.const 2)))
        (call $fib (i32.sub (get_local $n)(i32.const 1)))
      )
    )
  )
)
```

1. Run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(5) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(VMCxt, "fibonacci.wasm",
FuncName, Params, 1, Returns, 1);
  /*
   * Developers can run the WASM binary from buffer with the
`WasmEdge_VMRunWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMRunWasmFromASTModule()` API.
   */

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 5th Fibonacci number is 8 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 8
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need the WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(10) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
`WasmEdge_VMLoadWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
```

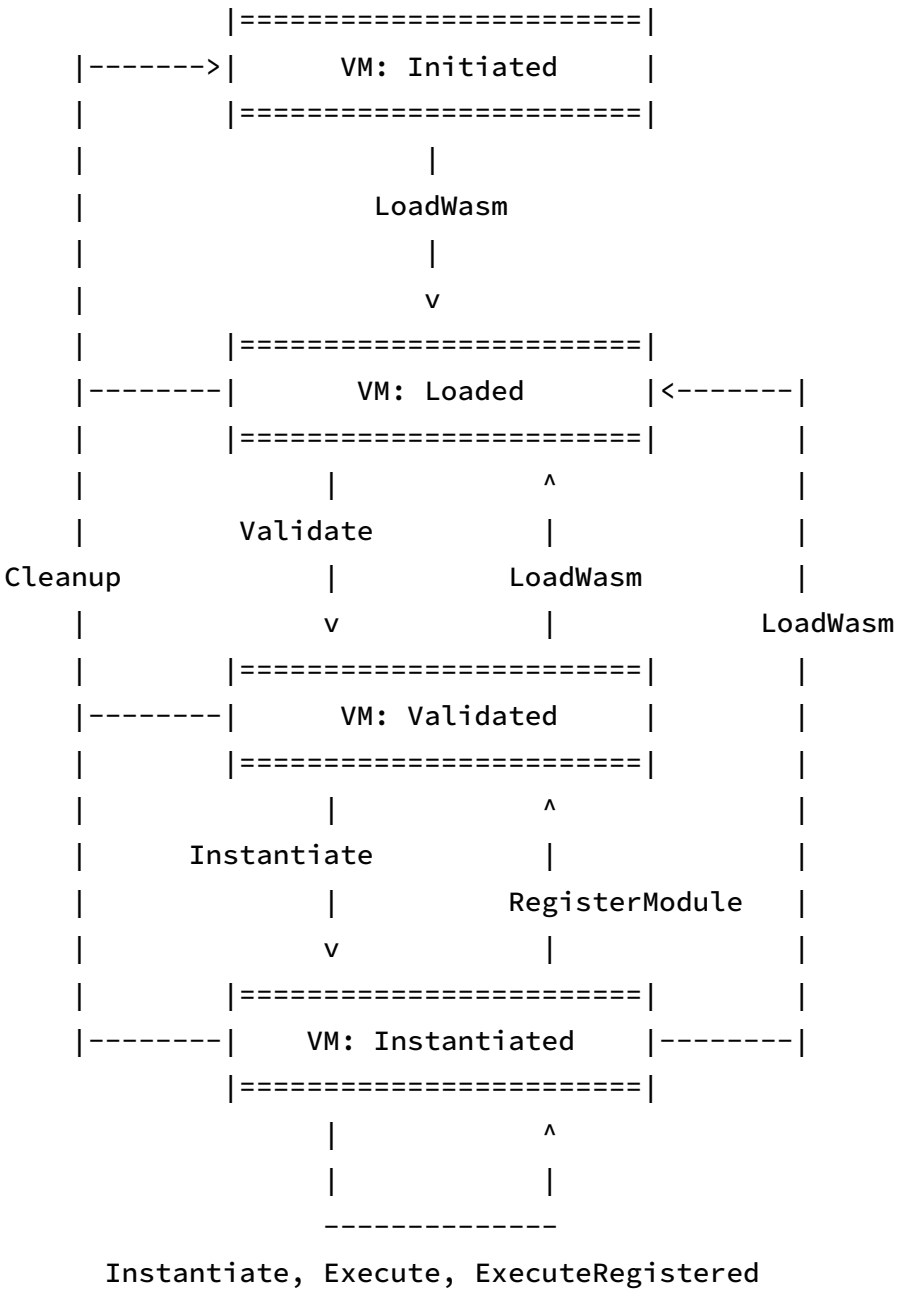
```
  /*
   * Developers can load, validate, and instantiate another WASM module to
replace the
   * instantiated one. In this case, the old module will be cleared, but
the registered
   * modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Execute WASM functions. You can execute functions repeatedly
after instantiation. */
  Res = WasmEdge_VMExecute(VMCxt, FuncName, Params, 1, Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 10th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 89
```

The following graph explains the status of the `VM` context.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or module instances in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation API accepts the `Configure` context and the `Store` context. If developers only need the default settings, just pass `NULL` to the creation API. The details of the `Store` context will be introduced in Store.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, StoreCxt);
/* The caller should guarantee the life cycle if the store context. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_VMGetStatisticsContext(VMCxt);
/* The VM context already contains the statistics context and can be retrieved
by this API. */
/*
 * Note that the retrieved store and statistics contexts from the VM contexts
by VM APIs
 * should __NOT__ be destroyed and owned by the VM contexts.
 */
WasmEdge_VMDelete(VMCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` context.

   ```
   WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
   WasmEdge_ConfigureAddHostRegistration(ConfCxt,
   WasmEdge_HostRegistration_Wasi);
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
   /* The following API can retrieve the pre-registration module instances
   from the VM context. */
   /* This API will return `NULL` if the corresponding pre-registration is not
   set into the configuration. */
   WasmEdge_ModuleInstanceContext *WasiModule =
     WasmEdge_VMGetImportModuleContext(VMCxt, WasmEdge_HostRegistration_Wasi);
   /* Initialize the WASI. */
   WasmEdge_ModuleInstanceInitWASI(WasiModule, /* ... ignored */ );
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_ConfigureDelete(ConfCxt);
   ```

And also can create the WASI module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

   This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` plugin.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasmEdge_Process);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration module instances
from the VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not
set into the configuration or the plugin load failed. */
WasmEdge_ModuleInstanceContext *ProcModule =
  WasmEdge_VMGetImportModuleContext(VMCxt,
WasmEdge_HostRegistration_WasmEdge_Process);
/* Initialize the WasmEdge_Process. */
WasmEdge_ModuleInstanceInitWasmEdgeProcess(ProcModule, /* ... ignored */ );
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

   And also can create the WasmEdge_Process module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

3. WASI-NN proposal (`0.10.1` or upper only)

   Developers can turn on the WASI-NN proposal support for VM in the `Configure` context.

Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration module instances
from the VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not
set into the configuration or the plugin load failed. */
WasmEdge_ModuleInstanceContext *NNModule =
  WasmEdge_VMGetImportModuleContext(VMCxt,
WasmEdge_HostRegistration_WasiNN);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-NN module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

4. WASI-Crypto proposal (`0.10.1` or upper only)

   Developers can turn on the WASI-Crypto proposal support for VM in the `Configure` context.

Note: Please check that the dependencies and prerequests are satisfied.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* The WASI-Crypto related configures are suggested to turn on together. */
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiCrypto_AsymmetricCommon);
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiCrypto_Kx);
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiCrypto_Signatures);
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasiCrypto_Symmetric);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration module instances
from the VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not
set into the configuration or the plugin load failed. */
WasmEdge_ModuleInstanceContext *CryptoCommonModule =
  WasmEdge_VMGetImportModuleContext(VMCxt,
WasmEdge_HostRegistration_WasiCrypto_Common);
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

And also can create the WASI-Crypto module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, the host functions are composed into host modules as `WasmEdge_ModuleInstanceContext` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` context.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_ModuleInstanceContext *WasiModule =
  WasmEdge_ModuleInstanceCreateWASI( /* ... ignored ... */ );
/* You can also create and register the WASI host modules by this API. */
WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModule);
/* The result status should be checked. */

/* ... */

WasmEdge_ModuleInstanceDelete(WasiModule);
/* The created module instances should be deleted by the developers when the VM
deallocation. */
WasmEdge_VMDelete(VMCxt);
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM modules.

1. Register the WASM modules with exported module names

   Unless the module instances have already contained the module names, every WASM module should be named uniquely when registering. Assume that the WASM file `fibonacci.wasm` is copied into the current directory.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
"fibonacci.wasm");
/*
 * Developers can register the WASM module from buffer with the
`WasmEdge_VMRegisterModuleFromBuffer()` API,
 * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMRegisterModuleFromASTModule()` API.
 */
/*
 * The result status should be checked.
 * The error will occur if the WASM module instantiation failed or the
module name conflicts.
 */
WasmEdge_StringDelete(ModName);
WasmEdge_VMDelete(VMCxt);
```

2. Execute the functions in registered WASM modules

   Assume that the C file `test.c` is as follows:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(20) };
  WasmEdge_Value Returns[1];
  /* Names. */
  WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Register the WASM module into VM. */
  Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
"fibonacci.wasm");
  /*
  * Developers can register the WASM module from buffer with the
`WasmEdge_VMRegisterModuleFromBuffer()` API,
  * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMRegisterModuleFromASTModule()` API.
  */
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM registration failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
  * The function "fib" in the "fibonacci.wasm" was exported with the module
name "mod".
  * As the same as host functions, other modules can import the function
`"mod" "fib"`.
  */

  /*
  * Execute WASM functions in registered modules.
  * Unlike the execution of functions, the registered functions can be
invoked without
  * `WasmEdge_VMInstantiate()` because the WASM module was instantiated
```

```
when registering.
  * Developers can also invoke the host functions directly with this API.
  */
  Res = WasmEdge_VMExecuteRegistered(VMCxt, ModName, FuncName, Params, 1,
Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  WasmEdge_StringDelete(ModName);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_VMDelete(VMCxt);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 10946
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(20) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Asynchronously run the WASM function from file and get the
`WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncRunWasmFromFile(VMCxt,
"fibonacci.wasm", FuncName, Params, 1);
  /*
   * Developers can run the WASM binary from buffer with the
`WasmEdge_VMAsyncRunWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMAsyncRunWasmFromASTModule()` API.
   */

  /* Wait for the execution. */
  WasmEdge_AsyncWait(Async);
  /*
   * Developers can also use the `WasmEdge_AsyncGetReturnsLength()` or
`WasmEdge_AsyncGet()` APIs
   * to wait for the asynchronous execution. These APIs will wait until the
execution finished.
   */

  /* Check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
known the return arity. */

  /* Get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Returns, Arity);

  if (WasmEdge_ResultOK(Res)) {
```

```
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(25) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
`WasmEdge_VMLoadWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
  /*
   * Developers can load, validate, and instantiate another WASM module to
replace the
   * instantiated one. In this case, the old module will be cleared, but
the registered
```

```
   * modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Asynchronously execute the WASM function and get the
`WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncExecute(VMCxt, FuncName, Params,
1);
  /*
   * Developers can execute functions repeatedly after instantiation.
   * For invoking the registered functions, you can use the
`WasmEdge_VMAsyncExecuteRegistered()` API.
   */

  /* Wait and check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
known the return arity. */

  /* Get the result. */
  Res = WasmEdge_AsyncGet(Async, Returns, Arity);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
}
```

Then you can compile and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` context supplies the APIs to retrieve the instances.

1. Store

   If the `VM` context is created without assigning a `Store` context, the `VM` context will allocate and own a `Store` context.

   ```
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
   WasmEdge_StoreContext *StoreCxt = WasmEdge_VMGetStoreContext(VMCxt);
   /* The object should __NOT__ be deleted by `WasmEdge_StoreDelete()`. */
   WasmEdge_VMDelete(VMCxt);
   ```

   Developers can also create the `VM` context with a `Store` context. In this case, developers should guarantee the life cycle of the `Store` context. Please refer to the Store Contexts for the details about the `Store` context APIs.

   ```
   WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);
   WasmEdge_StoreContext *StoreCxtMock = WasmEdge_VMGetStoreContext(VMCxt);
   /* The `StoreCxt` and the `StoreCxtMock` are the same. */
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_StoreDelete(StoreCxt);
   ```

2. List exported functions

   After the WASM module instantiation, developers can use the `WasmEdge_VMExecute()` API to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);

  WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  WasmEdge_VMValidate(VMCxt);
  WasmEdge_VMInstantiate(VMCxt);

  /* List the exported functions. */
  /* Get the number of exported functions. */
  uint32_t FuncNum = WasmEdge_VMGetFunctionListLength(VMCxt);
  /* Create the name buffers and the function type buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  WasmEdge_FunctionTypeContext *FuncTypes[BUF_LEN];
  /*
   * Get the export function list.
   * If the function list length is larger than the buffer length, the
overflowed data will be discarded.
   * The `FuncNames` and `FuncTypes` can be NULL if developers don't need
them.
   */
  uint32_t RealFuncNum = WasmEdge_VMGetFunctionList(VMCxt, FuncNames,
FuncTypes, BUF_LEN);

  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size,
Buf);
    /*
     * The function names should be __NOT__ destroyed.
     * The returned function type contexts should __NOT__ be destroyed.
     */
  }
  return 0;
}
```

Then you can compile and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get exported function string length: 3, name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` context from the `VM` context and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

The `VM` context provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
const WasmEdge_FunctionTypeContext *FuncType =
WasmEdge_VMGetFunctionType(VMCxt, FuncName);
/*
 * Developers can get the function types of functions in the registered
modules
 * via the `WasmEdge_VMGetFunctionTypeRegistered()` API with the module
name.
 * If the function is not found, these APIs will return `NULL`.
 * The returned function type contexts should __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

4. Get the active module

After the WASM module instantiation, an anonymous module is instantiated and owned by the `VM` context. Developers may need to retrieve it to get the instances beyond the module. Then developers can use the `WasmEdge_VMGetActiveModule()` API to get that anonymous module instance. Please refer to the Module instance for the details about the module instance APIs.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
const WasmEdge_ModuleInstanceContext *ModCxt =
WasmEdge_VMGetActiveModule(VMCxt);
/*
 * If there's no WASM module instantiated, this API will return `NULL`.
 * The returned module instance context should __NOT__ be destroyed.
 */
```

5. Get the components

   The `VM` context is composed by the `Loader`, `Validator`, and `Executor` contexts. For the developers who want to use these contexts without creating another instances, these APIs can help developers to get them from the `VM` context. The get contexts are owned by the `VM` context, and developers should not call their delete functions.

```
WasmEdge_LoaderContext *LoadCxt = WasmEdge_VMGetLoaderContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_LoaderDelete()`. */
WasmEdge_ValidatorContext *ValidCxt =
WasmEdge_VMGetValidatorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ValidatorDelete()`. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_VMGetExecutorContext(VMCxt);
/* The object should __NOT__ be deleted by `WasmEdge_ExecutorDelete()`. */
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` context, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` contexts. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. This step is not necessary because we didn't
adjust any setting. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* Create the statistics context. This step is not necessary if the
statistics in runtime is not needed. */
  WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
  /* Create the store context. The store context is the object to link the
modules for imports and exports. */
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  /* Result. */
  WasmEdge_Result Res;

  /* Create the loader context. The configure context can be NULL. */
  WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);
  /* Create the validator context. The configure context can be NULL. */
  WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
  /* Create the executor context. The configure context and the statistics
context can be NULL. */
  WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);

  /* Load the WASM file or the compiled-WASM file and convert into the AST
module context. */
  WasmEdge_ASTModuleContext *ASTCxt = NULL;
  Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Validate the WASM module. */
  Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Instantiate the WASM module into store context. */
  WasmEdge_ModuleInstanceContext *ModCxt = NULL;
  Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }

  /* Try to list the exported functions of the instantiated WASM module. */
  uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
  /* Create the name buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  /* If the list length is larger than the buffer length, the overflowed data
```

```
will be discarded. */
  uint32_t RealFuncNum = WasmEdge_ModuleInstanceListFunction(ModCxt, FuncNames,
BUF_LEN);
  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size, Buf);
    /* The function names should __NOT__ be destroyed. */
  }

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(18) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Find the exported function by function name. */
  WasmEdge_FunctionInstanceContext *FuncCxt =
WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
  if (FuncCxt == NULL) {
    printf("Function `fib` not found.\n");
    return 1;
  }
  /* Invoke the WASM fnction. */
  Res = WasmEdge_ExecutorInvoke(ExecCxt, FuncCxt, Params, 1, Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ASTModuleDelete(ASTCxt);
  WasmEdge_ModuleInstanceDelete(ModCxt);
  WasmEdge_LoaderDelete(LoadCxt);
  WasmEdge_ValidatorDelete(ValidCxt);
  WasmEdge_ExecutorDelete(ExecCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StoreDelete(StoreCxt);
  WasmEdge_StatisticsDelete(StatCxt);
  return 0;
}
```

Then you can compile and run: (the 18th Fibonacci number is 4181 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get exported function string length: 3, name: fib
Get the result: 4181
```

Loader

The `Loader` context loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
uint8_t Buf[4096];
/* ... Read the WASM code to the buffer. */
uint32_t FileSize = ...;
/* The `FileSize` is the length of the WASM code. */

/* Developers can adjust settings in the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);

WasmEdge_ASTModuleContext *ASTCxt = NULL;
WasmEdge_Result Res;

/* Load WASM or compiled-WASM from the file. */
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

/* Load WASM or compiled-WASM from the buffer. */
Res = WasmEdge_LoaderParseFromBuffer(LoadCxt, &ASTCxt, Buf, FileSize);
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Validator

The `Validator` context can validate the WASM module. Every WASM module should be validated before instantiation.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the loader
context.
 * Assume that the `ConfCxt` is the configure context.
 */
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
WasmEdge_Result Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
WasmEdge_ValidatorDelete(ValidCxt);
```

Executor

The `Executor` context is the executor for both WASM and compiled-WASM. This object should work base on the `Store` context. For the details of the `Store` context, please refer to the next chapter.

1. Instantiate and register an `AST module` as a named `Module` instance

   As the same of registering host modules or importing WASM modules in `VM` contexts, developers can instantiate and register an `AST module` contexts into the `Store` context as a named `Module` instance by the `Executor` APIs. After the registration, the result `Module` instance is exported with the given module name and can be linked when instantiating another module. For the details about the `Module` instances APIs, please refer to the Instances.

```
/*
* ...
* Assume that the `ASTCxt` is the output AST module context from the loader
context
* and has passed the validation.
* Assume that the `ConfCxt` is the configure context.
*/
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/* Create the executor context. The configure and the statistics contexts
can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);
/* Create the store context. The store context is the object to link the
modules for imports and exports. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/* Register the WASM module into the store with the export module name
"mod". */
Res = WasmEdge_ExecutorRegister(ExecCxt, &ModCxt, StoreCxt, ASTCxt,
ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
WasmEdge_StringDelete(ModName);

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

2. Register an existing `Module` instance and export the module name

   Besides instantiating and registering an `AST module` contexts, developers can register an existing `Module` instance into the store with exporting the module name (which is in the `Module` instance already). This case occurs when developers create a `Module` instance for the host functions and want to register it for linking. For the details about the construction of host functions in `Module` instances, please refer to the Host Functions.

```
/*
* ...
* Assume that the `ASTCxt` is the output AST module context from the loader
context
* and has passed the validation.
* Assume that the `ConfCxt` is the configure context.
*/
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/* Create the executor context. The configure and the statistics contexts
can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);
/* Create the store context. The store context is the object to link the
modules for imports and exports. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create a module instance for host functions. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("host-module");
WasmEdge_ModuleInstanceContext *HostModCxt =
WasmEdge_ModuleInstanceCreate(ModName);
WasmEdge_StringDelete(ModName);
/*
 * ...
 * Create and add the host functions, tables, memories, and globals into
the module instance.
 */

/* Register the module instance into store with the exported module name.
*/
/* The export module name is in the module instance already. */
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, HostModCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */
```

```
/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

3. Instantiate an `AST module` to an anonymous `Module` instance

   WASM or compiled-WASM modules should be instantiated before the function invocation. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` context for linking.

```
/*
* ...
* Assume that the `ASTCxt` is the output AST module context from the loader
context
* and has passed the validation.
* Assume that the `ConfCxt` is the configure context.
*/
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/* Create the executor context. The configure and the statistics contexts
can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);
/* Create the store context. The store context is the object to link the
modules for imports and exports. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/* Instantiate the WASM module. */
WasmEdge_Result Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt,
StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed: %s\n",
WasmEdge_ResultGetMessage(Res));
  return -1;
}

/* ... */

/* After the execution, the resources should be released. */
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
```

4. Invoke functions

After registering or instantiating and get the result `Module` instance, developers can retrieve the exported `Function` instances from the `Module` instance for invocation. For the details about the `Module` instances APIs, please refer to the Instances. Please

refer to the example above for the `Function` instance invocation with the `WasmEdge_ExecutorInvoke()` API.

AST Module

The `AST Module` context presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST Module` context.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that a WASM is loaded into an AST module context. */

/* Create the import type context buffers. */
const uint32_t BUF_LEN = 256;
const WasmEdge_ImportTypeContext *ImpTypes[BUF_LEN];
uint32_t ImportNum = WasmEdge_ASTModuleListImportsLength(ASTCxt);
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealImportNum = WasmEdge_ASTModuleListImports(ASTCxt, ImpTypes,
BUF_LEN);
for (uint32_t I = 0; I < RealImportNum && I < BUF_LEN; I++) {
  /* Working with the import type `ImpTypes[I]` ... */
}

/* Create the export type context buffers. */
const WasmEdge_ExportTypeContext *ExpTypes[BUF_LEN];
uint32_t ExportNum = WasmEdge_ASTModuleListExportsLength(ASTCxt);
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealExportNum = WasmEdge_ASTModuleListExports(ASTCxt, ExpTypes,
BUF_LEN);
for (uint32_t I = 0; I < RealExportNum && I < BUF_LEN; I++) {
  /* Working with the export type `ExpTypes[I]` ... */
}

WasmEdge_ASTModuleDelete(ASTCxt);
/* After deletion of `ASTCxt`, all data queried from the `ASTCxt` should not be
accessed. */
```

Store

Store is the runtime structure for the representation of all global state that can be manipulated by WebAssembly programs. The `Store` context in WasmEdge is an object to provide the instance exporting and importing when instantiating WASM modules. Developers can retrieve the named modules from the `Store` context.

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/*
 * ...
 * Register a WASM module via the executor context.
 */

/* Try to list the registered WASM modules. */
uint32_t ModNum = WasmEdge_StoreListModuleLength(StoreCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String ModNames[BUF_LEN];
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealModNum = WasmEdge_StoreListModule(StoreCxt, ModNames, BUF_LEN);
for (uint32_t I = 0; I < RealModNum && I < BUF_LEN; I++) {
  /* Working with the module name `ModNames[I]` ... */
  /* The module names should __NOT__ be destroyed. */
}

/* Find named module by name. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module");
const WasmEdge_ModuleInstanceContext *ModCxt =
WasmEdge_StoreFindModule(StoreCxt, ModName);
/* If the module with name not found, the `ModCxt` will be NULL. */
WasmEdge_StringDelete(ModName);
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the `Module` instances from the `Store` contexts, and retrieve the other instances from the `Module` instances. A single instance can be allocated by its creation function. Developers can construct instances into an `Module` instance for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed by developers, EXCEPT they are added into an `Module` instance.

1. Module instance

   After instantiating or registering an `AST module` context, developers will get a `Module` instance as the result, and have the responsibility to destroy it when not in use. A `Module` instance can also be created for the host module. Please refer to the host function for the details. `Module` instance provides APIs to list and find the exported instances in the module.

```
/*
* ...
* Instantiate a WASM module via the executor context and get the `ModCxt`
as the output module instance.
*/

/* Try to list the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
uint32_t FuncNum = WasmEdge_ModuleInstanceListFunctionLength(ModCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealFuncNum = WasmEdge_ModuleInstanceListFunction(ModCxt,
FuncNames, BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  /* Working with the function name `FuncNames[I]` ... */
  /* The function names should __NOT__ be destroyed. */
}

/* Try to find the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FuncCxt =
WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
/* `FuncCxt` will be `NULL` if the function not found. */
/* The returned instance is owned by the module instance context and should
__NOT__ be destroyed. */
WasmEdge_StringDelete(FuncName);
```

2. Function instance

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` contexts for host functions and add them into an `Module` instance context for registering into a `VM` or a `Store`. Developers can retrieve the `Function Type` from the `Function` contexts through the API. For the details of the `Host Function` guide, please refer to the next chapter.

```
/* Retrieve the function instance from the module instance context. */
WasmEdge_FunctionInstanceContext *FuncCxt = ...;
WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_FunctionInstanceGetFunctionType(FuncCxt);
/* The `FuncTypeCxt` is owned by the `FuncCxt` and should __NOT__ be
destroyed. */

/* For the function instance creation, please refer to the `Host Function`
guide. */
```

3. Table instance

In WasmEdge, developers can create the `Table` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Table` contexts supply APIs to control the data in table instances.

```
WasmEdge_Limit TabLimit = {.HasMax = true, .Shared = false, .Min = 10, .Max
= 20};
/* Create the table type with limit and the `FuncRef` element type. */
WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TabLimit);
/* Create the table instance with table type. */
WasmEdge_TableInstanceContext *HostTable =
WasmEdge_TableInstanceCreate(TabTypeCxt);
/* Delete the table type. */
WasmEdge_TableTypeDelete(TabTypeCxt);
WasmEdge_Result Res;
WasmEdge_Value Data;

TabTypeCxt = WasmEdge_TableInstanceGetTableType(HostTable);
/* The `TabTypeCxt` got from table instance is owned by the `HostTable` and
should __NOT__ be destroyed. */
enum WasmEdge_RefType RefType = WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `RefType` will be `WasmEdge_RefType_FuncRef`. */
Data = WasmEdge_ValueGenFuncRef(5);
Res = WasmEdge_TableInstanceSetData(HostTable, Data, 3);
/* Set the function index 5 to the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceSetData(HostTable, Data, 13);
 */
Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 3);
/* Get the FuncRef value of the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 13);
 */

uint32_t Size = WasmEdge_TableInstanceGetSize(HostTable);
/* `Size` will be 10. */
Res = WasmEdge_TableInstanceGrow(HostTable, 6);
/* Grow the table size of 6, the table size will be 16. */
/*
 * This will get an "out of bounds table access" error because
```

```
  * the size (16 + 6) will reach the table limit(20):
  *   Res = WasmEdge_TableInstanceGrow(HostTable, 6);
  */

 WasmEdge_TableInstanceDelete(HostTable);
```

4. Memory instance

   In WasmEdge, developers can create the `Memory` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Memory` contexts supply APIs to control the data in memory instances.

```
WasmEdge_Limit MemLimit = {.HasMax = true, .Shared = false, .Min = 1, .Max
= 5};
/* Create the memory type with limit. The memory page size is 64KiB. */
WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_MemoryTypeCreate(MemLimit);
/* Create the memory instance with memory type. */
WasmEdge_MemoryInstanceContext *HostMemory =
WasmEdge_MemoryInstanceCreate(MemTypeCxt);
/* Delete the memory type. */
WasmEdge_MemoryTypeDelete(MemTypeCxt);
WasmEdge_Result Res;
uint8_t Buf[256];

Buf[0] = 0xAA;
Buf[1] = 0xBB;
Buf[2] = 0xCC;
Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0x1000, 3);
/* Set the data[0:2] to the memory[4096:4098]. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */
Buf[0] = 0;
Buf[1] = 0;
Buf[2] = 0;
Res = WasmEdge_MemoryInstanceGetData(HostMemory, Buf, 0x1000, 3);
/* Get the memory[4096:4098]. Buf[0:2] will be `{0xAA, 0xBB, 0xCC}`. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */

uint32_t PageSize = WasmEdge_MemoryInstanceGetPageSize(HostMemory);
/* `PageSize` will be 1. */
Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 2);
/* Grow the page size of 2, the page size of the memory instance will be 3.
*/
/*
```

```
  * This will get an "out of bounds memory access" error because
  * the page size (3 + 3) will reach the memory limit(5):
  *   Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 3);
  */

 WasmEdge_MemoryInstanceDelete(HostMemory);
```

5. Global instance

   In WasmEdge, developers can create the `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`. The `Global` contexts supply APIs to control the value in global instances.

```
WasmEdge_Value Val = WasmEdge_ValueGenI64(1000);
/* Create the global type with value type and mutation. */
WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_GlobalTypeCreate(WasmEdge_ValType_I64, WasmEdge_Mutability_Var);
/* Create the global instance with value and global type. */
WasmEdge_GlobalInstanceContext *HostGlobal =
WasmEdge_GlobalInstanceCreate(GlobTypeCxt, Val);
/* Delete the global type. */
WasmEdge_GlobalTypeDelete(GlobTypeCxt);
WasmEdge_Result Res;

GlobTypeCxt = WasmEdge_GlobalInstanceGetGlobalType(HostGlobal);
/* The `GlobTypeCxt` got from global instance is owned by the `HostGlobal`
and should __NOT__ be destroyed. */
enum WasmEdge_ValType ValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `ValType` will be `WasmEdge_ValType_I64`. */
enum WasmEdge_Mutability ValMut =
WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `ValMut` will be `WasmEdge_Mutability_Var`. */

WasmEdge_GlobalInstanceSetValue(HostGlobal, WasmEdge_ValueGenI64(888));
/*
 * Set the value u64(888) to the global.
 * This function will do nothing if the value type mismatched or
 * the global mutability is `WasmEdge_Mutability_Const`.
 */
WasmEdge_Value GlobVal = WasmEdge_GlobalInstanceGetValue(HostGlobal);
/* Get the value (888 now) of the global context. */

WasmEdge_GlobalInstanceDelete(HostGlobal);
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function`, `Memory`, `Table`, and `Global` contexts and add them into an `Module` instance context for registering into a `VM` or a `Store`.

1. Host function allocation

Developers can define C functions with the following function signature as the host function body:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
  void *Data,
  WasmEdge_MemoryInstanceContext *MemCxt,
  const WasmEdge_Value *Params,
  WasmEdge_Value *Returns);
```

The example of an `add` host function to add 2 `i32` values:

```
WasmEdge_Result Add(void *, WasmEdge_MemoryInstanceContext *,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /*
  * Params: {i32, i32}
  * Returns: {i32}
  * Developers should take care about the function type.
  */
  /* Retrieve the value 1. */
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  /* Retrieve the value 2. */
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  /* Output value 1 is Val1 + Val2. */
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Return the status of success. */
  return WasmEdge_Result_Success;
}
```

Then developers can create `Function` context with the host function body and the function type:

```
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
/* Create a function type: {i32, i32} -> {i32}. */
WasmEdge_FunctionTypeContext *HostFType =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
/*
 * Create a function context with the function type and host function body.
 * The `Cost` parameter can be 0 if developers do not need the cost
measuring.
 */
WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostType);

/* If the function instance is not added into a module instance context, it
should be deleted. */
WasmEdge_FunctionInstanceDelete(HostFunc);
```

2. Construct a module instance with host instances

   Besides creating a `Module` instance by registering or instantiating a WASM module, developers can create a `Module` instance with a module name and add the `Function`, `Memory`, `Table`, and `Global` instances into it with their exporting names.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create a module instance. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ModuleInstanceContext *HostModCxt =
WasmEdge_ModuleInstanceCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the module instance. */
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
WasmEdge_FunctionTypeContext *HostFType =
  WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
  WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ModuleInstanceAddFunction(HostModCxt, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/* Create and add a table instance into the import object. */
WasmEdge_Limit TableLimit = {.HasMax = true, .Shared = false, .Min = 10,
.Max = 20};
WasmEdge_TableTypeContext *HostTType =
  WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TableLimit);
WasmEdge_TableInstanceContext *HostTable =
WasmEdge_TableInstanceCreate(HostTType);
```

```
WasmEdge_TableTypeDelete(HostTType);
WasmEdge_String TableName = WasmEdge_StringCreateByCString("table");
WasmEdge_ModuleInstanceAddTable(HostModCxt, TableName, HostTable);
WasmEdge_StringDelete(TableName);

/* Create and add a memory instance into the import object. */
WasmEdge_Limit MemoryLimit = {.HasMax = true, .Shared = false, .Min = 1,
.Max = 2};
WasmEdge_MemoryTypeContext *HostMType =
WasmEdge_MemoryTypeCreate(MemoryLimit);
WasmEdge_MemoryInstanceContext *HostMemory =
WasmEdge_MemoryInstanceCreate(HostMType);
WasmEdge_MemoryTypeDelete(HostMType);
WasmEdge_String MemoryName = WasmEdge_StringCreateByCString("memory");
WasmEdge_ModuleInstanceAddMemory(HostModCxt, MemoryName, HostMemory);
WasmEdge_StringDelete(MemoryName);

/* Create and add a global instance into the module instance. */
WasmEdge_GlobalTypeContext *HostGType =
  WasmEdge_GlobalTypeCreate(WasmEdge_ValType_I32, WasmEdge_Mutability_Var);
WasmEdge_GlobalInstanceContext *HostGlobal =
  WasmEdge_GlobalInstanceCreate(HostGType, WasmEdge_ValueGenI32(666));
WasmEdge_GlobalTypeDelete(HostGType);
WasmEdge_String GlobalName = WasmEdge_StringCreateByCString("global");
WasmEdge_ModuleInstanceAddGlobal(HostModCxt, GlobalName, HostGlobal);
WasmEdge_StringDelete(GlobalName);

/*
 * The module instance should be deleted.
 * Developers should __NOT__ destroy the instances added into the module
instance contexts.
 */
WasmEdge_ModuleInstanceDelete(HostModCxt);
```

3. Specified module instance

`WasmEdge_ModuleInstanceCreateWASI()` API can create and initialize the `WASI` module instance.

`WasmEdge_ModuleInstanceCreateWasiNN()` API can create and initialize the `wasi_ephemeral_nn` module instance for `WASI-NN` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasiCryptoCommon()` API can create and initialize the `wasi_ephemeral_crypto_common` module instance for `WASI-Crypto` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasiCryptoAsymmetricCommon()` API can create and initialize the `wasi_ephemeral_crypto_asymmetric_common` module instance for `WASI-Crypto` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasiCryptoKx()` API can create and initialize the `wasi_ephemeral_crypto_kx` module instance for `WASI-Crypto` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasiCryptoSignatures()` API can create and initialize the `wasi_ephemeral_crypto_signatures` module instance for `WASI-Crypto` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasiCryptoSymmetric()` API can create and initialize the `wasi_ephemeral_crypto_symmetric` module instance for `WASI-Crypto` plugin (`0.10.1` or upper only).

`WasmEdge_ModuleInstanceCreateWasmEdgeProcess()` API can create and initialize the `wasmedge_process` module instance for `wasmedge_process` plugin.

Developers can create these module instance contexts and register them into the `Store` or `VM` contexts rather than adjust the settings in the `Configure` contexts.

> Note: For the `WASI-NN` plugin, please check that the dependencies and prerequests are satisfied. Note: For the `WASI-Crypto` plugin, please check that the dependencies and prerequests are satisfied. And the 5 modules are recommended to all be created and registered together.

```
WasmEdge_ModuleInstanceContext *WasiModCxt =
WasmEdge_ModuleInstanceCreateWASI( /* ... ignored */ );
WasmEdge_ModuleInstanceContext *ProcModCxt =
WasmEdge_ModuleInstanceCreateWasmEdgeProcess( /* ... ignored */ );
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
/* Register the WASI and WasmEdge_Process into the VM context. */
WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiModCxt);
WasmEdge_VMRegisterModuleFromImport(VMCxt, ProcModCxt);
/* Get the WASI exit code. */
uint32_t ExitCode = WasmEdge_ModuleInstanceWASIGetExitCode(WasiModCxt);
/*
 * The `ExitCode` will be EXIT_SUCCESS if the execution has no error.
 * Otherwise, it will return with the related exit code.
 */
WasmEdge_VMDelete(VMCxt);
/* The module instances should be deleted. */
WasmEdge_ModuleInstanceDelete(WasiModCxt);
WasmEdge_ModuleInstanceDelete(ProcModCxt);
```

4. Example

   Assume that a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

   And the `test.c` as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
```

```
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B
  };

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
  enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
  WasmEdge_FunctionTypeContext *HostFType =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = { WasmEdge_ValueGenI32(1234),
WasmEdge_ValueGenI32(5678) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
    VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
```

```
  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
```

5. Host Data Example

   Developers can set a external data object to the `Function` context, and access to the object in the function body. Assume that a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

   And the `test.c` as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Also set the result to the data. */
  int32_t *DataPtr = (int32_t *)Data;
  *DataPtr = Val1 + Val2;
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
```

```
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B
  };

  /* The external data object: an integer. */
  int32_t Data;

  /* Create the module instance. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ModuleInstanceContext *HostModCxt =
WasmEdge_ModuleInstanceCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
  enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
  WasmEdge_FunctionTypeContext *HostFType =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, &Data, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ModuleInstanceAddFunction(HostModCxt, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, HostModCxt);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = { WasmEdge_ValueGenI32(1234),
WasmEdge_ValueGenI32(5678) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
    VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);
```

```
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  printf("Data value: %d\n", Data);

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ModuleInstanceDelete(HostModCxt);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options.

WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* ... Adjust settings in the configure context. */
  /* Result. */
  WasmEdge_Result Res;

  /* Create the compiler context. The configure context can be NULL. */
  WasmEdge_CompilerContext *CompilerCxt = WasmEdge_CompilerCreate(ConfCxt);
  /* Compile the WASM file with input and output paths. */
  Res = WasmEdge_CompilerCompile(CompilerCxt, "fibonacci.wasm",
"fibonacci.wasm.so");
  if (!WasmEdge_ResultOK(Res)) {
      printf("Compilation failed: %s\n", WasmEdge_ResultGetMessage(Res));
      return 1;
  }

  WasmEdge_CompilerDelete(CompilerCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  return 0;
}
```

Then you can compile and run (the output file is "fibonacci.wasm.so"):

```
$ gcc test.c -lwasmedge_c
$ ./a.out
[2021-07-02 11:08:08.651] [info] compile start
[2021-07-02 11:08:08.653] [info] verify start
[2021-07-02 11:08:08.653] [info] optimize start
[2021-07-02 11:08:08.670] [info] codegen start
[2021-07-02 11:08:08.706] [info] compile done
```

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
/// AOT compiler optimization level enumeration.
enum WasmEdge_CompilerOptimizationLevel {
  /// Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  /// Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  /// Optimize for fast execution as much as possible without triggering
  /// significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  /// Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  /// Optimize for small code size as much as possible without triggering
  /// significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  /// Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

/// AOT compiler output binary format enumeration.
enum WasmEdge_CompilerOutputFormat {
  /// Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  /// WebAssembly with AOT compiled codes in custom sections.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

Please refer to the AOT compiler options configuration for details.

Upgrade to WasmEdge 0.11.0

Due to the WasmEdge C API breaking changes, this document shows the guideline for programming with WasmEdge C API to upgrade from the `0.10.1` to the `0.11.0` version.

Concepts

1. Supported the user-defined error code in host functions.

   Developers can use the new API `WasmEdge_ResultGen()` to generate a `WasmEdge_Result` struct with `WasmEdge_ErrCategory_UserLevelError` and the error code. With this support, developers can specify the host function error code when failed by themselves. For the examples to specify the user-defined error code, please refer to the example below.

2. Calling frame for the host function extension

   In the previous versions, host functions only pass the memory instance into the function body. For supporting the WASM multiple memories proposal and providing the recursive invocation in host functions, the new context `WasmEdge_CallingFrameContext` replaced the memory instance in the second argument of the host function definition. For the examples of the new host function definition, please refer to the example below.

3. Apply the SONAME and SOVERSION.

   When linking the WasmEdge shared library, please notice that `libwasmedge_c.so` is renamed to `libwasmedge.so` after the 0.11.0 release. Please use `-lwasmedge` instead of `-lwasmedge_c` for the linker option.

User Defined Error Code In Host Functions

Assume that we want to specify that the host function failed in the versions before `0.10.1`:

```
/* Host function body definition. */
WasmEdge_Result FaildFunc(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* This will create a trap in WASM. */
  return WasmEdge_Result_Fail;
}
```

When the execution is finished, developers will get the `WasmEdge_Result`. If developers call the `WasmEdge_ResultOK()` with the returned result, they will get `false`. If developers call the `WasmEdge_ResultGetCode()` with the returned result, they will always get `2`.

For the versions after `0.11.0`, developers can specify the error code within 24-bit (smaller than `16777216`) size.

```
/* Host function body definition. */
WasmEdge_Result FaildFunc(void *Data,
                          const WasmEdge_CallingFrameContext *CallFrameCxt,
                          const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* This will create a trap in WASM with the error code. */
  return WasmEdge_ResultGen(WasmEdge_ErrCategory_UserLevelError, 12345678);
}
```

Therefore when developers call the `WasmEdge_ResultGetCode()` with the returned result, they will get the error code `12345678`. Noticed that if developers call the `WasmEdge_ResultGetMessage()`, they will always get the C string `"user defined error code"`.

Calling Frame In Host Functions

When implementing the host functions, developers usually use the input memory instance to load or store data. In the WasmEdge versions before `0.10.1`, the argument before the input and return value list of the host function definition is the memory instance context, so that developers can access the data in the memory instance.

```
/* Host function body definition. */
WasmEdge_Result LoadOffset(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                           const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {i32} -> {} */
  uint32_t Offset = (uint32_t)WasmEdge_ValueGetI32(In[0]);
  uint32_t Num = 0;
  WasmEdge_Result Res =
      WasmEdge_MemoryInstanceGetData(MemCxt, (uint8_t *)(&Num), Offset, 4);
  if (WasmEdge_ResultOK(Res)) {
    printf("u32 at memory[%u]: %u\n", Offset, Num);
  } else {
    return Res;
  }
  return WasmEdge_Result_Success;
}
```

The input memory instance is the one that belongs to the module instance on the top calling frame of the stack. However, after applying the WASM multiple memories proposal, there may be more than 1 memory instance in a WASM module. Furthermore, there may be requests for accessing the module instance on the top frame of the stack to get the exported WASM functions, such as recursive invocation in host functions. To support these, the `WasmEdge_CallingFrameContext` is designed to replace the memory instance input of the host function.

In the WasmEdge versions after `0.11.0`, the host function definitions are changed:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
    void *Data, const WasmEdge_CallingFrameContext *CallFrameCxt,
    const WasmEdge_Value *Params, WasmEdge_Value *Returns);

typedef WasmEdge_Result (*WasmEdge_WrapFunc_t)(
    void *This, void *Data, const WasmEdge_CallingFrameContext *CallFrameCxt,
    const WasmEdge_Value *Params, const uint32_t ParamLen,
    WasmEdge_Value *Returns, const uint32_t ReturnLen);
```

Developers need to change to use the `WasmEdge_CallingFrameContext` related APIs to access the memory instance:

```
/* Host function body definition. */
WasmEdge_Result LoadOffset(void *Data,
                           const WasmEdge_CallingFrameContext *CallFrameCxt,
                           const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /* Function type: {i32} -> {} */
  uint32_t Offset = (uint32_t)WasmEdge_ValueGetI32(In[0]);
  uint32_t Num = 0;

  /* Get the 0th memory instance of the module of the top frame on the stack.
*/
  WasmEdge_MemoryInstanceContext *MemCxt =
      WasmEdge_CallingFrameGetMemoryInstance(CallFrameCxt, 0);
  WasmEdge_Result Res =
      WasmEdge_MemoryInstanceGetData(MemCxt, (uint8_t *)(&Num), Offset, 4);
  if (WasmEdge_ResultOK(Res)) {
    printf("u32 at memory[%u]: %u\n", Offset, Num);
  } else {
    return Res;
  }
  return WasmEdge_Result_Success;
}
```

The `WasmEdge_CallingFrameGetModuleInstance()` API can help developers to get the module instance of the top frame on the stack. With the module instance context, developers can use the module instance-related APIs to get its contents.

The `WasmEdge_CallingFrameGetExecutor()` API can help developers to get the currently used executor context. Therefore developers can use the executor to recursively invoke other WASM functions without creating a new executor context.

WasmEdge 0.9.1 C API Documentation

WasmEdge C API denotes an interface to access the WasmEdge runtime at version `0.9.1`. The following are the guides to working with the C APIs of WasmEdge.

Developers can refer here to upgrade to 0.10.0.

Table of Contents

WasmEdge Installation

Download And Install

The easiest way to install WasmEdge is to run the following command. Your system should have `git` and `wget` as prerequisites.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.9.1
```

For more details, please refer to the Installation Guide for the WasmEdge installation.

Compile Sources

After the installation of WasmEdge, the following guide can help you to test for the availability of the WasmEdge C API.

1. Prepare the test C file (and assumed saved as `test.c`):

    ```
    #include <wasmedge/wasmedge.h>
    #include <stdio.h>
    int main() {
      printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
      return 0;
    }
    ```

2. Compile the file with `gcc` or `clang`.

    ```
    gcc test.c -lwasmedge_c
    ```

3. Run and get the expected output.

```
$ ./a.out
WasmEdge version: 0.9.1
```

WasmEdge Basics

In this part, we will introduce the utilities and concepts of WasmEdge shared library.

Version

The `Version` related APIs provide developers to check for the WasmEdge shared library version.

```
#include <wasmedge/wasmedge.h>
printf("WasmEdge version: %s\n", WasmEdge_VersionGet());
printf("WasmEdge version major: %u\n", WasmEdge_VersionGetMajor());
printf("WasmEdge version minor: %u\n", WasmEdge_VersionGetMinor());
printf("WasmEdge version patch: %u\n", WasmEdge_VersionGetPatch());
```

Logging Settings

The `WasmEdge_LogSetErrorLevel()` and `WasmEdge_LogSetDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Value Types

In WasmEdge, developers should convert the values to `WasmEdge_Value` objects through APIs for matching to the WASM value types.

1. Number types: `i32`, `i64`, `f32`, `f64`, and `v128` for the `SIMD` proposal

```
WasmEdge_Value Val;
Val = WasmEdge_ValueGenI32(123456);
printf("%d\n", WasmEdge_ValueGetI32(Val));
/* Will print "123456" */
Val = WasmEdge_ValueGenI64(1234567890123LL);
printf("%ld\n", WasmEdge_ValueGetI64(Val));
/* Will print "1234567890123" */
Val = WasmEdge_ValueGenF32(123.456f);
printf("%f\n", WasmEdge_ValueGetF32(Val));
/* Will print "123.456001" */
Val = WasmEdge_ValueGenF64(123456.123456789);
printf("%.10f\n", WasmEdge_ValueGetF64(Val));
/* Will print "123456.1234567890" */
```

2. Reference types: `funcref` and `externref` for the `Reference-Types` proposal

```
WasmEdge_Value Val;
void *Ptr;
bool IsNull;
uint32_t Num = 10;
/* Generate a externref to NULL. */
Val = WasmEdge_ValueGenNullRef(WasmEdge_RefType_ExternRef);
IsNull = WasmEdge_ValueIsNullRef(Val);
/* The `IsNull` will be `TRUE`. */
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `NULL`. */

/* Generate a funcref with function index 20. */
Val = WasmEdge_ValueGenFuncRef(20);
uint32_t FuncIdx = WasmEdge_ValueGetFuncIdx(Val);
/* The `FuncIdx` will be 20. */

/* Generate a externref to `Num`. */
Val = WasmEdge_ValueGenExternRef(&Num);
Ptr = WasmEdge_ValueGetExternRef(Val);
/* The `Ptr` will be `&Num`. */
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "10" */
Num += 55;
printf("%u\n", *(uint32_t *)Ptr);
/* Will print "65" */
```

Strings

The `WasmEdge_String` object is for the instance names when invoking a WASM function or finding the contexts of instances.

1. Create a `WasmEdge_String` from a C string (`const char *` with NULL termination) or a buffer with length.

   The content of the C string or buffer will be copied into the `WasmEdge_String` object.

```
char Buf[4] = {50, 55, 60, 65};
WasmEdge_String Str1 = WasmEdge_StringCreateByCString("test");
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
/* The objects should be deleted by `WasmEdge_StringDelete()`. */
WasmEdge_StringDelete(Str1);
WasmEdge_StringDelete(Str2);
```

2. Wrap a `WasmEdge_String` to a buffer with length.

   The content will not be copied, and the caller should guarantee the life cycle of the input buffer.

```
const char CStr[] = "test";
WasmEdge_String Str = WasmEdge_StringWrap(CStr, 4);
/* The object should __NOT__ be deleted by `WasmEdge_StringDelete()`. */
```

3. String comparison

```
const char CStr[] = "abcd";
char Buf[4] = {0x61, 0x62, 0x63, 0x64};
WasmEdge_String Str1 = WasmEdge_StringWrap(CStr, 4);
WasmEdge_String Str2 = WasmEdge_StringCreateByBuffer(Buf, 4);
bool IsEq = WasmEdge_StringIsEqual(Str1, Str2);
/* The `IsEq` will be `TRUE`. */
WasmEdge_StringDelete(Str2);
```

4. Convert to C string

```
char Buf[256];
WasmEdge_String Str =
WasmEdge_StringCreateByCString("test_wasmedge_string");
uint32_t StrLength = WasmEdge_StringCopy(Str, Buf, sizeof(Buf));
/* StrLength will be 20 */
printf("String: %s\n", Buf);
/* Will print "test_wasmedge_string". */
```

Results

The `WasmEdge_Result` object specifies the execution status. APIs about WASM execution will

return the `WasmEdge_Result` to denote the status.

```
WasmEdge_Result Res = WasmEdge_Result_Success;
bool IsSucceeded = WasmEdge_ResultOK(Res);
/* The `IsSucceeded` will be `TRUE`. */
uint32_t Code = WasmEdge_ResultGetCode(Res);
/* The `Code` will be 0. */
const char *Msg = WasmEdge_ResultGetMessage(Res);
/* The `Msg` will be "success". */
```

Contexts

The objects, such as `VM`, `Store`, and `Function`, are composed of `Context`s. All of the contexts can be created by calling the corresponding creation APIs and should be destroyed by calling the corresponding deletion APIs. Developers have responsibilities to manage the contexts for memory management.

```
/* Create the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Delete the configure context. */
WasmEdge_ConfigureDelete(ConfCxt);
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `WasmEdge_Limit` struct is defined in the header:

```
/// Struct of WASM limit.
typedef struct WasmEdge_Limit {
  /// Boolean to describe has max value or not.
  bool HasMax;
  /// Minimum value.
  uint32_t Min;
  /// Maximum value. Will be ignored if the `HasMax` is false.
  uint32_t Max;
} WasmEdge_Limit;
```

Developers can initialize the struct by assigning it's value, and the `Max` value is needed to be larger or equal to the `Min` value. The API `WasmEdge_LimitIsEqual()` is provided to compare with 2 `WasmEdge_Limit` structs.

2. Function type context

   The `Function Type` context is used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `Function Type` context APIs to get the parameter or return value types information.

```
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I64 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_FuncRef };
WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);

enum WasmEdge_ValType Buf[16];
uint32_t ParamLen = WasmEdge_FunctionTypeGetParametersLength(FuncTypeCxt);
/* `ParamLen` will be 2. */
uint32_t GotParamLen = WasmEdge_FunctionTypeGetParameters(FuncTypeCxt, Buf,
16);
/* `GotParamLen` will be 2, and `Buf[0]` and `Buf[1]` will be the same as
`ParamList`. */
uint32_t ReturnLen = WasmEdge_FunctionTypeGetReturnsLength(FuncTypeCxt);
/* `ReturnLen` will be 1. */
uint32_t GotReturnLen = WasmEdge_FunctionTypeGetReturns(FuncTypeCxt, Buf,
16);
/* `GotReturnLen` will be 1, and `Buf[0]` will be the same as `ReturnList`.
*/

WasmEdge_FunctionTypeDelete(FuncTypeCxt);
```

3. Table type context

   The `Table Type` context is used for `Table` instance creation or getting information from `Table` instances.

```
WasmEdge_Limit TabLim = {.HasMax = true, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_TableTypeCreate(WasmEdge_RefType_ExternRef, TabLim);

enum WasmEdge_RefType GotRefType =
WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `GotRefType` will be WasmEdge_RefType_ExternRef. */
WasmEdge_Limit GotTabLim = WasmEdge_TableTypeGetLimit(TabTypeCxt);
/* `GotTabLim` will be the same value as `TabLim`. */

WasmEdge_TableTypeDelete(TabTypeCxt);
```

4. Memory type context

The `Memory Type` context is used for `Memory` instance creation or getting information from `Memory` instances.

```
WasmEdge_Limit MemLim = {.HasMax = true, .Min = 10, .Max = 20};
WasmEdge_MemoryTypeContext *MemTypeCxt = WasmEdge_MemoryTypeCreate(MemLim);

WasmEdge_Limit GotMemLim = WasmEdge_MemoryTypeGetLimit(MemTypeCxt);
/* `GotMemLim` will be the same value as `MemLim`. */

WasmEdge_MemoryTypeDelete(MemTypeCxt)
```

5. Global type context

The `Global Type` context is used for `Global` instance creation or getting information from `Global` instances.

```
WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_GlobalTypeCreate(WasmEdge_ValType_F64, WasmEdge_Mutability_Var);

WasmEdge_ValType GotValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `GotValType` will be WasmEdge_ValType_F64. */
WasmEdge_Mutability GotValMut =
WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `GotValMut` will be WasmEdge_Mutability_Var. */

WasmEdge_GlobalTypeDelete(GlobTypeCxt);
```

6. Import type context

The `Import Type` context is used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `Import Type` context. The details about querying `Import Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
result of loading a WASM file. */
const WasmEdge_ImportTypeContext *ImpType = ...;
/* Assume that `ImpType` is queried from the `ASTCxt` for the import. */

enum WasmEdge_ExternalType ExtType =
WasmEdge_ImportTypeGetExternalType(ImpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
`WasmEdge_ExternalType_Table`,
 * `WasmEdge_ExternalType_Memory`, or `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ModName = WasmEdge_ImportTypeGetModuleName(ImpType);
WasmEdge_String ExtName = WasmEdge_ImportTypeGetExternalName(ImpType);
/* The `ModName` and `ExtName` should not be destroyed and the string
buffers are binded into the `ASTCxt`. */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_ImportTypeGetFunctionType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
`FuncTypeCxt` will be NULL. */
const WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_ImportTypeGetTableType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
will be NULL. */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_ImportTypeGetMemoryType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
will be NULL. */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_ImportTypeGetGlobalType(ASTCxt, ImpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt` will be NULL. */
```

7. Export type context

   The `Export Type` context is used for getting the exports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`) and external name from an `Export Type` context. The details about querying `Export Type` contexts will be introduced in the AST Module.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that `ASTCxt` is returned by the `WasmEdge_LoaderContext` for the
result of loading a WASM file. */
const WasmEdge_ExportTypeContext *ExpType = ...;
/* Assume that `ExpType` is queried from the `ASTCxt` for the export. */

enum WasmEdge_ExternalType ExtType =
WasmEdge_ExportTypeGetExternalType(ExpType);
/*
 * The `ExtType` can be one of `WasmEdge_ExternalType_Function`,
`WasmEdge_ExternalType_Table`,
 * `WasmEdge_ExternalType_Memory`, or `WasmEdge_ExternalType_Global`.
 */
WasmEdge_String ExtName = WasmEdge_ExportTypeGetExternalName(ExpType);
/* The `ExtName` should not be destroyed and the string buffer is binded
into the `ASTCxt`. */
const WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_ExportTypeGetFunctionType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Function`, the
`FuncTypeCxt` will be NULL. */
const WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_ExportTypeGetTableType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Table`, the `TabTypeCxt`
will be NULL. */
const WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_ExportTypeGetMemoryType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Memory`, the `MemTypeCxt`
will be NULL. */
const WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_ExportTypeGetGlobalType(ASTCxt, ExpType);
/* If the `ExtType` is not `WasmEdge_ExternalType_Global`, the
`GlobTypeCxt` will be NULL. */
```

Async

After calling the asynchronous execution APIs, developers will get the `WasmEdge_Async` object. Developers own the object and should call the `WasmEdge_AsyncDelete()` API to destroy it.

1. Wait for the asynchronous execution

   Developers can wait the execution until finished:

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution. */
   WasmEdge_AsyncWait(Async);
   WasmEdge_AsyncDelete(Async);
   ```

   Or developers can wait for a time limit. If the time limit exceeded, developers can choose to cancel the execution. For the interruptible execution in AOT mode, developers should set `TRUE` through the `WasmEdge_ConfigureCompilerSetInterruptible()` API into the configure context for the AOT compiler.

   ```
   WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
   */
   /* Blocking and waiting for the execution for 1 second. */
   bool IsEnd = WasmEdge_AsyncWaitFor(Async, 1000);
   if (IsEnd) {
     /* The execution finished. Developers can get the result. */
     WasmEdge_Result Res = WasmEdge_AsyncGet(/* ... Ignored */);
   } else {
     /* The time limit exceeded. Developers can keep waiting or cancel the
   execution. */
     WasmEdge_AsyncCancel(Async);
     WasmEdge_Result Res = WasmEdge_AsyncGet(Async, 0, NULL);
     /* The result error code will be `WasmEdge_ErrCode_Interrupted`. */
   }
   WasmEdge_AsyncDelete(Async);
   ```

2. Get the execution result of the asynchronous execution

   Developers can use the `WasmEdge_AsyncGetReturnsLength()` API to get the return value list length. This function will block and wait for the execution. If the execution has finished, this function will return the length immediately. If the execution failed, this function will return `0`. This function can help the developers to create the buffer to get the return values. If developers have already known the buffer length, they can skip this function and use the `WasmEdge_AsyncGet()` API to get the result.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return value list
length. */
uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
WasmEdge_AsyncDelete(Async);
```

The `WasmEdge_AsyncGet()` API will block and wait for the execution. If the execution has finished, this function will fill the return values into the buffer and return the execution result immediately.

```
WasmEdge_Async *Async = ...; /* Ignored. Asynchronous execute a function.
*/
/* Blocking and waiting for the execution and get the return values. */
const uint32_t BUF_LEN = 256;
WasmEdge_Value Buf[BUF_LEN];
WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Buf, BUF_LEN);
WasmEdge_AsyncDelete(Async);
```

Configurations

The configuration context, `WasmEdge_ConfigureContext`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` context to create other runtime contexts.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` context.

```
enum WasmEdge_Proposal {
  WasmEdge_Proposal_ImportExportMutGlobals = 0,
  WasmEdge_Proposal_NonTrapFloatToIntConversions,
  WasmEdge_Proposal_SignExtensionOperators,
  WasmEdge_Proposal_MultiValue,
  WasmEdge_Proposal_BulkMemoryOperations,
  WasmEdge_Proposal_ReferenceTypes,
  WasmEdge_Proposal_SIMD,
  WasmEdge_Proposal_TailCall,
  WasmEdge_Proposal_MultiMemories,
  WasmEdge_Proposal_Annotations,
  WasmEdge_Proposal_Memory64,
  WasmEdge_Proposal_ExceptionHandling,
  WasmEdge_Proposal_Threads,
  WasmEdge_Proposal_FunctionReferences
};
```

Developers can add or remove the proposals into the `Configure` context.

```
/*
 * By default, the following proposals have turned on initially:
 * * Import/Export of mutable globals
 * * Non-trapping float-to-int conversions
 * * Sign-extension operators
 * * Multi-value returns
 * * Bulk memory operations
 * * Reference types
 * * Fixed-width SIMD
 */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddProposal(ConfCxt, WasmEdge_Proposal_MultiMemories);
WasmEdge_ConfigureRemoveProposal(ConfCxt,
WasmEdge_Proposal_ReferenceTypes);
bool IsBulkMem = WasmEdge_ConfigureHasProposal(ConfCxt,
WasmEdge_Proposal_BulkMemoryOperations);
/* The `IsBulkMem` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

2. Host registrations

This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` contexts.

```
enum WasmEdge_HostRegistration {
  WasmEdge_HostRegistration_Wasi = 0,
  WasmEdge_HostRegistration_WasmEdge_Process
};
```

The details will be introduced in the preregistrations of VM context.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
bool IsHostWasi = WasmEdge_ConfigureHasHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `FALSE`. */
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
IsHostWasi = WasmEdge_ConfigureHasHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
/* The `IsHostWasi` will be `TRUE`. */
WasmEdge_ConfigureDelete(ConfCxt);
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
uint32_t PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* By default, the maximum memory page size is 65536. */
WasmEdge_ConfigureSetMaxMemoryPage(ConfCxt, 1024);
/* Limit the memory size of each memory instance with not larger than 1024
pages (64 MiB). */
PageSize = WasmEdge_ConfigureGetMaxMemoryPage(ConfCxt);
/* The `PageSize` will be 1024. */
WasmEdge_ConfigureDelete(ConfCxt);
```

4. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output

format, dump IR, and generic binary.

```
enum WasmEdge_CompilerOptimizationLevel {
  /// Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  /// Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  /// Optimize for fast execution as much as possible without triggering
  /// significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  /// Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  /// Optimize for small code size as much as possible without triggering
  /// significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  /// Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

enum WasmEdge_CompilerOutputFormat {
  /// Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  /// WebAssembly with AOT compiled codes in custom section.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

These configurations are only effective in `Compiler` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the optimization level is O3. */
WasmEdge_ConfigureCompilerSetOptimizationLevel(ConfCxt,
WasmEdge_CompilerOptimizationLevel_O2);
/* By default, the output format is universal WASM. */
WasmEdge_ConfigureCompilerSetOutputFormat(ConfCxt,
WasmEdge_CompilerOutputFormat_Native);
/* By default, the dump IR is `FALSE`. */
WasmEdge_ConfigureCompilerSetDumpIR(ConfCxt, TRUE);
/* By default, the generic binary is `FALSE`. */
WasmEdge_ConfigureCompilerSetGenericBinary(ConfCxt, TRUE);
/* By default, the interruptible is `FALSE`.
/* Set this option to `TRUE` to support the interruptible execution in AOT
mode. */
WasmEdge_ConfigureCompilerSetInterruptible(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

5. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` contexts.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* By default, the instruction counting is `FALSE` when running a compiled-
WASM or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetInstructionCounting(ConfCxt, TRUE);
/* By default, the cost measurement is `FALSE` when running a compiled-WASM
or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetCostMeasuring(ConfCxt, TRUE);
/* By default, the time measurement is `FALSE` when running a compiled-WASM
or a pure-WASM. */
WasmEdge_ConfigureStatisticsSetTimeMeasuring(ConfCxt, TRUE);
WasmEdge_ConfigureDelete(ConfCxt);
```

Statistics

The statistics context, `WasmEdge_StatisticsContext`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` context from the `VM` context, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
   /* ....
    * After running the WASM functions with the `Statistics` context
    */
   uint32_t Count = WasmEdge_StatisticsGetInstrCount(StatCxt);
   double IPS = WasmEdge_StatisticsGetInstrPerSecond(StatCxt);
   WasmEdge_StatisticsDelete(StatCxt);
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` context. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
uint64_t CostTable[16] = {
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0
};
/* Developers can set the costs of each instruction. The value not covered
will be 0. */
WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
WasmEdge_StatisticsSetCostLimit(StatCxt, 5000000);
/* ....
 * After running the WASM functions with the `Statistics` context
 */
uint64_t Cost = WasmEdge_StatisticsGetTotalCost(StatCxt);
WasmEdge_StatisticsDelete(StatCxt);
```

WasmEdge VM

In this partition, we will introduce the functions of `WasmEdge_VMContext` object and show examples of executing WASM functions.

WASM Execution Example With VM Context

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
 (export "fib" (func $fib))
 (func $fib (param $n i32) (result i32)
  (if
   (i32.lt_s (get_local $n)(i32.const 2))
   (return (i32.const 1))
  )
  (return
   (i32.add
    (call $fib (i32.sub (get_local $n)(i32.const 2)))
    (call $fib (i32.sub (get_local $n)(i32.const 1)))
   )
  )
 )
)
```

1. Run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(5) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(VMCxt, "fibonacci.wasm",
FuncName, Params, 1, Returns, 1);
  /*
   * Developers can run the WASM binary from buffer with the
`WasmEdge_VMRunWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMRunWasmFromASTModule()` API.
   */

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 5th Fibonacci number is 8 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 8
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context and add the WASI support. */
  /* This step is not necessary unless you need the WASI support. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  /* The configure and store context to the VM creation can be NULL. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(10) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
`WasmEdge_VMLoadWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
```

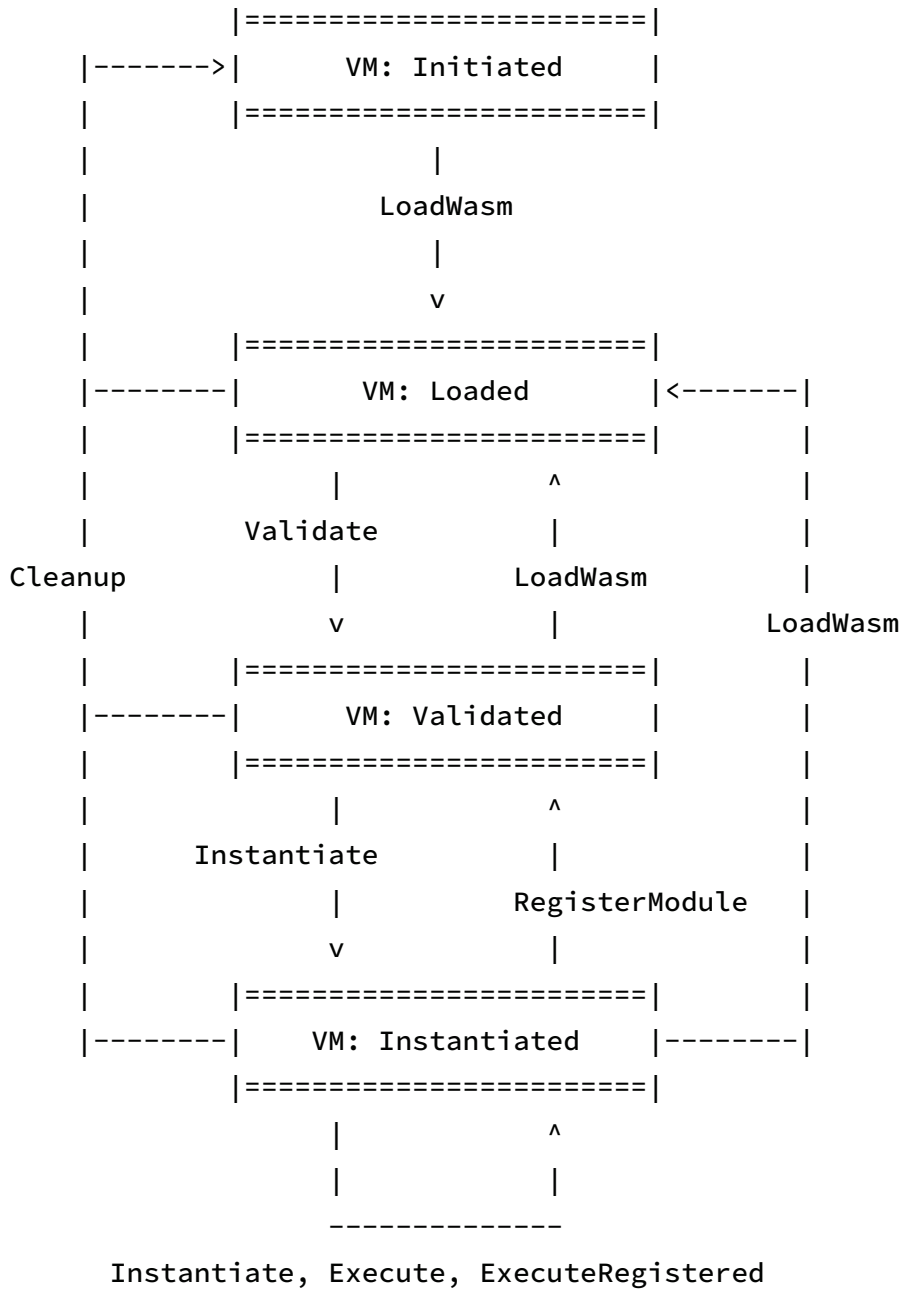
```
  /*
   * Developers can load, validate, and instantiate another WASM module to
replace the
   * instantiated one. In this case, the old module will be cleared, but
the registered
   * modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Execute WASM functions. You can execute functions repeatedly
after instantiation. */
  Res = WasmEdge_VMExecute(VMCxt, FuncName, Params, 1, Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 10th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 89
```

The following graph explains the status of the `VM` context.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or import objects in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation API accepts the `Configure` context and the `Store` context. If developers only need the default settings, just pass `NULL` to the creation API. The details of the `Store` context will be introduced in Store.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, StoreCxt);
/* The caller should guarantee the life cycle if the store context. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_VMGetStatisticsContext(VMCxt);
/* The VM context already contains the statistics context and can be retrieved
by this API. */
/*
 * Note that the retrieved store and statistics contexts from the VM contexts
by VM APIs
 * should __NOT__ be destroyed and owned by the VM contexts.
 */
WasmEdge_VMDelete(VMCxt);
WasmEdge_StoreDelete(StoreCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` context.

   ```
   WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
   WasmEdge_ConfigureAddHostRegistration(ConfCxt,
   WasmEdge_HostRegistration_Wasi);
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
   /* The following API can retrieve the pre-registration import objects from
   the VM context. */
   /* This API will return `NULL` if the corresponding pre-registration is not
   set into the configuration. */
   WasmEdge_ImportObjectContext *WasiObject =
     WasmEdge_VMGetImportModuleContext(VMCxt, WasmEdge_HostRegistration_Wasi);
   /* Initialize the WASI. */
   WasmEdge_ImportObjectInitWASI(WasiObject, /* ... ignored */ );
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_ConfigureDelete(ConfCxt);
   ```

And also can create the WASI import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

   This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` host functions.

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_WasmEdge_Process);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration import objects from
the VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not
set into the configuration. */
WasmEdge_ImportObjectContext *ProcObject =
  WasmEdge_VMGetImportModuleContext(VMCxt,
WasmEdge_HostRegistration_WasmEdge_Process);
/* Initialize the WasmEdge_Process. */
WasmEdge_ImportObjectInitWasmEdgeProcess(ProcObject, /* ... ignored */ );
WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

   And also can create the WasmEdge_Process import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, the host functions are composed into host modules as `WasmEdge_ImportObjectContext` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` context.

```
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
WasmEdge_ImportObjectContext *WasiObject =
  WasmEdge_ImportObjectCreateWASI( /* ... ignored ... */ );
/* You can also create and register the WASI host modules by this API. */
WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiObject);
/* The result status should be checked. */
WasmEdge_ImportObjectDelete(WasiObject);
/* The created import objects should be deleted. */
WasmEdge_VMDelete(VMCxt);
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM modules.

1. Register the WASM modules with exported module names

   Unless the import objects have already contained the module names, every WASM module should be named uniquely when registering. Assume that the WASM file `fibonacci.wasm` is copied into the current directory.

   ```
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
   WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
   WasmEdge_Result Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
   "fibonacci.wasm");
   /*
    * Developers can register the WASM module from buffer with the
   `WasmEdge_VMRegisterModuleFromBuffer()` API,
    * or from `WasmEdge_ASTModuleContext` object with the
   `WasmEdge_VMRegisterModuleFromASTModule()` API.
    */
   /*
    * The result status should be checked.
    * The error will occur if the WASM module instantiation failed or the
   module name conflicts.
    */
   WasmEdge_StringDelete(ModName);
   WasmEdge_VMDelete(VMCxt);
   ```

2. Execute the functions in registered WASM modules

   Assume that the C file `test.c` is as follows:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(20) };
  WasmEdge_Value Returns[1];
  /* Names. */
  WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Register the WASM module into VM. */
  Res = WasmEdge_VMRegisterModuleFromFile(VMCxt, ModName,
"fibonacci.wasm");
  /*
  * Developers can register the WASM module from buffer with the
`WasmEdge_VMRegisterModuleFromBuffer()` API,
  * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMRegisterModuleFromASTModule()` API.
  */
  if (!WasmEdge_ResultOK(Res)) {
    printf("WASM registration failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /*
  * The function "fib" in the "fibonacci.wasm" was exported with the module
name "mod".
  * As the same as host functions, other modules can import the function
`"mod" "fib"`.
  */

  /*
  * Execute WASM functions in registered modules.
  * Unlike the execution of functions, the registered functions can be
invoked without
  * `WasmEdge_VMInstantiate()` because the WASM module was instantiated
```

```
when registering.
  * Developers can also invoke the host functions directly with this API.
  */
  Res = WasmEdge_VMExecuteRegistered(VMCxt, ModName, FuncName, Params, 1,
Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  WasmEdge_StringDelete(ModName);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_VMDelete(VMCxt);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 89 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 10946
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(20) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Asynchronously run the WASM function from file and get the
`WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncRunWasmFromFile(VMCxt,
"fibonacci.wasm", FuncName, Params, 1);
  /*
   * Developers can run the WASM binary from buffer with the
`WasmEdge_VMAsyncRunWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMAsyncRunWasmFromASTModule()` API.
   */

  /* Wait for the execution. */
  WasmEdge_AsyncWait(Async);
  /*
   * Developers can also use the `WasmEdge_AsyncGetReturnsLength()` or
`WasmEdge_AsyncGet()` APIs
   * to wait for the asynchronous execution. These APIs will wait until the
execution finished.
   */

  /* Check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
known the return arity. */

  /* Get the result. */
  WasmEdge_Result Res = WasmEdge_AsyncGet(Async, Returns, Arity);

  if (WasmEdge_ResultOK(Res)) {
```

```
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  return 0;
}
```

Then you can compile and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(25) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Result. */
  WasmEdge_Result Res;

  /* Step 1: Load WASM file. */
  Res = WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  /*
   * Developers can load the WASM binary from buffer with the
`WasmEdge_VMLoadWasmFromBuffer()` API,
   * or from `WasmEdge_ASTModuleContext` object with the
`WasmEdge_VMLoadWasmFromASTModule()` API.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 2: Validate the WASM module. */
  Res = WasmEdge_VMValidate(VMCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 3: Instantiate the WASM module. */
  Res = WasmEdge_VMInstantiate(VMCxt);
  /*
   * Developers can load, validate, and instantiate another WASM module to
replace the
   * instantiated one. In this case, the old module will be cleared, but
the registered
```

```
   * modules are still kept.
   */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Step 4: Asynchronously execute the WASM function and get the
`WasmEdge_Async` object. */
  WasmEdge_Async *Async = WasmEdge_VMAsyncExecute(VMCxt, FuncName, Params,
1);
  /*
   * Developers can execute functions repeatedly after instantiation.
   * For invoking the registered functions, you can use the
`WasmEdge_VMAsyncExecuteRegistered()` API.
   */

  /* Wait and check the return values length. */
  uint32_t Arity = WasmEdge_AsyncGetReturnsLength(Async);
  /* The `Arity` should be 1. Developers can skip this step if they have
known the return arity. */

  /* Get the result. */
  Res = WasmEdge_AsyncGet(Async, Returns, Arity);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_AsyncDelete(Async);
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
}
```

Then you can compile and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` context supplies the APIs to retrieve the instances.

1. Store

   If the `VM` context is created without assigning a `Store` context, the `VM` context will allocate and own a `Store` context.

   ```
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
   WasmEdge_StoreContext *StoreCxt = WasmEdge_VMGetStoreContext(VMCxt);
   /* The object should __NOT__ be deleted by `WasmEdge_StoreDelete()`. */
   WasmEdge_VMDelete(VMCxt);
   ```

   Developers can also create the `VM` context with a `Store` context. In this case, developers should guarantee the life cycle of the `Store` context. Please refer to the Store Contexts for the details about the `Store` context APIs.

   ```
   WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
   WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);
   WasmEdge_StoreContext *StoreCxtMock = WasmEdge_VMGetStoreContext(VMCxt);
   /* The `StoreCxt` and the `StoreCxtMock` are the same. */
   WasmEdge_VMDelete(VMCxt);
   WasmEdge_StoreDelete(StoreCxt);
   ```

2. List exported functions

   After the WASM module instantiation, developers can use the `WasmEdge_VMExecute()` API to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, StoreCxt);

  WasmEdge_VMLoadWasmFromFile(VMCxt, "fibonacci.wasm");
  WasmEdge_VMValidate(VMCxt);
  WasmEdge_VMInstantiate(VMCxt);

  /* List the exported functions. */
  /* Get the number of exported functions. */
  uint32_t FuncNum = WasmEdge_VMGetFunctionListLength(VMCxt);
  /* Create the name buffers and the function type buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  WasmEdge_FunctionTypeContext *FuncTypes[BUF_LEN];
  /*
   * Get the export function list.
   * If the function list length is larger than the buffer length, the
overflowed data will be discarded.
   * The `FuncNames` and `FuncTypes` can be NULL if developers don't need
them.
   */
  uint32_t RealFuncNum = WasmEdge_VMGetFunctionList(VMCxt, FuncNames,
FuncTypes, BUF_LEN);

  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size,
Buf);
    /*
     * The function names should be __NOT__ destroyed.
     * The returned function type contexts should __NOT__ be destroyed.
     */
  }
  return 0;
}
```

Then you can compile and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get exported function string length: 3, name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` context from the `VM` context and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

The `VM` context provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
/*
 * ...
 * Assume that a WASM module is instantiated in `VMCxt`.
 */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
const WasmEdge_FunctionTypeContext *FuncType =
WasmEdge_VMGetFunctionType(VMCxt, FuncName);
/*
 * Developers can get the function types of functions in the registered
modules
 * via the `WasmEdge_VMGetFunctionTypeRegistered()` API with the module
name.
 * If the function is not found, these APIs will return `NULL`.
 * The returned function type contexts should __NOT__ be destroyed.
 */
WasmEdge_StringDelete(FuncName);
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` context, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` contexts. Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. This step is not necessary because we didn't
adjust any setting. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* Create the statistics context. This step is not necessary if the
statistics in runtime is not needed. */
  WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
  /* Create the store context. The store context is the WASM runtime structure
core. */
  WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
  /* Result. */
  WasmEdge_Result Res;

  /* Create the loader context. The configure context can be NULL. */
  WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);
  /* Create the validator context. The configure context can be NULL. */
  WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
  /* Create the executor context. The configure context and the statistics
context can be NULL. */
  WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);

  /* Load the WASM file or the compiled-WASM file and convert into the AST
module context. */
  WasmEdge_ASTModuleContext *ASTCxt = NULL;
  Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
  if (!WasmEdge_ResultOK(Res)) {
    printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Validate the WASM module. */
  Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }
  /* Instantiate the WASM module into store context. */
  Res = WasmEdge_ExecutorInstantiate(ExecCxt, StoreCxt, ASTCxt);
  if (!WasmEdge_ResultOK(Res)) {
    printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
    return 1;
  }

  /* Try to list the exported functions of the instantiated WASM module. */
  uint32_t FuncNum = WasmEdge_StoreListFunctionLength(StoreCxt);
  /* Create the name buffers. */
  const uint32_t BUF_LEN = 256;
  WasmEdge_String FuncNames[BUF_LEN];
  /* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
```

```
  uint32_t RealFuncNum = WasmEdge_StoreListFunction(StoreCxt, FuncNames,
BUF_LEN);
  for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
    char Buf[BUF_LEN];
    uint32_t Size = WasmEdge_StringCopy(FuncNames[I], Buf, sizeof(Buf));
    printf("Get exported function string length: %u, name: %s\n", Size, Buf);
    /* The function names should __NOT__ be destroyed. */
  }

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(18) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
  /* Invoke the WASM fnction. */
  Res = WasmEdge_ExecutorInvoke(ExecCxt, StoreCxt, FuncName, Params, 1,
Returns, 1);
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  }

  /* Resources deallocations. */
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ASTModuleDelete(ASTCxt);
  WasmEdge_LoaderDelete(LoadCxt);
  WasmEdge_ValidatorDelete(ValidCxt);
  WasmEdge_ExecutorDelete(ExecCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  WasmEdge_StoreDelete(StoreCxt);
  WasmEdge_StatisticsDelete(StatCxt);
  return 0;
}
```

Then you can compile and run: (the 18th Fibonacci number is 4181 in 0-based index)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Get exported function string length: 3, name: fib
Get the result: 4181
```

Loader

The `Loader` context loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
uint8_t Buf[4096];
/* ... Read the WASM code to the buffer. */
uint32_t FileSize = ...;
/* The `FileSize` is the length of the WASM code. */

/* Developers can adjust settings in the configure context. */
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(ConfCxt);

WasmEdge_ASTModuleContext *ASTCxt = NULL;
WasmEdge_Result Res;

/* Load WASM or compiled-WASM from the file. */
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

/* Load WASM or compiled-WASM from the buffer. */
Res = WasmEdge_LoaderParseFromBuffer(LoadCxt, &ASTCxt, Buf, FileSize);
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
/* The output AST module context should be destroyed. */
WasmEdge_ASTModuleDelete(ASTCxt);

WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Validator

The `Validator` context can validate the WASM module. Every WASM module should be validated before instantiation.

```
/*
 * ...
 * Assume that the `ASTCxt` is the output AST module context from the loader
context.
 * Assume that the `ConfCxt` is the configure context.
 */
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(ConfCxt);
WasmEdge_Result Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
WasmEdge_ValidatorDelete(ValidCxt);
```

Executor

The `Executor` context is the executor for both WASM and compiled-WASM. This object should work base on the `Store` context. For the details of the `Store` context, please refer to the next chapter.

1. Register modules

   As the same of registering host modules or importing WASM modules in `VM` context, developers can register `Import Object` or `AST module` contexts into the `Store` context by the `Executor` APIs. For the details of import objects, please refer to the Host Functions.

```
/*
* ...
* Assume that the `ASTCxt` is the output AST module context from the loader
context
* and has passed the validation.
* Assume that the `ConfCxt` is the configure context.
*/
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/* Create the executor context. The configure and the statistics contexts
can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);
/* Create the store context. The store context is the WASM runtime
structure core. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Register the WASM module into store with the export module name "mod".
*/
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
Res = WasmEdge_ExecutorRegisterModule(ExecCxt, StoreCxt, ASTCxt, ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
WasmEdge_StringDelete(ModName);

/*
 * Assume that the `ImpCxt` is the import object context for host
functions.
 */
WasmEdge_ImportObjectContext *ImpCxt = ...;
/* The import module context has already contained the export module name.
*/
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, ImpCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Import object registration failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}
```

```
WasmEdge_ImportObjectDelete(ImpCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
```

2. Instantiate modules

   WASM or compiled-WASM modules should be instantiated before the function invocation. Note that developers can only instantiate one module into the `Store` context, and in that case, the old instantiated module will be cleaned. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` context.

```
/*
* ...
* Assume that the `ASTCxt` is the output AST module context from the loader
context
* and has passed the validation.
* Assume that the `ConfCxt` is the configure context.
*/
/* Create the statistics context. This step is not necessary. */
WasmEdge_StatisticsContext *StatCxt = WasmEdge_StatisticsCreate();
/* Create the executor context. The configure and the statistics contexts
can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(ConfCxt,
StatCxt);
/* Create the store context. The store context is the WASM runtime
structure core. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();

/* Instantiate the WASM module. */
WasmEdge_Result Res = WasmEdge_ExecutorInstantiate(ExecCxt, StoreCxt,
ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM instantiation failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}

WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StatisticsDelete(StatCxt);
WasmEdge_StoreDelete(StoreCxt);
```

3. Invoke functions

   As the same as function invocation via the `VM` context, developers can invoke the functions of the instantiated or registered modules. The APIs, `WasmEdge_ExecutorInvoke()` and `WasmEdge_ExecutorInvokeRegistered()`, are similar as the APIs of the `VM` context. Please refer to the VM context workflows for details.

AST Module

The `AST Module` context presents the loaded structure from a WASM file or buffer.

Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST Module` context.

```
WasmEdge_ASTModuleContext *ASTCxt = ...;
/* Assume that a WASM is loaded into an AST module context. */

/* Create the import type context buffers. */
const uint32_t BUF_LEN = 256;
const WasmEdge_ImportTypeContext *ImpTypes[BUF_LEN];
uint32_t ImportNum = WasmEdge_ASTModuleListImportsLength(ASTCxt);
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealImportNum = WasmEdge_ASTModuleListImports(ASTCxt, ImpTypes,
BUF_LEN);
for (uint32_t I = 0; I < RealImportNum && I < BUF_LEN; I++) {
  /* Working with the import type `ImpTypes[I]` ... */
}

/* Create the export type context buffers. */
const WasmEdge_ExportTypeContext *ExpTypes[BUF_LEN];
uint32_t ExportNum = WasmEdge_ASTModuleListExportsLength(ASTCxt);
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealExportNum = WasmEdge_ASTModuleListExports(ASTCxt, ExpTypes,
BUF_LEN);
for (uint32_t I = 0; I < RealExportNum && I < BUF_LEN; I++) {
  /* Working with the export type `ExpTypes[I]` ... */
}

WasmEdge_ASTModuleDelete(ASTCxt);
/* After deletion of `ASTCxt`, all data queried from the `ASTCxt` should not be
accessed. */
```

Store

Store is the runtime structure for the representation of all instances of `Function` s, `Table` s, `Memory` s, and `Global` s that have been allocated during the lifetime of the abstract machine. The `Store` context in WasmEdge provides APIs to list the exported instances with their names or find the instances by exported names. For adding instances into `Store` contexts, please instantiate or register WASM modules or `Import Object` contexts via the `Executor` context.

1. List instances

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* ... Instantiate a WASM module via the executor context. */
...

/* Try to list the exported functions of the instantiated WASM module. */
/* Take the function instances for example here. */
uint32_t FuncNum = WasmEdge_StoreListFunctionLength(StoreCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String FuncNames[BUF_LEN];
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealFuncNum = WasmEdge_StoreListFunction(StoreCxt, FuncNames,
BUF_LEN);
for (uint32_t I = 0; I < RealFuncNum && I < BUF_LEN; I++) {
  /* Working with the function name `FuncNames[I]` ... */
  /* The function names should __NOT__ be destroyed. */
}
```

Developers can list the function instance exported names of the registered modules via the `WasmEdge_StoreListFunctionRegisteredLength()` and the `WasmEdge_StoreListFunctionRegistered()` APIs with the module name.

2. Find instances

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* ... Instantiate a WASM module via the executor context. */
...

/* Try to find the exported instance of the instantiated WASM module. */
/* Take the function instances for example here. */
/* Function name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FuncCxt =
WasmEdge_StoreFindFunction(StoreCxt, FuncName);
/* `FuncCxt` will be `NULL` if the function not found. */
/* The returned instance is owned by the store context and should __NOT__
be destroyed. */
WasmEdge_StringDelete(FuncName);
```

Developers can retrieve the exported function instances of the registered modules via the `WasmEdge_StoreFindFunctionRegistered()` API with the module name.

3. List registered modules

   With the module names, developers can list the exported instances of the registered modules with their names.

```
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* ... Register a WASM module via the executor context. */
...

/* Try to list the registered WASM modules. */
uint32_t ModNum = WasmEdge_StoreListModuleLength(StoreCxt);
/* Create the name buffers. */
const uint32_t BUF_LEN = 256;
WasmEdge_String ModNames[BUF_LEN];
/* If the list length is larger than the buffer length, the overflowed data
will be discarded. */
uint32_t RealModNum = WasmEdge_StoreListModule(StoreCxt, ModNames,
BUF_LEN);
for (uint32_t I = 0; I < RealModNum && I < BUF_LEN; I++) {
  /* Working with the module name `ModNames[I]` ... */
  /* The module names should __NOT__ be destroyed. */
}
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the instances from the `Store` contexts. The `Store` contexts will allocate instances when a WASM module or `Import Object` is registered or instantiated through the `Executor`. A single instance can be allocated by its creation function. Developers can construct instances into an `Import Object` for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed, EXCEPT they are added into an `Import Object` context.

1. Function instance

   Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` contexts for host

functions and add them into an `Import Object` context for registering into a `VM` or a `Store`. For both host functions and the functions get from `Store`, developers can retrieve the `Function Type` from the `Function` contexts. For the details of the `Host Function` guide, please refer to the next chapter.

```
/* Retrieve the function instance from the store context. */
WasmEdge_FunctionInstanceContext *FuncCxt = ...;
WasmEdge_FunctionTypeContext *FuncTypeCxt =
WasmEdge_FunctionInstanceGetFunctionType(FuncCxt);
/* The `FuncTypeCxt` is owned by the `FuncCxt` and should __NOT__ be
destroyed. */
```

2. Table instance

In WasmEdge, developers can create the `Table` contexts and add them into an `Import Object` context for registering into a `VM` or a `Store`. The `Table` contexts supply APIs to control the data in table instances.

```
WasmEdge_Limit TabLimit = {.HasMax = true, .Min = 10, .Max = 20};
/* Create the table type with limit and the `FuncRef` element type. */
WasmEdge_TableTypeContext *TabTypeCxt =
WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TabLimit);
/* Create the table instance with table type. */
WasmEdge_TableInstanceContext *HostTable =
WasmEdge_TableInstanceCreate(TabTypeCxt);
/* Delete the table type. */
WasmEdge_TableTypeDelete(TabTypeCxt);
WasmEdge_Result Res;
WasmEdge_Value Data;

TabTypeCxt = WasmEdge_TableInstanceGetTableType(HostTable);
/* The `TabTypeCxt` got from table instance is owned by the `HostTable` and
should __NOT__ be destroyed. */
enum WasmEdge_RefType RefType = WasmEdge_TableTypeGetRefType(TabTypeCxt);
/* `RefType` will be `WasmEdge_RefType_FuncRef`. */
Data = WasmEdge_ValueGenFuncRef(5);
Res = WasmEdge_TableInstanceSetData(HostTable, Data, 3);
/* Set the function index 5 to the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceSetData(HostTable, Data, 13);
 */
Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 3);
/* Get the FuncRef value of the table[3]. */
/*
 * This will get an "out of bounds table access" error
 * because the position (13) is out of the table size (10):
 *   Res = WasmEdge_TableInstanceGetData(HostTable, &Data, 13);
 */

uint32_t Size = WasmEdge_TableInstanceGetSize(HostTable);
/* `Size` will be 10. */
Res = WasmEdge_TableInstanceGrow(HostTable, 6);
/* Grow the table size of 6, the table size will be 16. */
/*
 * This will get an "out of bounds table access" error because
 * the size (16 + 6) will reach the table limit(20):
```

```
  *   Res = WasmEdge_TableInstanceGrow(HostTable, 6);
  */

 WasmEdge_TableInstanceDelete(HostTable);
```

3. Memory instance

   In WasmEdge, developers can create the `Memory` contexts and add them into an `Import Object` context for registering into a `VM` or a `Store`. The `Memory` contexts supply APIs to control the data in memory instances.

```
WasmEdge_Limit MemLimit = {.HasMax = true, .Min = 1, .Max = 5};
/* Create the memory type with limit. The memory page size is 64KiB. */
WasmEdge_MemoryTypeContext *MemTypeCxt =
WasmEdge_MemoryTypeCreate(MemLimit);
/* Create the memory instance with memory type. */
WasmEdge_MemoryInstanceContext *HostMemory =
WasmEdge_MemoryInstanceCreate(MemTypeCxt);
/* Delete the memory type. */
WasmEdge_MemoryTypeDelete(MemTypeCxt);
WasmEdge_Result Res;
uint8_t Buf[256];

Buf[0] = 0xAA;
Buf[1] = 0xBB;
Buf[2] = 0xCC;
Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0x1000, 3);
/* Set the data[0:2] to the memory[4096:4098]. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */
Buf[0] = 0;
Buf[1] = 0;
Buf[2] = 0;
Res = WasmEdge_MemoryInstanceGetData(HostMemory, Buf, 0x1000, 3);
/* Get the memory[4096:4098]. Buf[0:2] will be `{0xAA, 0xBB, 0xCC}`. */
/*
 * This will get an "out of bounds memory access" error
 * because [65535:65537] is out of 1 page size (65536):
 *   Res = WasmEdge_MemoryInstanceSetData(HostMemory, Buf, 0xFFFF, 3);
 */

uint32_t PageSize = WasmEdge_MemoryInstanceGetPageSize(HostMemory);
/* `PageSize` will be 1. */
Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 2);
/* Grow the page size of 2, the page size of the memory instance will be 3.
*/
/*
 * This will get an "out of bounds memory access" error because
```

```
  * the page size (3 + 3) will reach the memory limit(5):
  *   Res = WasmEdge_MemoryInstanceGrowPage(HostMemory, 3);
  */

 WasmEdge_MemoryInstanceDelete(HostMemory);
```

4. Global instance

   In WasmEdge, developers can create the `Global` contexts and add them into an `Import Object` context for registering into a `VM` or a `Store`. The `Global` contexts supply APIs to control the value in global instances.

```
WasmEdge_Value Val = WasmEdge_ValueGenI64(1000);
/* Create the global type with value type and mutation. */
WasmEdge_GlobalTypeContext *GlobTypeCxt =
WasmEdge_GlobalTypeCreate(WasmEdge_ValType_I64, WasmEdge_Mutability_Var);
/* Create the global instance with value and global type. */
WasmEdge_GlobalInstanceContext *HostGlobal =
WasmEdge_GlobalInstanceCreate(GlobTypeCxt, Val);
/* Delete the global type. */
WasmEdge_GlobalTypeDelete(GlobTypeCxt);
WasmEdge_Result Res;

GlobTypeCxt = WasmEdge_GlobalInstanceGetGlobalType(HostGlobal);
/* The `GlobTypeCxt` got from global instance is owned by the `HostGlobal`
and should __NOT__ be destroyed. */
enum WasmEdge_ValType ValType = WasmEdge_GlobalTypeGetValType(GlobTypeCxt);
/* `ValType` will be `WasmEdge_ValType_I64`. */
enum WasmEdge_Mutability ValMut =
WasmEdge_GlobalTypeGetMutability(GlobTypeCxt);
/* `ValMut` will be `WasmEdge_Mutability_Var`. */

WasmEdge_GlobalInstanceSetValue(HostGlobal, WasmEdge_ValueGenI64(888));
/*
 * Set the value u64(888) to the global.
 * This function will do nothing if the value type mismatched or
 * the global mutability is `WasmEdge_Mutability_Const`.
 */
WasmEdge_Value GlobVal = WasmEdge_GlobalInstanceGetValue(HostGlobal);
/* Get the value (888 now) of the global context. */

WasmEdge_GlobalInstanceDelete(HostGlobal);
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function`, `Memory`, `Table`, and `Global` contexts and add them into an `Import Object` context for registering into a `VM` or a `Store`.

1. Host function allocation

   Developers can define C functions with the following function signature as the host

function body:

```
typedef WasmEdge_Result (*WasmEdge_HostFunc_t)(
  void *Data,
  WasmEdge_MemoryInstanceContext *MemCxt,
  const WasmEdge_Value *Params,
  WasmEdge_Value *Returns);
```

The example of an `add` host function to add 2 `i32` values:

```
WasmEdge_Result Add(void *, WasmEdge_MemoryInstanceContext *,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  /*
  * Params: {i32, i32}
  * Returns: {i32}
  * Developers should take care about the function type.
  */
  /* Retrieve the value 1. */
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  /* Retrieve the value 2. */
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  /* Output value 1 is Val1 + Val2. */
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Return the status of success. */
  return WasmEdge_Result_Success;
}
```

Then developers can create `Function` context with the host function body and function type:

```
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
/* Create a function type: {i32, i32} -> {i32}. */
HostFType = WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
/*
 * Create a function context with the function type and host function body.
 * The `Cost` parameter can be 0 if developers do not need the cost
measuring.
 */
WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */

/* If the function instance is not added into an import object context, it
should be deleted. */
WasmEdge_FunctionInstanceDelete(HostFunc);
```

2. Import object context

   The `Import Object` context holds an exporting module name and the instances. Developers can add the `Function`, `Memory`, `Table`, and `Global` instances with their exporting names.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create the import object. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ImportObjectContext *ImpObj =
WasmEdge_ImportObjectCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the import object. */
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
WasmEdge_FunctionTypeContext *HostFType =
  WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
  WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ImportObjectAddFunction(ImpObj, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/* Create and add a table instance into the import object. */
WasmEdge_Limit TableLimit = {.HasMax = true, .Min = 10, .Max = 20};
WasmEdge_TableTypeContext *HostTType =
  WasmEdge_TableTypeCreate(WasmEdge_RefType_FuncRef, TableLimit);
WasmEdge_TableInstanceContext *HostTable =
WasmEdge_TableInstanceCreate(HostTType);
WasmEdge_TableTypeDelete(HostTType);
```

```
WasmEdge_String TableName = WasmEdge_StringCreateByCString("table");
WasmEdge_ImportObjectAddTable(ImpObj, TableName, HostTable);
WasmEdge_StringDelete(TableName);

/* Create and add a memory instance into the import object. */
WasmEdge_Limit MemoryLimit = {.HasMax = true, .Min = 1, .Max = 2};
WasmEdge_MemoryTypeContext *HostMType =
WasmEdge_MemoryTypeCreate(MemoryLimit);
WasmEdge_MemoryInstanceContext *HostMemory =
WasmEdge_MemoryInstanceCreate(HostMType);
WasmEdge_MemoryTypeDelete(HostMType);
WasmEdge_String MemoryName = WasmEdge_StringCreateByCString("memory");
WasmEdge_ImportObjectAddMemory(ImpObj, MemoryName, HostMemory);
WasmEdge_StringDelete(MemoryName);

/* Create and add a global instance into the import object. */
WasmEdge_GlobalTypeContext *HostGType =
  WasmEdge_GlobalTypeCreate(WasmEdge_ValType_I32, WasmEdge_Mutability_Var);
WasmEdge_GlobalInstanceContext *HostGlobal =
  WasmEdge_GlobalInstanceCreate(HostGType, WasmEdge_ValueGenI32(666));
WasmEdge_GlobalTypeDelete(HostGType);
WasmEdge_String GlobalName = WasmEdge_StringCreateByCString("global");
WasmEdge_ImportObjectAddGlobal(ImpObj, GlobalName, HostGlobal);
WasmEdge_StringDelete(GlobalName);

/*
 * The import objects should be deleted.
 * Developers should __NOT__ destroy the instances added into the import
object contexts.
 */
WasmEdge_ImportObjectDelete(ImpObj);
```

3. Specified import object

`WasmEdge_ImportObjectCreateWASI()` API can create and initialize the `WASI` import object. `WasmEdge_ImportObjectCreateWasmEdgeProcess()` API can create and initialize the `wasmedge_process` import object. Developers can create these import object contexts and register them into the `Store` or `VM` contexts rather than adjust the settings in the `Configure` contexts.

```
WasmEdge_ImportObjectContext *WasiObj = WasmEdge_ImportObjectCreateWASI( /*
... ignored */ );
WasmEdge_ImportObjectContext *ProcObj =
WasmEdge_ImportObjectCreateWasmEdgeProcess( /* ... ignored */ );
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);
/* Register the WASI and WasmEdge_Process into the VM context. */
WasmEdge_VMRegisterModuleFromImport(VMCxt, WasiObj);
WasmEdge_VMRegisterModuleFromImport(VMCxt, ProcObj);
/* Get the WASI exit code. */
uint32_t ExitCode = WasmEdge_ImportObjectWASIGetExitCode(WasiObj);
/*
 * The `ExitCode` will be EXIT_SUCCESS if the execution has no error.
 * Otherwise, it will return with the related exit code.
 */
WasmEdge_VMDelete(VMCxt);
/* The import objects should be deleted. */
WasmEdge_ImportObjectDelete(WasiObj);
WasmEdge_ImportObjectDelete(ProcObj);
```

4. Example

   Assume that a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

   And the `test.c` as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
```

```
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B
  };

  /* Create the import object. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ImportObjectContext *ImpObj =
WasmEdge_ImportObjectCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
  enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
  WasmEdge_FunctionTypeContext *HostFType =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ImportObjectAddFunction(ImpObj, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, ImpObj);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = { WasmEdge_ValueGenI32(1234),
WasmEdge_ValueGenI32(5678) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
    VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);

  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
```

```
  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ImportObjectDelete(ImpObj);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
```

5. Host Data Example

   Developers can set a external data object to the function context, and access to the object in the function body. Assume that a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

   And the `test.c` as following:

```c
#include <wasmedge/wasmedge.h>
#include <stdio.h>

/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  printf("Host function \"Add\": %d + %d\n", Val1, Val2);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  /* Also set the result to the data. */
  int32_t *DataPtr = (int32_t *)Data;
  *DataPtr = Val1 + Val2;
  return WasmEdge_Result_Success;
}

int main() {
  /* Create the VM context. */
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(NULL, NULL);

  /* The WASM module buffer. */
  uint8_t WASM[] = {
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
```

```
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B
  };

  /* The external data object: an integer. */
  int32_t Data;

  /* Create the import object. */
  WasmEdge_String ExportName = WasmEdge_StringCreateByCString("extern");
  WasmEdge_ImportObjectContext *ImpObj =
WasmEdge_ImportObjectCreate(ExportName);
  enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
  enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
  WasmEdge_FunctionTypeContext *HostFType =
WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
  WasmEdge_FunctionInstanceContext *HostFunc =
WasmEdge_FunctionInstanceCreate(HostFType, Add, &Data, 0);
  WasmEdge_FunctionTypeDelete(HostFType);
  WasmEdge_String HostFuncName = WasmEdge_StringCreateByCString("func-
add");
  WasmEdge_ImportObjectAddFunction(ImpObj, HostFuncName, HostFunc);
  WasmEdge_StringDelete(HostFuncName);

  WasmEdge_VMRegisterModuleFromImport(VMCxt, ImpObj);

  /* The parameters and returns arrays. */
  WasmEdge_Value Params[2] = { WasmEdge_ValueGenI32(1234),
WasmEdge_ValueGenI32(5678) };
  WasmEdge_Value Returns[1];
  /* Function name. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("addTwo");
  /* Run the WASM function from file. */
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromBuffer(
    VMCxt, WASM, sizeof(WASM), FuncName, Params, 2, Returns, 1);
```

```
  if (WasmEdge_ResultOK(Res)) {
    printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
  } else {
    printf("Error message: %s\n", WasmEdge_ResultGetMessage(Res));
  }
  printf("Data value: %d\n", Data);

  /* Resources deallocations. */
  WasmEdge_VMDelete(VMCxt);
  WasmEdge_StringDelete(FuncName);
  WasmEdge_ImportObjectDelete(ImpObj);
  return 0;
}
```

Then you can compile and run: (the result of 1234 + 5678 is 6912)

```
$ gcc test.c -lwasmedge_c
$ ./a.out
Host function "Add": 1234 + 5678
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options.

WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

Assume that the WASM file `fibonacci.wasm` is copied into the current directory, and the C file `test.c` is as following:

```
#include <wasmedge/wasmedge.h>
#include <stdio.h>
int main() {
  /* Create the configure context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  /* ... Adjust settings in the configure context. */
  /* Result. */
  WasmEdge_Result Res;

  /* Create the compiler context. The configure context can be NULL. */
  WasmEdge_CompilerContext *CompilerCxt = WasmEdge_CompilerCreate(ConfCxt);
  /* Compile the WASM file with input and output paths. */
  Res = WasmEdge_CompilerCompile(CompilerCxt, "fibonacci.wasm",
"fibonacci.wasm.so");
  if (!WasmEdge_ResultOK(Res)) {
      printf("Compilation failed: %s\n", WasmEdge_ResultGetMessage(Res));
      return 1;
  }

  WasmEdge_CompilerDelete(CompilerCxt);
  WasmEdge_ConfigureDelete(ConfCxt);
  return 0;
}
```

Then you can compile and run (the output file is "fibonacci.wasm.so"):

```
$ gcc test.c -lwasmedge_c
$ ./a.out
[2021-07-02 11:08:08.651] [info] compile start
[2021-07-02 11:08:08.653] [info] verify start
[2021-07-02 11:08:08.653] [info] optimize start
[2021-07-02 11:08:08.670] [info] codegen start
[2021-07-02 11:08:08.706] [info] compile done
```

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
/// AOT compiler optimization level enumeration.
enum WasmEdge_CompilerOptimizationLevel {
  /// Disable as many optimizations as possible.
  WasmEdge_CompilerOptimizationLevel_O0 = 0,
  /// Optimize quickly without destroying debuggability.
  WasmEdge_CompilerOptimizationLevel_O1,
  /// Optimize for fast execution as much as possible without triggering
  /// significant incremental compile time or code size growth.
  WasmEdge_CompilerOptimizationLevel_O2,
  /// Optimize for fast execution as much as possible.
  WasmEdge_CompilerOptimizationLevel_O3,
  /// Optimize for small code size as much as possible without triggering
  /// significant incremental compile time or execution time slowdowns.
  WasmEdge_CompilerOptimizationLevel_Os,
  /// Optimize for small code size as much as possible.
  WasmEdge_CompilerOptimizationLevel_Oz
};

/// AOT compiler output binary format enumeration.
enum WasmEdge_CompilerOutputFormat {
  /// Native dynamic library format.
  WasmEdge_CompilerOutputFormat_Native = 0,
  /// WebAssembly with AOT compiled codes in custom sections.
  WasmEdge_CompilerOutputFormat_Wasm
};
```

Please refer to the AOT compiler options configuration for details.

Upgrade to WasmEdge 0.10.0

Due to the WasmEdge C API breaking changes, this document shows the guideline of programming with WasmEdge C API to upgrade from the `0.9.1` to the `0.10.0` version.

Concepts

1. Merged the `WasmEdge_ImportObjectContext` into the `WasmEdge_ModuleInstanceContext`.

   The `WasmEdge_ImportObjectContext` which is for the host functions is merged into `WasmEdge_ModuleInstanceContext`. Developers can use the related APIs to construct host modules.

   - `WasmEdge_ImportObjectCreate()` is changed to `WasmEdge_ModuleInstanceCreate()`.
   - `WasmEdge_ImportObjectDelete()` is changed to `WasmEdge_ModuleInstanceDelete()`.
   - `WasmEdge_ImportObjectAddFunction()` is changed to `WasmEdge_ModuleInstanceAddFunction()`.
   - `WasmEdge_ImportObjectAddTable()` is changed to `WasmEdge_ModuleInstanceAddTable()`.
   - `WasmEdge_ImportObjectAddMemory()` is changed to `WasmEdge_ModuleInstanceAddMemory()`.
   - `WasmEdge_ImportObjectAddGlobal()` is changed to `WasmEdge_ModuleInstanceAddGlobal()`.
   - `WasmEdge_ImportObjectCreateWASI()` is changed to `WasmEdge_ModuleInstanceCreateWASI()`.
   - `WasmEdge_ImportObjectCreateWasmEdgeProcess()` is changed to `WasmEdge_ModuleInstanceCreateWasmEdgeProcess()`.
   - `WasmEdge_ImportObjectInitWASI()` is changed to `WasmEdge_ModuleInstanceInitWASI()`.
   - `WasmEdge_ImportObjectInitWasmEdgeProcess()` is changed to `WasmEdge_ModuleInstanceInitWasmEdgeProcess()`.

   For the new host function examples, please refer to the example below.

2. Used the pointer to `WasmEdge_FunctionInstanceContext` instead of the index in the

`FuncRef` value type.

For the better performance and security, the `FuncRef` related APIs used the `const WasmEdge_FunctionInstanceContext *` for the parameters and returns.

- `WasmEdge_ValueGenFuncRef()` is changed to use the `const WasmEdge_FunctionInstanceContext *` as it's argument.
- `WasmEdge_ValueGetFuncRef()` is changed to return the `const WasmEdge_FunctionInstanceContext *`.

3. Supported multiple anonymous WASM module instantiation.

   In the version before `0.9.1`, WasmEdge only supports 1 anonymous WASM module to be instantiated at one time. If developers instantiate a new WASM module, the old one will be replaced. After the `0.10.0` version, developers can instantiate multiple anonymous WASM module by `Executor` and get the `Module` instance. But for the source code using the `VM` APIs, the behavior is not changed. For the new examples of instantiating multiple anonymous WASM modules, please refer to the example below.

4. Behavior changed of `WasmEdge_StoreContext`.

   The `Function`, `Table`, `Memory`, and `Global` instances retrievement from the `Store` is moved to the `Module` instance. The `Store` only manage the module linking when instantiation and the named module searching after the `0.10.0` version.

   - `WasmEdge_StoreListFunctionLength()` and `WasmEdge_StoreListFunctionRegisteredLength()` is replaced by `WasmEdge_ModuleInstanceListFunctionLength()`.
   - `WasmEdge_StoreListTableLength()` and `WasmEdge_StoreListTableRegisteredLength()` is replaced by `WasmEdge_ModuleInstanceListTableLength()`.
   - `WasmEdge_StoreListMemoryLength()` and `WasmEdge_StoreListMemoryRegisteredLength()` is replaced by `WasmEdge_ModuleInstanceListMemoryLength()`.
   - `WasmEdge_StoreListGlobalLength()` and `WasmEdge_StoreListGlobalRegisteredLength()` is replaced by `WasmEdge_ModuleInstanceListGlobalLength()`.
   - `WasmEdge_StoreListFunction()` and `WasmEdge_StoreListFunctionRegistered()` is replaced by `WasmEdge_ModuleInstanceListFunction()`.
   - `WasmEdge_StoreListTable()` and `WasmEdge_StoreListTableRegistered()` is replaced by `WasmEdge_ModuleInstanceListTable()`.
   - `WasmEdge_StoreListMemory()` and `WasmEdge_StoreListMemoryRegistered()` is

replaced by `WasmEdge_ModuleInstanceListMemory()`.
- `WasmEdge_StoreListGlobal()` and `WasmEdge_StoreListGlobalRegistered()` is replaced by `WasmEdge_ModuleInstanceListGlobal()`.
- `WasmEdge_StoreFindFunction()` and `WasmEdge_StoreFindFunctionRegistered()` is replaced by `WasmEdge_ModuleInstanceFindFunction()`.
- `WasmEdge_StoreFindTable()` and `WasmEdge_StoreFindTableRegistered()` is replaced by `WasmEdge_ModuleInstanceFindTable()`.
- `WasmEdge_StoreFindMemory()` and `WasmEdge_StoreFindMemoryRegistered()` is replaced by `WasmEdge_ModuleInstanceFindMemory()`.
- `WasmEdge_StoreFindGlobal()` and `WasmEdge_StoreFindGlobalRegistered()` is replaced by `WasmEdge_ModuleInstanceFindGlobal()`.

For the new examples of retrieving instances, please refer to the example below.

5. The `WasmEdge_ModuleInstanceContext`-based resource management.

   Except the creation of `Module` instance for the host functions, the `Executor` will output a `Module` instance after instantiation. No matter the anonymous or named modules, developers have the responsibility to destroy them by `WasmEdge_ModuleInstanceDelete()` API. The `Store` will link to the named `Module` instance after registering. After the destroyment of a `Module` instance, the `Store` will unlink to that automatically; after the destroyment of the `Store`, the all `Module` instances the `Store` linked to will unlink to that `Store` automatically.

WasmEdge VM changes

The `VM` APIs are basically not changed, except the `ImportObject` related APIs.

The following is the example of WASI initialization in WasmEdge `0.9.1` C API:

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt, WasmEdge_HostRegistration_Wasi);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration import objects from the
VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not set
into the configuration. */
WasmEdge_ImportObjectContext *WasiObject =
    WasmEdge_VMGetImportModuleContext(VMCxt, WasmEdge_HostRegistration_Wasi);
/* Initialize the WASI. */
WasmEdge_ImportObjectInitWASI(WasiObject, /* ... ignored */ );

/* ... */

WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

Developers can change to use the WasmEdge `0.10.0` C API as follows, with only replacing the `WasmEdge_ImportObjectContext` into `WasmEdge_ModuleInstanceContext`:

```
WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
WasmEdge_ConfigureAddHostRegistration(ConfCxt, WasmEdge_HostRegistration_Wasi);
WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
/* The following API can retrieve the pre-registration module instances from
the VM context. */
/* This API will return `NULL` if the corresponding pre-registration is not set
into the configuration. */
WasmEdge_ModuleInstanceContext *WasiModule =
    WasmEdge_VMGetImportModuleContext(VMCxt, WasmEdge_HostRegistration_Wasi);
/* Initialize the WASI. */
WasmEdge_ModuleInstanceInitWASI(WasiModule, /* ... ignored */ );

/* ... */

WasmEdge_VMDelete(VMCxt);
WasmEdge_ConfigureDelete(ConfCxt);
```

The `VM` provides a new API for getting the current instantiated anonymous `Module` instance. For example, if developer want to get the exported `Global` instance:

```
/* Assume that a WASM module is instantiated in `VMCxt`, and exports the
"global_i32". */
WasmEdge_StoreContext *StoreCxt = WasmEdge_VMGetStoreContext(VMCxt);
WasmEdge_String GlobName = WasmEdge_StringCreateByCString("global_i32");
WasmEdge_GlobalInstanceContext *GlobCxt = WasmEdge_StoreFindGlobal(StoreCxt,
GlobName);
WasmEdge_StringDelete(GlobName);
```

After the WasmEdge `0.10.0` C API, developers can use the `WasmEdge_VMGetActiveModule()` to get the module instance:

```
/* Assume that a WASM module is instantiated in `VMCxt`, and exports the
"global_i32". */
const WasmEdge_ModuleInstanceContext *ModCxt =
WasmEdge_VMGetActiveModule(VMCxt);
/* The example of retrieving the global instance. */
WasmEdge_String GlobName = WasmEdge_StringCreateByCString("global_i32");
WasmEdge_GlobalInstanceContext *GlobCxt =
WasmEdge_ModuleInstanceFindGlobal(ModCxt, GlobName);
WasmEdge_StringDelete(GlobName);
```

WasmEdge Executor changes

`Executor` helps to instantiate a WASM module, register a WASM module into `Store` with module name, register the host modules with host functions, or invoke functions.

1. WASM module instantiation

   In WasmEdge `0.9.1` version, developers can instantiate a WASM module by the `Executor` API:

   ```
   WasmEdge_ASTModuleContext *ASTCxt;
   /*
    * Assume that `ASTCxt` is a loaded WASM from file or buffer and has passed
   the validation.
    * Assume that `ExecCxt` is a `WasmEdge_ExecutorContext`.
    * Assume that `StoreCxt` is a `WasmEdge_StoreContext`.
    */
   WasmEdge_Result Res = WasmEdge_ExecutorInstantiate(ExecCxt, StoreCxt,
   ASTCxt);
   if (!WasmEdge_ResultOK(Res)) {
     printf("Instantiation phase failed: %s\n",
   WasmEdge_ResultGetMessage(Res));
   }
   ```

   Then the WASM module is instantiated into an anonymous module instance and handled by the `Store`. If a new WASM module is instantiated by this API, the old instantiated module instance will be cleaned. After the WasmEdge `0.10.0` version, the instantiated anonymous module will be outputted and handled by caller, and not only

1 anonymous module instance can be instantiated. Developers have the responsibility to destroy the outputted module instances.

```
WasmEdge_ASTModuleContext *ASTCxt1, *ASTCxt2;
/*
 * Assume that `ASTCxt1` and `ASTCxt2` are loaded WASMs from different
files or buffers,
 * and have both passed the validation.
 * Assume that `ExecCxt` is a `WasmEdge_ExecutorContext`.
 * Assume that `StoreCxt` is a `WasmEdge_StoreContext`.
 */
WasmEdge_ModuleInstanceContext *ModCxt1 = NULL;
WasmEdge_ModuleInstanceContext *ModCxt2 = NULL;
WasmEdge_Result Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt1,
StoreCxt, ASTCxt1);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}
Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt2, StoreCxt, ASTCxt2);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}
```

2. WASM module registration with module name

When instantiating and registering a WASM module with module name, developers can use the `WasmEdge_ExecutorRegisterModule()` API before WasmEdge `0.9.1`.

```
WasmEdge_ASTModuleContext *ASTCxt;
/*
 * Assume that `ASTCxt` is a loaded WASM from file or buffer and has passed
the validation.
 * Assume that `ExecCxt` is a `WasmEdge_ExecutorContext`.
 * Assume that `StoreCxt` is a `WasmEdge_StoreContext`.
 */

/* Register the WASM module into store with the export module name "mod".
*/
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
Res = WasmEdge_ExecutorRegisterModule(ExecCxt, StoreCxt, ASTCxt, ModName);
WasmEdge_StringDelete(ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
```

The same feature is implemented in WasmEdge `0.10.0`, but in different API `WasmEdge_ExecutorRegister()`:

```
WasmEdge_ASTModuleContext *ASTCxt;
/*
 * Assume that `ASTCxt` is a loaded WASM from file or buffer and has passed
the validation.
 * Assume that `ExecCxt` is a `WasmEdge_ExecutorContext`.
 * Assume that `StoreCxt` is a `WasmEdge_StoreContext`.
 */

/* Register the WASM module into store with the export module name "mod".
*/
WasmEdge_String ModName = WasmEdge_StringCreateByCString("mod");
/* The output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
Res = WasmEdge_ExecutorRegister(ExecCxt, &ModCxt, StoreCxt, ASTCxt,
ModName);
WasmEdge_StringDelete(ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("WASM registration failed: %s\n", WasmEdge_ResultGetMessage(Res));
}
```

Developers have the responsibility to destroy the outputted module instances.

3. Host module registration

In WasmEdge `0.9.1`, developers can create a `WasmEdge_ImportObjectContext` and register into `Store`.

```
/* Create the import object with the export module name. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module");
WasmEdge_ImportObjectContext *ImpObj =
WasmEdge_ImportObjectCreate(ModName);
WasmEdge_StringDelete(ModName);
/*
 * ...
 * Add the host functions, tables, memories, and globals into the import
object.
 */
/* The import module context has already contained the export module name.
*/
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, ImpObj);
if (!WasmEdge_ResultOK(Res)) {
  printf("Import object registration failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}
```

After WasmEdge `0.10.0`, developers should use the `WasmEdge_ModuleInstanceContext` instead:

```
/* Create the module instance with the export module name. */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module");
WasmEdge_ModuleInstanceContext *ModCxt =
WasmEdge_ModuleInstanceCreate(ModName);
WasmEdge_StringDelete(ModName);
/*
 * ...
 * Add the host functions, tables, memories, and globals into the module
instance.
 */
/* The module instance context has already contained the export module
name. */
Res = WasmEdge_ExecutorRegisterImport(ExecCxt, StoreCxt, ModCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Module instance registration failed: %s\n",
WasmEdge_ResultGetMessage(Res));
}
```

Developers have the responsibility to destroy the created module instances.

4. WASM function invocation

   This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat. In WasmEdge `0.9.1` version, developers can invoke a WASM function with the export function name:

```
/* Create the store context. The store context holds the instances. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(NULL);
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(NULL);
/* Create the executor context. The configure context and the statistics
context can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(NULL, NULL);

/* Load the WASM file or the compiled-WASM file and convert into the AST
module context. */
WasmEdge_ASTModuleContext *ASTCxt = NULL;
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Validate the WASM module. */
Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Instantiate the WASM module into the store context. */
Res = WasmEdge_ExecutorInstantiate(ExecCxt, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Invoke the function which is exported with the function name "fib". */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(18) };
WasmEdge_Value Returns[1];
Res = WasmEdge_ExecutorInvoke(ExecCxt, StoreCxt, FuncName, Params, 1,
Returns, 1);
```

```
if (WasmEdge_ResultOK(Res)) {
  printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
} else {
  printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}

WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StoreDelete(StoreCxt);
```

After the WasmEdge `0.10.0`, developers should retrieve the `Function` instance by function name first.

```
/*
 * ...
 * Ignore the unchanged steps before validation. Please refer to the sample
code above.
 */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
/* Instantiate the WASM module. */
Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt1, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n",
WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Retrieve the function instance by name. */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FuncCxt =
WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
WasmEdge_StringDelete(FuncName);
/* Invoke the function. */
WasmEdge_Value Params[1] = { WasmEdge_ValueGenI32(18) };
WasmEdge_Value Returns[1];
Res = WasmEdge_ExecutorInvoke(ExecCxt, FuncCxt, Params, 1, Returns, 1);
if (WasmEdge_ResultOK(Res)) {
  printf("Get the result: %d\n", WasmEdge_ValueGetI32(Returns[0]));
} else {
  printf("Execution phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}

WasmEdge_ModuleInstanceDelete(ModCxt);
WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StoreDelete(StoreCxt);
```

Instances retrievement

This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

Before the WasmEdge `0.9.1` versions, developers can retrieve all exported instances of named or anonymous modules from `Store`:

```
/* Create the store context. The store context holds the instances. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(NULL);
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(NULL);
/* Create the executor context. The configure context and the statistics
context can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(NULL, NULL);

/* Load the WASM file or the compiled-WASM file and convert into the AST module
context. */
WasmEdge_ASTModuleContext *ASTCxt = NULL;
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Validate the WASM module. */
Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Example: register and instantiate the WASM module with the module name
"module_fib". */
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module_fib");
Res = WasmEdge_ExecutorRegisterModule(ExecCxt, StoreCxt, ASTCxt, ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Example: Instantiate the WASM module into the store context. */
Res = WasmEdge_ExecutorInstantiate(ExecCxt, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
WasmEdge_StringDelete(ModName);

/* Now, developers can retrieve the exported instances from the store. */
/* Take the exported functions as example. This WASM exports the function
"fib". */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
WasmEdge_FunctionInstanceContext *FoundFuncCxt;
/* Find the function "fib" from the instantiated anonymous module. */
FoundFuncCxt = WasmEdge_StoreFindFunction(StoreCxt, FuncName);
/* Find the function "fib" from the registered module "module_fib". */
ModName = WasmEdge_StringCreateByCString("module_fib");
```

```
FoundFuncCxt = WasmEdge_StoreFindFunctionRegistered(StoreCxt, ModName,
FuncName);
WasmEdge_StringDelete(ModName);
WasmEdge_StringDelete(FuncName);

WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StoreDelete(StoreCxt);
```

After the WasmEdge `0.10.0`, developers can instantiate several anonymous `Module` instances, and should retrieve the exported instances from named or anonymous `Module` instances:

```
/* Create the store context. The store context is the object to link the
modules for imports and exports. */
WasmEdge_StoreContext *StoreCxt = WasmEdge_StoreCreate();
/* Result. */
WasmEdge_Result Res;

/* Create the loader context. The configure context can be NULL. */
WasmEdge_LoaderContext *LoadCxt = WasmEdge_LoaderCreate(NULL);
/* Create the validator context. The configure context can be NULL. */
WasmEdge_ValidatorContext *ValidCxt = WasmEdge_ValidatorCreate(NULL);
/* Create the executor context. The configure context and the statistics
context can be NULL. */
WasmEdge_ExecutorContext *ExecCxt = WasmEdge_ExecutorCreate(NULL, NULL);

/* Load the WASM file or the compiled-WASM file and convert into the AST module
context. */
WasmEdge_ASTModuleContext *ASTCxt = NULL;
Res = WasmEdge_LoaderParseFromFile(LoadCxt, &ASTCxt, "fibonacci.wasm");
if (!WasmEdge_ResultOK(Res)) {
  printf("Loading phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Validate the WASM module. */
Res = WasmEdge_ValidatorValidate(ValidCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Validation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Example: register and instantiate the WASM module with the module name
"module_fib". */
WasmEdge_ModuleInstanceContext *NamedModCxt = NULL;
WasmEdge_String ModName = WasmEdge_StringCreateByCString("module_fib");
Res = WasmEdge_ExecutorRegister(ExecCxt, &NamedModCxt, StoreCxt, ASTCxt,
ModName);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
/* Example: Instantiate the WASM module and get the output module instance. */
WasmEdge_ModuleInstanceContext *ModCxt = NULL;
Res = WasmEdge_ExecutorInstantiate(ExecCxt, &ModCxt, StoreCxt, ASTCxt);
if (!WasmEdge_ResultOK(Res)) {
  printf("Instantiation phase failed: %s\n", WasmEdge_ResultGetMessage(Res));
  return -1;
}
WasmEdge_StringDelete(ModName);

/* Now, developers can retrieve the exported instances from the module
instances. */
/* Take the exported functions as example. This WASM exports the function
"fib". */
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("fib");
```

```
WasmEdge_FunctionInstanceContext *FoundFuncCxt;
/* Find the function "fib" from the instantiated anonymous module. */
FoundFuncCxt = WasmEdge_ModuleInstanceFindFunction(ModCxt, FuncName);
/* Find the function "fib" from the registered module "module_fib". */
FoundFuncCxt = WasmEdge_ModuleInstanceFindFunction(NamedModCxt, FuncName);
/* Or developers can get the named module instance from the store: */
ModName = WasmEdge_StringCreateByCString("module_fib");
const WasmEdge_ModuleInstanceContext *ModCxtGot =
WasmEdge_StoreFindModule(StoreCxt, ModName);
WasmEdge_StringDelete(ModName);
FoundFuncCxt = WasmEdge_ModuleInstanceFindFunction(ModCxtGot, FuncName);
WasmEdge_StringDelete(FuncName);

WasmEdge_ModuleInstanceDelete(NamedModCxt);
WasmEdge_ModuleInstanceDelete(ModCxt);
WasmEdge_ASTModuleDelete(ASTCxt);
WasmEdge_LoaderDelete(LoadCxt);
WasmEdge_ValidatorDelete(ValidCxt);
WasmEdge_ExecutorDelete(ExecCxt);
WasmEdge_StoreDelete(StoreCxt);
```

Host functions

The difference of host functions are the replacement of `WasmEdge_ImportObjectContext`.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create the import object. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ImportObjectContext *ImpObj = WasmEdge_ImportObjectCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the import object. */
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ImportObjectAddFunction(ImpObj, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/*
 * The import objects should be deleted.
 * Developers should __NOT__ destroy the instances added into the import object
contexts.
 */
WasmEdge_ImportObjectDelete(ImpObj);
```

Developers can use the `WasmEdge_ModuleInstanceContext` to upgrade to WasmEdge `0.10.0` easily.

```
/* Host function body definition. */
WasmEdge_Result Add(void *Data, WasmEdge_MemoryInstanceContext *MemCxt,
                    const WasmEdge_Value *In, WasmEdge_Value *Out) {
  int32_t Val1 = WasmEdge_ValueGetI32(In[0]);
  int32_t Val2 = WasmEdge_ValueGetI32(In[1]);
  Out[0] = WasmEdge_ValueGenI32(Val1 + Val2);
  return WasmEdge_Result_Success;
}

/* Create a module instance. */
WasmEdge_String ExportName = WasmEdge_StringCreateByCString("module");
WasmEdge_ModuleInstanceContext *HostModCxt =
WasmEdge_ModuleInstanceCreate(ExportName);
WasmEdge_StringDelete(ExportName);

/* Create and add a function instance into the module instance. */
enum WasmEdge_ValType ParamList[2] = { WasmEdge_ValType_I32,
WasmEdge_ValType_I32 };
enum WasmEdge_ValType ReturnList[1] = { WasmEdge_ValType_I32 };
WasmEdge_FunctionTypeContext *HostFType =
    WasmEdge_FunctionTypeCreate(ParamList, 2, ReturnList, 1);
WasmEdge_FunctionInstanceContext *HostFunc =
    WasmEdge_FunctionInstanceCreate(HostFType, Add, NULL, 0);
/*
 * The third parameter is the pointer to the additional data object.
 * Developers should guarantee the life cycle of the data, and it can be
 * `NULL` if the external data is not needed.
 */
WasmEdge_FunctionTypeDelete(HostFType);
WasmEdge_String FuncName = WasmEdge_StringCreateByCString("add");
WasmEdge_ModuleInstanceAddFunction(HostModCxt, FuncName, HostFunc);
WasmEdge_StringDelete(FuncName);

/*
 * The module instance should be deleted.
 * Developers should __NOT__ destroy the instances added into the module
instance contexts.
 */
WasmEdge_ModuleInstanceDelete(HostModCxt);
```

WasmEdge Go SDK

The following are the guide to work with the WasmEdge Go API. You can embed the WasmEdge into your go application through the WasmEdge Go API.

Getting Started

The WasmEdge-go requires golang version >= 1.16. Please check your golang version before installation. You can download golang here.

```
$ go version
go version go1.16.5 linux/amd64
```

Meantime, please make sure you have installed the WasmEdge shared library with the same `WasmEdge-go` release version.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2
```

If you need the `TensorFlow` or `Image` extension for `WasmEdge-go`, please install the `WasmEdge` with extensions:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2 -e tensorflow,image
```

Noticed that the `TensorFlow` and `Image` extensions are only for the `Linux` platforms.

Install the `WasmEdge-go` package and build in your Go project directory:

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build
```

WasmEdge-go Extensions

By default, the `WasmEdge-go` only turns on the basic runtime.

`WasmEdge-go` has the following extensions:

- TensorFlow
  - This extension supports the host functions in WasmEdge-tensorflow.
  - To install the `tensorflow` extension, please use the `-e tensorflow` flag in the WasmEdge installer command.
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflow
    ```

- Image
  - This extension supports the host functions in WasmEdge-image.
  - To install the `image` extension, please use the `-e image` flag in the WasmEdge installer command.
  - For using this extension, the tag `image` when building is required:

    ```
    go build -tags image
    ```

You can also turn on the multiple extensions when building:

```
go build -tags image,tensorflow
```

For examples, please refer to the example repository.

WasmEdge AOT Compiler in Go

The go_WasmAOT example demonstrates how to compile a WASM file into a native binary (AOT compile) from within a Go application.

Examples

- Embed a standalone Wasm app
- Embed a Wasm function
- Pass complex parameters to Wasm functions
- Embed a Tensorflow inference function

API References

Embed a standalone WASM app

The WasmEdge Go SDK can embed standalone WebAssembly applications — ie a Rust application with a `main()` function compiled into WebAssembly.

Our demo Rust application reads from a file. Note that the WebAssembly program's input and output data are now passed by the STDIN and STDOUT.

```
use std::env;
use std::fs::File;
use std::io::{self, BufRead};

fn main() {
  // Get the argv.
  let args: Vec<String> = env::args().collect();
  if args.len() <= 1 {
    println!("Rust: ERROR - No input file name.");
    return;
  }

  // Open the file.
  println!("Rust: Opening input file \"{}\"...", args[1]);
  let file = match File::open(&args[1]) {
    Err(why) => {
      println!("Rust: ERROR - Open file \"{}\" failed: {}", args[1], why);
      return;
    },
    Ok(file) => file,
  };

  // Read lines.
  let reader = io::BufReader::new(file);
  let mut texts:Vec<String> = Vec::new();
  for line in reader.lines() {
    if let Ok(text) = line {
      texts.push(text);
    }
  }
  println!("Rust: Read input file \"{}\" succeeded.", args[1]);

  // Get stdin to print lines.
  println!("Rust: Please input the line number to print the line of file.");
  let stdin = io::stdin();
  for line in stdin.lock().lines() {
    let input = line.unwrap();
    match input.parse::<usize>() {
      Ok(n) => if n > 0 && n <= texts.len() {
        println!("{}", texts[n - 1]);
      } else {
        println!("Rust: ERROR - Line \"{}\" is out of range.", n);
      },
      Err(e) => println!("Rust: ERROR - Input \"{}\" is not an integer: {}",
input, e),
    }
  }
  println!("Rust: Process end.");
}
```

Compile the application into WebAssembly.

```
cd rust_readfile
cargo build --target wasm32-wasi
# The output file will be target/wasm32-wasi/debug/rust_readfile.wasm
```

The Go source code to run the WebAssembly function in WasmEdge is as follows.

```
package main

import (
  "os"
  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()

  var conf = wasmedge.NewConfigure(wasmedge.REFERENCE_TYPES)
  conf.AddConfig(wasmedge.WASI)
  var vm = wasmedge.NewVMWithConfig(conf)
  var wasi = vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping directories
  )

  // Instantiate wasm. _start refers to the main() function
  vm.RunWasmFile(os.Args[1], "_start")

  vm.Release()
  conf.Release()
}
```

Next, let's build the Go application with the WasmEdge Go SDK.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build
```

Run the Golang application.

```
$ ./read_file rust_readfile/target/wasm32-wasi/debug/rust_readfile.wasm
file.txt
Rust: Opening input file "file.txt"...
Rust: Read input file "file.txt" succeeded.
Rust: Please input the line number to print the line of file.
# Input "5" and press Enter.
5
# The output will be the 5th line of `file.txt`:
abcDEF___!@#$%^
# To terminate the program, send the EOF (Ctrl + D).
^D
# The output will print the terminate message:
Rust: Process end.
```

More examples can be found at the WasmEdge-go-examples GitHub repo.

Embed a Wasm function

The WasmEdge Go SDK allows WebAssembly functions to be embedded into a Go host app. You can use the Go SDK API to pass call parameters to the embedded WebAssembly functions, and then capture the return values. However, the WebAssembly spec only supports a few simple data types out of the box. It does not support types such as string and array. In order to pass rich types in Go to WebAssembly, we could hand-code memory pointers (see here), or use an automated tool to manage the data exchange.

The wasmedge-bindgen project provides Rust macros for functions to accept and return complex data types, and then for Go functions to call such Rust functions running in WasmEdge. The full source code for the demo in this chapter is available here.

Rust function compiled into WebAssembly

In the Rust project, all you need is to annotate your functions with a `[wasmedge_bindgen]` macro. Those annotated functions will be automatically instrumented by the Rust compiler and turned into WebAssembly functions that can be called from the bindgen related functions of WasmEdge GO SDK. In the example below, we have several Rust functions that take complex call parameters and return complex values.

```
use wasmedge_bindgen::*;
use wasmedge_bindgen_macro::*;
use num_integer::lcm;
use sha3::{Digest, Sha3_256, Keccak256};
use serde::{Serialize, Deserialize};

#[derive(Serialize, Deserialize, Debug)]
struct Point {
  x: f32,
  y: f32
}

#[derive(Serialize, Deserialize, Debug)]
struct Line {
  points: Vec<Point>,
  valid: bool,
  length: f32,
  desc: String
}

#[wasmedge_bindgen]
pub fn create_line(p1: String, p2: String, desc: String) -> Result<Vec<u8>,
String> {
  let point1: Point = serde_json::from_str(p1.as_str()).unwrap();
  let point2: Point = serde_json::from_str(p2.as_str()).unwrap();
  let length = ((point1.x - point2.x) * (point1.x - point2.x) + (point1.y -
point2.y) * (point1.y - point2.y)).sqrt();

  let valid = if length == 0.0 { false } else { true };

  let line = Line { points: vec![point1, point2], valid: valid, length: length,
desc: desc };

  return Ok(serde_json::to_vec(&line).unwrap());
}

#[wasmedge_bindgen]
pub fn say(s: String) -> Result<Vec<u8>, String> {
  let r = String::from("hello ");
  return Ok((r + s.as_str()).as_bytes().to_vec());
}

#[wasmedge_bindgen]
pub fn obfusticate(s: String) -> Result<Vec<u8>, String> {
  let r: String = (&s).chars().map(|c| {
    match c {
      'A' ..= 'M' | 'a' ..= 'm' => ((c as u8) + 13) as char,
      'N' ..= 'Z' | 'n' ..= 'z' => ((c as u8) - 13) as char,
      _ => c
    }
  }).collect();
  Ok(r.as_bytes().to_vec())
```

```
}

#[wasmedge_bindgen]
pub fn lowest_common_multiple(a: i32, b: i32) -> Result<Vec<u8>, String> {
  let r = lcm(a, b);
  return Ok(r.to_string().as_bytes().to_vec());
}

#[wasmedge_bindgen]
pub fn sha3_digest(v: Vec<u8>) -> Result<Vec<u8>, String> {
  return Ok(Sha3_256::digest(&v).as_slice().to_vec());
}

#[wasmedge_bindgen]
pub fn keccak_digest(s: Vec<u8>) -> Result<Vec<u8>, String> {
  return Ok(Keccak256::digest(&s).as_slice().to_vec());
}
```

You can build the WebAssembly bytecode file using standard `Cargo` commands.

```
cd rust_bindgen_funcs
cargo build --target wasm32-wasi --release
# The output WASM will be target/wasm32-wasi/release
/rust_bindgen_funcs_lib.wasm.
cp target/wasm32-wasi/release/rust_bindgen_funcs_lib.wasm ../
cd ../
```

Go host application

In the Go host application, you can create and set up the WasmEdge VM using the WasmEdge Go SDK. However, instead of calling `vm.Instantiate()`, you should now call `bindgen.Instantiate(vm)` to instantiate the VM and return a `bindgen` object.

```
func main() {
  // Expected Args[0]: program name (./bindgen_funcs)
  // Expected Args[1]: wasm file (rust_bindgen_funcs_lib.wasm))

  wasmedge.SetLogErrorLevel()
  var conf = wasmedge.NewConfigure(wasmedge.WASI)
  var vm = wasmedge.NewVMWithConfig(conf)
  var wasi = vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping preopens
  )
  vm.LoadWasmFile(os.Args[1])
  vm.Validate()

  // Instantiate the bindgen and vm
  bg := bindgen.Instantiate(vm)
```

Next, you can call any `[wasmedge_bindgen]` annotated functions in the VM via the `bindgen` object.

```
  // create_line: string, string, string -> string (inputs are JSON
stringified)
  res, err := bg.Execute("create_line", "{\"x\":2.5,\"y\":7.8}", "{\"x\":2.5,
\"y\":5.8}", "A thin red line")
  if err == nil {
    fmt.Println("Run bindgen -- create_line:", string(res))
  } else {
    fmt.Println("Run bindgen -- create_line FAILED", err)
  }

  // say: string -> string
  res, err = bg.Execute("say", "bindgen funcs test")
  if err == nil {
    fmt.Println("Run bindgen -- say:", string(res))
  } else {
    fmt.Println("Run bindgen -- say FAILED")
  }

  // obfusticate: string -> string
  res, err = bg.Execute("obfusticate", "A quick brown fox jumps over the lazy
dog")
  if err == nil {
    fmt.Println("Run bindgen -- obfusticate:", string(res))
  } else {
    fmt.Println("Run bindgen -- obfusticate FAILED")
  }

  // lowest_common_multiple: i32, i32 -> i32
  res, err = bg.Execute("lowest_common_multiple", int32(123), int32(2))
  if err == nil {
    num, _ := strconv.ParseInt(string(res), 10, 32)
    fmt.Println("Run bindgen -- lowest_common_multiple:", num)
  } else {
    fmt.Println("Run bindgen -- lowest_common_multiple FAILED")
  }

  // sha3_digest: array -> array
  res, err = bg.Execute("sha3_digest", []byte("This is an important message"))
  if err == nil {
    fmt.Println("Run bindgen -- sha3_digest:", res)
  } else {
    fmt.Println("Run bindgen -- sha3_digest FAILED")
  }

  // keccak_digest: array -> array
  res, err = bg.Execute("keccak_digest", []byte("This is an important
message"))
  if err == nil {
    fmt.Println("Run bindgen -- keccak_digest:", res)
  } else {
    fmt.Println("Run bindgen -- keccak_digest FAILED")
  }
```

```
  bg.Release()
  vm.Release()
  conf.Release()
}
```

Finally, you can build and run the Go host application.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build
./bindgen_funcs rust_bindgen_funcs_lib.wasm
```

The standard output of this example will be the following.

```
Run bindgen -- create_line: {"points":[{"x":1.5,"y":3.8},
{"x":2.5,"y":5.8}],"valid":true,"length":2.2360682,"desc":"A thin red line"}
Run bindgen -- say: hello bindgen funcs test
Run bindgen -- obfusticate: N dhvpx oebja sbk whzcf bire gur ynml qbt
Run bindgen -- lowest_common_multiple: 246
Run bindgen -- sha3_digest: [87 27 231 209 189 105 251 49 159 10 211 250 15 159
154 181 43 218 26 141 56 199 25 45 60 10 20 163 54 211 195 203]
Run bindgen -- keccak_digest: [126 194 241 200 151 116 227 33 216 99 159 22 107
3 177 169 216 191 114 156 174 193 32 159 246 228 245 133 52 75 55 27]
```

Pass complex parameters to Wasm functions

An issue with the WebAssembly spec is that it only supports a very limited number of data types. If you want to embed a WebAssembly function with complex call parameters or return values, you will need to manage memory pointers both on Go SDK and WebAssembly function sides. Such complex call parameters and return values include dynamic memory structures such as strings and byte arrays. In this section, we will discuss several examples.

Pass strings to Rust functions

In this example, we will demonstrate how to call a Rust-based WebAssembly function from a Go app. Specially, we will discuss how to pass string data.

> An alternative approach to pass and return complex values to Rust functions in WebAssembly is to use the `wasmedge_bindgen` compiler tool. You can learn more here.

The Rust function takes a memory pointer for the string, and constructs the Rust string itself.

```
use std::ffi::{CStr, CString};
use std::mem;
use std::os::raw::{c_char, c_void};

#[no_mangle]
pub extern fn allocate(size: usize) -> *mut c_void {
  let mut buffer = Vec::with_capacity(size);
  let pointer = buffer.as_mut_ptr();
  mem::forget(buffer);

  pointer as *mut c_void
}

#[no_mangle]
pub extern fn deallocate(pointer: *mut c_void, capacity: usize) {
  unsafe {
    let _ = Vec::from_raw_parts(pointer, 0, capacity);
  }
}

#[no_mangle]
pub extern fn greet(subject: *mut c_char) -> *mut c_char {
  let subject = unsafe { CStr::from_ptr(subject).to_bytes().to_vec() };
  let mut output = b"Hello, ".to_vec();
  output.extend(&subject);
  output.extend(&[b'!']);

  unsafe { CString::from_vec_unchecked(output) }.into_raw()
}
```

Use standard Rust compiler tools to compile the Rust source code into a WebAssembly bytecode application.

```
cd rust_memory_greet
cargo build --target wasm32-wasi
# The output WASM will be `target/wasm32-wasi/debug
/rust_memory_greet_lib.wasm`.
```

The Go SDK application must call `allocate` from the WasmEdge VM to get a pointer to the string parameter. It will then call the `greet` function in Rust with the pointer. After the function returns, the Go application will call `deallocate` to free the memory space.

```
package main

import (
  "fmt"
  "os"
  "strings"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  vm := wasmedge.NewVMWithConfig(conf)

  wasi := vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],
    os.Environ(),
    []string{".:."},
  )

  err := vm.LoadWasmFile(os.Args[1])
  if err != nil {
    fmt.Println("failed to load wasm")
  }
  vm.Validate()
  vm.Instantiate()

  subject := "WasmEdge"
  lengthOfSubject := len(subject)

  // Allocate memory for the subject, and get a pointer to it.
  // Include a byte for the NULL terminator we add below.
  allocateResult, _ := vm.Execute("allocate", int32(lengthOfSubject + 1))
  inputPointer := allocateResult[0].(int32)

  // Write the subject into the memory.
  mod := vm.GetActiveModule()
  mem := mod.FindMemory("memory")
  memData, _ := mem.GetData(uint(inputPointer), uint(lengthOfSubject+1))
  copy(memData, subject)

  // C-string terminates by NULL.
  memData[lengthOfSubject] = 0

  // Run the `greet` function. Given the pointer to the subject.
  greetResult, _ := vm.Execute("greet", inputPointer)
  outputPointer := greetResult[0].(int32)

  pageSize := mem.GetPageSize()
  // Read the result of the `greet` function.
```

```
  memData, _ = mem.GetData(uint(0), uint(pageSize * 65536))
  nth := 0
  var output strings.Builder

  for {
    if memData[int(outputPointer) + nth] == 0 {
      break
    }

    output.WriteByte(memData[int(outputPointer) + nth])
    nth++
  }

  lengthOfOutput := nth

  fmt.Println(output.String())

  // Deallocate the subject, and the output.
  vm.Execute("deallocate", inputPointer, int32(lengthOfSubject+1))
  vm.Execute("deallocate", outputPointer, int32(lengthOfOutput+1))

  vm.Release()
  conf.Release()
}
```

To build the Go SDK example, run the following commands.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build greet_memory.go
```

Now you can use the Go application to run the WebAssembly plug-in compiled from Rust.

```
$ ./greet_memory rust_memory_greet_lib.wasm
Hello, WasmEdge!
```

Pass strings to TinyGo functions

In this example, we will demonstrate how to call a TinyGo-based WebAssembly function from a Go app.

The TinyGo function takes a memory pointer for the string, and constructs the TinyGo string itself.

The empty `main()` is needed to the compiled WebAssembly program to set up WASI

properly.

```
package main

import (
  "strings"
  "unsafe"
)

func main() {}

//export greet
func greet(subject *int32) *int32 {
  nth := 0
  var subjectStr strings.Builder
  pointer := uintptr(unsafe.Pointer(subject))
  for {
    s := *(*int32)(unsafe.Pointer(pointer + uintptr(nth)))
    if s == 0 {
      break
    }

    subjectStr.WriteByte(byte(s))
    nth++
  }

  output := []byte("Hello, " + subjectStr.String() + "!")

  r := make([]int32, 2)
  r[0] = int32(uintptr(unsafe.Pointer(&(output[0]))))
  r[1] = int32(len(output))

  return &r[0]
}
```

Use the TinyGo compiler tools to compile the Go source code into a WebAssembly bytecode application.

```
tinygo build -o greet.wasm -target wasi greet.go
```

The Go SDK application must call `malloc` from the WasmEdge VM to get a pointer to the string parameter. It will then call the `greet` function in TinyGo with the pointer. After the function returns, the Go application will call `free` to free the memory space.

```
package main

import (
  "fmt"
  "os"
  "encoding/binary"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  vm := wasmedge.NewVMWithConfig(conf)

  wasi := vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],
    os.Environ(),
    []string{".:."},
  )

  err := vm.LoadWasmFile(os.Args[1])
  if err != nil {
    fmt.Println("failed to load wasm")
  }
  vm.Validate()
  vm.Instantiate()

  subject := "WasmEdge"
  lengthOfSubject := len(subject)

  // Allocate memory for the subject, and get a pointer to it.
  // Include a byte for the NULL terminator we add below.
  allocateResult, _ := vm.Execute("malloc", int32(lengthOfSubject+1))
  inputPointer := allocateResult[0].(int32)

  // Write the subject into the memory.
  mod := vm.GetActiveModule()
  mem := mod.FindMemory("memory")
  memData, _ := mem.GetData(uint(inputPointer), uint(lengthOfSubject+1))
  copy(memData, subject)

  // C-string terminates by NULL.
  memData[lengthOfSubject] = 0

  // Run the `greet` function. Given the pointer to the subject.
  greetResult, _ := vm.Execute("greet", inputPointer)
  outputPointer := greetResult[0].(int32)

  memData, _ = mem.GetData(uint(outputPointer), 8)
  resultPointer := binary.LittleEndian.Uint32(memData[:4])
```

```
    resultLength := binary.LittleEndian.Uint32(memData[4:])

    // Read the result of the `greet` function.
    memData, _ = mem.GetData(uint(resultPointer), uint(resultLength))
    fmt.Println(string(memData))

    // Deallocate the subject, and the output.
    vm.Execute("free", inputPointer)

    vm.Release()
    conf.Release()
}
```

To build the Go SDK example, run the following commands.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build greet_memory.go
```

Now you can use the Go application to run the WebAssembly plug-in compiled from TinyGo.

```
$ ./greet_memory greet.wasm
Hello, WasmEdge!
```

Pass bytes to Rust functions

In this example, we will demonstrate how to call Rust-based WebAssembly functions and pass arrays to and from a Go app.

> An alternative approach to pass and return complex values to Rust functions in WebAssembly is to use the `wasmedge_bindgen` compiler tool. You can learn more here.

The `fib_array()` function takes a array as a call parameter and fill it with a fibonacci sequence of numbers. Alternatively, the `fib_array_return_memory()` function returns a array of fibonacci sequence of numbers.

For the array in the call parameter, the Rust function `fib_array()` takes a memory pointer and constructs the Rust `Vec` using `from_raw_parts`. For the array return value, the Rust function `fib_array_return_memory()` simply returns the pointer.

```
use std::mem;
use std::os::raw::{c_void, c_int};

#[no_mangle]
pub extern fn allocate(size: usize) -> *mut c_void {
  let mut buffer = Vec::with_capacity(size);
  let pointer = buffer.as_mut_ptr();
  mem::forget(buffer);

  pointer as *mut c_void
}

#[no_mangle]
pub extern fn deallocate(pointer: *mut c_void, capacity: usize) {
  unsafe {
    let _ = Vec::from_raw_parts(pointer, 0, capacity);
  }
}

#[no_mangle]
pub extern fn fib_array(n: i32, p: *mut c_int) -> i32 {
  unsafe {
    let mut arr = Vec::<i32>::from_raw_parts(p, 0, (4*n) as usize);
    for i in 0..n {
      if i < 2 {
        arr.push(i);
      } else {
        arr.push(arr[(i - 1) as usize] + arr[(i - 2) as usize]);
      }
    }
    let r = arr[(n - 1) as usize];
    mem::forget(arr);
    r
  }
}

#[no_mangle]
pub extern fn fib_array_return_memory(n: i32) -> *mut c_int {
  let mut arr = Vec::with_capacity((4 * n) as usize);
  let pointer = arr.as_mut_ptr();
  for i in 0..n {
    if i < 2 {
      arr.push(i);
    } else {
      arr.push(arr[(i - 1) as usize] + arr[(i - 2) as usize]);
    }
  }
  mem::forget(arr);
  pointer
}
```

Use standard Rust compiler tools to compile the Rust source code into a WebAssembly

bytecode application.

```
cd rust_access_memory
cargo build --target wasm32-wasi
# The output WASM will be target/wasm32-wasi/debug/rust_access_memory_lib.wasm.
```

The Go SDK application must call `allocate` from the WasmEdge VM to get a pointer to the array. It will then call the `fib_array()` function in Rust and pass in the pointer. After the functions return, the Go application will use the WasmEdge `store` API to construct an array from the pointer in the call parameter (`fib_array()`) or in the return value (`fib_array_return_memory()`). The Go app will eventually call `deallocate` to free the memory space.

```
package main

import (
  "fmt"
  "os"
  "unsafe"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  vm := wasmedge.NewVMWithConfig(conf)

  wasi := vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],
    os.Environ(),
    []string{".:."},
  )

  err := vm.LoadWasmFile(os.Args[1])
  if err != nil {
    fmt.Println("failed to load wasm")
  }
  vm.Validate()
  vm.Instantiate()

  n := int32(10)

  p, err := vm.Execute("allocate", 4 * n)
  if err != nil {
    fmt.Println("allocate failed:", err)
  }

  fib, err := vm.Execute("fib_array", n, p[0])
  if err != nil {
    fmt.Println("fib_rray failed:", err)
  } else {
    fmt.Println("fib_array() returned:", fib[0])
    fmt.Printf("fib_array memory at: %p\n", unsafe.Pointer((uintptr)(p[0].
(int32))))
    mod := vm.GetActiveModule()
    mem := mod.FindMemory("memory")
    if mem != nil {
      // int32 occupies 4 bytes
      fibArray, err := mem.GetData(uint(p[0].(int32)), uint(n * 4))
      if err == nil && fibArray != nil {
        fmt.Println("fibArray:", fibArray)
      }
    }
```

```
  }

  fibP, err := vm.Execute("fib_array_return_memory", n)
  if err != nil {
    fmt.Println("fib_array_return_memory failed:", err)
  } else {
    fmt.Printf("fib_array_return_memory memory at: %p\n",
unsafe.Pointer((uintptr)(fibP[0].(int32))))
    mod := vm.GetActiveModule()
    mem := mod.FindMemory("memory")
    if mem != nil {
      // int32 occupies 4 bytes
      fibArrayReturnMemory, err := mem.GetData(uint(fibP[0].(int32)), uint(n *
4))
      if err == nil && fibArrayReturnMemory != nil {
        fmt.Println("fibArrayReturnMemory:", fibArrayReturnMemory)
      }
    }
  }

  _, err = vm.Execute("deallocate", p[0].(int32), 4 * n)
  if err != nil {
    fmt.Println("free failed:", err)
  }


  exitcode := wasi.WasiGetExitCode()
  if exitcode != 0 {
    fmt.Println("Go: Running wasm failed, exit code:", exitcode)
  }

  vm.Release()
  conf.Release()
}
```

To build the Go SDK example, run the following commands.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build run.go
```

Now you can use the Go application to run the WebAssembly plug-in compiled from Rust.

```
$ ./run rust_access_memory_lib.wasm
fib_array() returned: 34
fib_array memory at: 0x102d80
fibArray: [0 0 0 0 1 0 0 0 1 0 0 0 2 0 0 0 3 0 0 0 5 0 0 0 8 0 0 0 13 0 0 0 21
0 0 0 34 0 0 0]
fib_array_return_memory memory at: 0x105430
fibArrayReturnMemory: [0 0 0 0 1 0 0 0 1 0 0 0 2 0 0 0 3 0 0 0 5 0 0 0 8 0 0 0
13 0 0 0 21 0 0 0 34 0 0 0]
```

Pass bytes to TinyGo functions

In this example, we will demonstrate how to call TinyGo-based WebAssembly functions and pass arrays to and from a Go app.

The `fibArray` function takes a array as a call parameter and fill it with a fibonacci sequence of numbers. Alternatively, the `fibArrayReturnMemory` function returns a array of fibonacci sequence of numbers.

```
package main

import (
  "fmt"
  "unsafe"
)

func main() {
  println("in main")
  n := int32(10)
  arr := make([]int32, n)
  arrP := &arr[0]
  fmt.Printf("call fibArray(%d, %p) = %d\n", n, arrP, fibArray(n, arrP))
  fmt.Printf("call fibArrayReturnMemory(%d) return %p\n", n,
fibArrayReturnMemory(n))
}

// export fibArray
func fibArray(n int32, p *int32) int32 {
  arr := unsafe.Slice(p, n)
  for i := int32(0); i < n; i++ {
    switch {
    case i < 2:
      arr[i] = i
    default:
      arr[i] = arr[i-1] + arr[i-2]
    }
  }
  return arr[n-1]
}

// export fibArrayReturnMemory
func fibArrayReturnMemory(n int32) *int32 {
  arr := make([]int32, n)
  for i := int32(0); i < n; i++ {
    switch {
    case i < 2:
      arr[i] = i
    default:
      arr[i] = arr[i-1] + arr[i-2]
    }
  }
  return &arr[0]
}
```

Use the TinyGo compiler tools to compile the Go source code into a WebAssembly bytecode application.

```
tinygo build -o fib.wasm -target wasi fib.go
```

The Go SDK application must call `malloc` from the WasmEdge VM to get a pointer to the array. It will then call the `fibArray()` function in TinyGo with the pointer. After the functions return, the Go app uses the WasmEdge SDK's `store` API to construct an array from the pointer in the call parameter (`fibArray()`) or in the return value (`fibArrayReturnMemory()`). The Go application will eventually call `free` to free the memory space.

```
package main

import (
  "fmt"
  "os"
  "unsafe"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  vm := wasmedge.NewVMWithConfig(conf)

  wasi := vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],
    os.Environ(),
    []string{".:."},
  )

  err := vm.LoadWasmFile(os.Args[1])
  if err != nil {
    fmt.Println("failed to load wasm")
  }
  vm.Validate()
  vm.Instantiate()

  n := int32(10)

  p, err := vm.Execute("malloc", n)
  if err != nil {
    fmt.Println("malloc failed:", err)
  }

  fib, err := vm.Execute("fibArray", n, p[0])
  if err != nil {
    fmt.Println("fibArray failed:", err)
  } else {
    fmt.Println("fibArray() returned:", fib[0])
    fmt.Printf("fibArray memory at: %p\n", unsafe.Pointer((uintptr)(p[0].
(int32))))
    mod := vm.GetActiveModule()
    mem := mod.FindMemory("memory")
    if mem != nil {
      // int32 occupies 4 bytes
      fibArray, err := mem.GetData(uint(p[0].(int32)), uint(n * 4))
      if err == nil && fibArray != nil {
        fmt.Println("fibArray:", fibArray)
      }
    }
```

```
  }

  fibP, err := vm.Execute("fibArrayReturnMemory", n)
  if err != nil {
    fmt.Println("fibArrayReturnMemory failed:", err)
  } else {
    fmt.Printf("fibArrayReturnMemory memory at: %p\n", unsafe.Pointer((uintptr)
(fibP[0].(int32))))
    mod := vm.GetActiveModule()
    mem := mod.FindMemory("memory")
    if mem != nil {
      // int32 occupies 4 bytes
      fibArrayReturnMemory, err := mem.GetData(uint(fibP[0].(int32)), uint(n *
4))
      if err == nil && fibArrayReturnMemory != nil {
        fmt.Println("fibArrayReturnMemory:", fibArrayReturnMemory)
      }
    }
  }

  _, err = vm.Execute("free", p...)
  if err != nil {
    fmt.Println("free failed:", err)
  }

  exitcode := wasi.WasiGetExitCode()
  if exitcode != 0 {
    fmt.Println("Go: Running wasm failed, exit code:", exitcode)
  }

  vm.Release()
  conf.Release()
}
```

To build the Go SDK example, run the following commands.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build run.go
```

Now you can use the Go application to run the WebAssembly plug-in compiled from TinyGo.

```
$ ./run fib.wasm
fibArray() returned: 34
fibArray memory at: 0x14d3c
fibArray: [0 0 0 0 1 0 0 0 1 0 0 0 2 0 0 0 3 0 0 0 5 0 0 0 8 0 0 0 13 0 0 0 21
0 0 0 34 0 0 0]
fibArrayReturnMemory memory at: 0x14d4c
fibArrayReturnMemory: [0 0 0 0 1 0 0 0 1 0 0 0 2 0 0 0 3 0 0 0 5 0 0 0 8 0 0 0
13 0 0 0 21 0 0 0 34 0 0 0]
```

Tensorflow

In this section, we will show you how to create a Tensorflow inference function in Rust for image classification, and then embed it into a Go application. The project source code is available here.

Rust function compiled into WebAssembly

The Rust function for image classification is available here. It utilizes the WasmEdge Tensorflow extension API as well as the wasmedge_bindgen for passing call parameters.

```
#[wasmedge_bindgen]
fn infer(image_data: Vec<u8>) -> Result<Vec<u8>, String> {
  ... ...
  let flat_img = image::imageops::thumbnail(&img, 192, 192);

  let model_data: &[u8] = include_bytes!("lite-
model_aiy_vision_classifier_food_V1_1.tflite");
  let labels = include_str!("aiy_food_V1_labelmap.txt");

  let mut session = wasmedge_tensorflow_interface::Session::new(
    model_data,
    wasmedge_tensorflow_interface::ModelType::TensorFlowLite,
  );
  session
    .add_input("input", &flat_img, &[1, 192, 192, 3])
    .run();
  let res_vec: Vec<u8> = session.get_output("MobilenetV1/Predictions/Softmax");
  ... ...
}
```

You can use the standard `Cargo` command to build it into a WebAssembly function.

```
cd rust_tflite_food
cargo build --target wasm32-wasi --release
cp target/wasm32-wasi/release/rust_tflite_food_lib.wasm ../
cd ../
```

You can use our AOT compiler `wasmedgec` to instrument the WebAssembly file to make it run much faster. Learn more.

```
wasmedgec rust_tflite_food_lib.wasm rust_tflite_food_lib.wasm
```

Go host app

The Go host app source code shows how to instantiate a WasmEdge runtime with the Tensorflow extension, and how to pass the image data to the Rust function in WasmEdge to run the inference.

```
func main() {
  // Expected Args[0]: program name (./tflite_food)
  // Expected Args[1]: wasm file (rust_tflite_food_lib.wasm)
  // Expected Args[2]: input image name (food.jpg)

  wasmedge.SetLogErrorLevel()

  // Set Tensorflow not to print debug info
  os.Setenv("TF_CPP_MIN_LOG_LEVEL", "3")
  os.Setenv("TF_CPP_MIN_VLOG_LEVEL", "3")

  var conf = wasmedge.NewConfigure(wasmedge.WASI)
  var vm = wasmedge.NewVMWithConfig(conf)
  var wasi = vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping preopens
  )

  // Register WasmEdge-tensorflow
  var tfmod = wasmedge.NewTensorflowModule()
  var tflitemod = wasmedge.NewTensorflowLiteModule()
  vm.RegisterModule(tfmod)
  vm.RegisterModule(tflitemod)

  // Load and validate the wasm
  vm.LoadWasmFile(os.Args[1])
  vm.Validate()

  // Instantiate the bindgen and vm
  bg := bindgen.Instantiate(vm)

  img, _ := ioutil.ReadFile(os.Args[2])
  if res, err := bg.Execute("infer", img); err != nil {
    fmt.Println(err)
  } else {
    fmt.Println(string(res))
  }

  bg.Release()
  vm.Release()
  conf.Release()
  tfmod.Release()
  tflitemod.Release()
}
```

Build and run

> You must have WasmEdge with its tensorflow extension installed on your machine. Checkout the install guide for details.

The following command builds the Go host application with the WasmEdge Go SDK and its tensorflow extension.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build -tags tensorflow
```

Now you can run the Go application. It calls the WebAssembly function in WasmEdge to run inference on the input image.

```
./tflite_food rust_tflite_food_lib.wasm food.jpg
```

The results are as follows.

```
Go: Args: [./tflite_food rust_tflite_food_lib.wasm food.jpg]
It is very likely a Hot dog in the picture
```

Embed a bindgen function

In this example, we will demonstrate how to call a few simple WebAssembly functions from a Go app. The functions are written in Rust, and require complex call parameters and return values. The `#[wasmedge_bindgen]` macro is needed for the compiler tools to auto-generate the correct code to pass call parameters from Go to WebAssembly.

The WebAssembly spec only supports a few simple data types out of the box. It does not support types such as string and array. In order to pass rich types in Go to WebAssembly, the compiler needs to convert them to simple integers. For example, it converts a string into an integer memory address and an integer length. The `wasmedge_bindgen` tool does this conversion automatically.

```
use num_integer::lcm;
use serde::{Deserialize, Serialize};
use sha3::{Digest, Keccak256, Sha3_256};
#[allow(unused_imports)]
use wasmedge_bindgen::*;
use wasmedge_bindgen_macro::*;

#[derive(Serialize, Deserialize, Debug)]
struct Point {
    x: f32,
    y: f32,
}

#[derive(Serialize, Deserialize, Debug)]
struct Line {
    points: Vec<Point>,
    valid: bool,
    length: f32,
    desc: String,
}

#[wasmedge_bindgen]
pub fn create_line(p1: String, p2: String, desc: String) -> String {
    let point1: Point = serde_json::from_str(&p1).unwrap();
    let point2: Point = serde_json::from_str(&p2).unwrap();
    let length = ((point1.x - point2.x) * (point1.x - point2.x)
        + (point1.y - point2.y) * (point1.y - point2.y))
        .sqrt();

    let valid = if length == 0.0 { false } else { true };

    let line = Line {
        points: vec![point1, point2],
        valid: valid,
        length: length,
        desc: desc,
    };

    return serde_json::to_string(&line).unwrap();
}

#[wasmedge_bindgen]
pub fn say(s: String) -> String {
    let r = String::from("hello ");
    return r + &s;
}

#[wasmedge_bindgen]
pub fn obfusticate(s: String) -> String {
    (&s).chars()
        .map(|c| match c {
            'A'..='M' | 'a'..='m' => ((c as u8) + 13) as char,
```

```
            'N'..='Z' | 'n'..='z' => ((c as u8) - 13) as char,
            _ => c,
        })
        .collect()
}

#[wasmedge_bindgen]
pub fn lowest_common_multiple(a: i32, b: i32) -> i32 {
    let r = lcm(a, b);
    return r;
}

#[wasmedge_bindgen]
pub fn sha3_digest(v: Vec<u8>) -> Vec<u8> {
    return Sha3_256::digest(&v).as_slice().to_vec();
}

#[wasmedge_bindgen]
pub fn keccak_digest(s: Vec<u8>) -> Vec<u8> {
    return Keccak256::digest(&s).as_slice().to_vec();
}
```

First, we will compile the Rust source code into WebAssembly bytecode functions.

```
$ cd rust_bindgen_funcs
$ cargo build --release --target wasm32-wasi
# The output WASM will be target/wasm32-wasi/release
/rust_bindgen_funcs_lib.wasm
```

The Go source code to run the WebAssembly function in WasmEdge is as follows. The `Execute()` function calls the WebAssembly function and passes the call parameters using the `#[wasmedge_bindgen]` convention.

```
package main

import (
  "fmt"
  "os"

  "github.com/second-state/WasmEdge-go/wasmedge"
  bindgen "github.com/second-state/wasmedge-bindgen/host/go"
)

func main() {
  // Expected Args[0]: program name (./bindgen_funcs)
  // Expected Args[1]: wasm or wasm-so file (rust_bindgen_funcs_lib.wasm))

  // Set not to print debug info
  wasmedge.SetLogErrorLevel()

  // Create configure
  var conf = wasmedge.NewConfigure(wasmedge.WASI)

  // Create VM with configure
  var vm = wasmedge.NewVMWithConfig(conf)

  // Init WASI
  var wasi = vm.GetImportModule(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping preopens
  )

  vm.LoadWasmFile(os.Args[1])
  vm.Validate()
  // Instantiate the bindgen and vm
  bg := bindgen.New(vm)
  bg.Instantiate()

  // Run bindgen functions
  var res []interface{}
  var err error
  // create_line: array, array, array -> array (inputs are JSON stringified)
  res, _, err = bg.Execute("create_line", "{\"x\":1.5,\"y\":3.8}", "{\"x\":2.5,
\"y\":5.8}", "A thin red line")
  if err == nil {
    fmt.Println("Run bindgen -- create_line:", res[0].(string))
  } else {
    fmt.Println("Run bindgen -- create_line FAILED")
  }
  // say: array -> array
  res, _, err = bg.Execute("say", "bindgen funcs test")
  if err == nil {
    fmt.Println("Run bindgen -- say:", res[0].(string))
```

```
  } else {
    fmt.Println("Run bindgen -- say FAILED")
  }
  // obfusticate: array -> array
  res, _, err = bg.Execute("obfusticate", "A quick brown fox jumps over the
lazy dog")
  if err == nil {
    fmt.Println("Run bindgen -- obfusticate:", res[0].(string))
  } else {
    fmt.Println("Run bindgen -- obfusticate FAILED")
  }
  // lowest_common_multiple: i32, i32 -> i32
  res, _, err = bg.Execute("lowest_common_multiple", int32(123), int32(2))
  if err == nil {
    fmt.Println("Run bindgen -- lowest_common_multiple:", res[0].(int32))
  } else {
    fmt.Println("Run bindgen -- lowest_common_multiple FAILED")
  }
  // sha3_digest: array -> array
  res, _, err = bg.Execute("sha3_digest", []byte("This is an important
message"))
  if err == nil {
    fmt.Println("Run bindgen -- sha3_digest:", res[0].([]byte))
  } else {
    fmt.Println("Run bindgen -- sha3_digest FAILED")
  }
  // keccak_digest: array -> array
  res, _, err = bg.Execute("keccak_digest", []byte("This is an important
message"))
  if err == nil {
    fmt.Println("Run bindgen -- keccak_digest:", res[0].([]byte))
  } else {
    fmt.Println("Run bindgen -- keccak_digest FAILED")
  }

  bg.Release()
  conf.Release()
}
```

Next, let's build the Go application with the WasmEdge Go SDK.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build
```

Run the Go application and it will run the WebAssembly functions embedded in the WasmEdge runtime.

```
$ ./bindgen_funcs rust_bindgen_funcs/target/wasm32-wasi/release
/rust_bindgen_funcs_lib.wasm
Run bindgen -- create_line: {"points":[{"x":1.5,"y":3.8},
{"x":2.5,"y":5.8}],"valid":true,"length":2.2360682,"desc":"A thin red line"}
Run bindgen -- say: hello bindgen funcs test
Run bindgen -- obfusticate: N dhvpx oebja sbk whzcf bire gur ynml qbt
Run bindgen -- lowest_common_multiple: 246
Run bindgen -- sha3_digest: [87 27 231 209 189 105 251 49 159 10 211 250 15 159
154 181 43 218 26 141 56 199 25 45 60 10 20 163 54 211 195 203]
Run bindgen -- keccak_digest: [126 194 241 200 151 116 227 33 216 99 159 22 107
3 177 169 216 191 114 156 174 193 32 159 246 228 245 133 52 75 55 27]
```

WasmEdge Go v0.11.2 API references

The following are the guides to working with the WasmEdge-Go SDK.

This document is for the `v0.11.2` version. For the older `v0.10.1` version, please refer to the document here.

Developers can refer to here to upgrade to v0.11.0.

Table of Contents

Getting Started

The WasmEdge-go requires golang version >= 1.16. Please check your golang version before installation. Developers can download golang here.

```
$ go version
go version go1.16.5 linux/amd64
```

WasmEdge Installation

Developers must install the WasmEdge shared library with the same `WasmEdge-go` release or pre-release version.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.11.2
```

For the developers need the `TensorFlow` or `Image` extension for `WasmEdge-go`, please install the `WasmEdge` with extensions:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e tf,image -v 0.11.2
```

Noticed that the `TensorFlow` and `Image` extensions are only for the `Linux` platforms. After installation, developers can use the `source` command to update the include and linking searching path.

Get WasmEdge-go

After the WasmEdge installation, developers can get the `WasmEdge-go` package and build it in your Go project directory.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
go build
```

The WasmEdge-Go version number should match the installed WasmEdge version.

WasmEdge-go Extensions

By default, the `WasmEdge-go` only turns on the basic runtime.

`WasmEdge-go` has the following extensions (on the Linux platforms only):

- Tensorflow
  - This extension supports the host functions in WasmEdge-tensorflow.
  - The `TensorFlow` and `TensorFlow-Lite` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e tensorflow` command.
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflow
    ```

- Tensorflow-Lite
  - This extension supports the host functions in WasmEdge-tensorflow with only `TensorFlow-Lite`.
  - The `TensorFlow-Lite` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e tensorflow` command.
  - **THIS TAG CANNOT BE USED WITH THE `tensorflow` TAG.**
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflowlite
    ```

- Image

- This extension supports the host functions in WasmEdge-image.
- The `Image` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e image` command.
- For using this extension, the tag `image` when building is required:

```
go build -tags image
```

Users can also turn on the multiple extensions when building:

```
go build -tags image,tensorflow
```

Example Repository

Developers can refer to the example repository for the WasmEdge-Go examples.

WasmEdge-go Basics

In this partition, we will introduce the utilities and concepts of WasmEdge-go APIs and data structures.

Version

The `Version` related APIs provide developers to check for the installed WasmEdge shared library version.

```
import "github.com/second-state/WasmEdge-go/wasmedge"

verstr := wasmedge.GetVersion() // Will be `string` of WasmEdge version.
vermajor := wasmedge.GetVersionMajor() // Will be `uint` of WasmEdge major
version number.
verminor := wasmedge.GetVersionMinor() // Will be `uint` of WasmEdge minor
version number.
verpatch := wasmedge.GetVersionPatch() // Will be `uint` of WasmEdge patch
version number.
```

Logging Settings

The `wasmedge.SetLogErrorLevel()` and `wasmedge.SetLogDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Developers can also use the `wasmedge.SetLogOff()` API to disable all logging. (`v0.11.2` or upper only)

Value Types

In WasmEdge-go, the APIs will automatically do the conversion for the built-in types, and implement the data structure for the reference types.

1. Number types: `i32` , `i64` , `f32` , and `f64`
    - Convert the `uint32` and `int32` to `i32` automatically when passing a value into WASM.
    - Convert the `uint64` and `int64` to `i64` automatically when passing a value into WASM.
    - Convert the `uint` and `int` to `i32` automatically when passing a value into WASM in 32-bit system.
    - Convert the `uint` and `int` to `i64` automatically when passing a value into WASM in 64-bit system.
    - Convert the `float32` to `f32` automatically when passing a value into WASM.
    - Convert the `float64` to `f64` automatically when passing a value into WASM.
    - Convert the `i32` from WASM to `int32` when getting a result.
    - Convert the `i64` from WASM to `int64` when getting a result.
    - Convert the `f32` from WASM to `float32` when getting a result.
    - Convert the `f64` from WASM to `float64` when getting a result.
2. Number type: `v128` for the `SIMD` proposal

    Developers should use the `wasmedge.NewV128()` to generate a `v128` value, and use the `wasmedge.GetV128()` to get the value.

```
val := wasmedge.NewV128(uint64(1234), uint64(5678))
high, low := val.GetVal()
// `high` will be uint64(1234), `low` will be uint64(5678)
```

3. Reference types: `FuncRef` and `ExternRef` for the `Reference-Types` proposal

```
var funccxt *wasmedge.Function = ... // Create or get function object.
funcref := wasmedge.NewFuncRef(funccxt)
// Create a `FuncRef` with the function object.

num := 1234
// `num` is a `int`.
externref := wasmedge.NewExternRef(&num)
// Create an `ExternRef` which reference to the `num`.
num = 5678
// Modify the `num` to 5678.
numref := externref.GetRef().(*int)
// Get the original reference from the `ExternRef`.
fmt.Println(*numref)
// Will print `5678`.
numref.Release()
// Should call the `Release` method.
```

Results

The `Result` object specifies the execution status. Developers can use the `Error()` function to get the error message.

```
// Assume that `vm` is a `wasmedge.VM` object.
res, err = vm.Execute(...) // Ignore the detail of parameters.
// Assume that `res, err` are the return values for executing a function with
`vm`.
if err != nil {
  fmt.Println("Error message:", err.Error())
  category := err.GetErrorCategory()
  // The `category` will be `wasmedge.ErrCategory_WASM`.
}

userdef_err := wasmedge.NewResult(wasmedge.ErrCategory_UserLevel, 123456)
// Generate the user-defined error with code.
code := userdef_err.GetCode()
// The `Code` will be 123456.
```

Contexts And Their Life Cycles

The objects, such as `VM`, `Store`, and `Function`, etc., are composed of `Context`s in the WasmEdge shared library. All of the contexts can be created by calling the corresponding `New` APIs, developers should also call the corresponding `Release` functions of the contexts to release the resources. Noticed that it's not necessary to call the `Release` functions for the contexts which are retrieved from other contexts but not created from the `New` APIs.

```
// Create a Configure.
conf := wasmedge.NewConfigure()
// Release the `conf` immediately.
conf.Release()
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `Limit` struct presents the minimum and maximum value data structure.

   ```
   lim1 := wasmedge.NewLimit(12)
   fmt.Println(lim1.HasMax())
   // Will print `false`.
   fmt.Println(lim1.GetMin())
   // Will print `12`.

   lim2 := wasmedge.NewLimitWithMax(15, 50)
   fmt.Println(lim2.HasMax())
   // Will print `true`.
   fmt.Println(lim2.GetMin())
   // Will print `15`.
   fmt.Println(lim2.GetMax())
   // Will print `50`.
   ```

   For the thread proposal, the `Limit` struct also supports the shared memory description.

```
lim3 := wasmedge.NewLimitShared(20)
fmt.Println(lim3.HasMax())
// Will print `false`.
fmt.Println(lim3.IsShared())
// Will print `true`.
fmt.Println(lim3.GetMin())
// Will print `20`.

lim4 := wasmedge.NewLimitSharedWithMax(30, 40)
fmt.Println(lim4.HasMax())
// Will print `true`.
fmt.Println(lim4.IsShared())
// Will print `true`.
fmt.Println(lim4.GetMin())
// Will print `30`.
fmt.Println(lim4.GetMax())
// Will print `40`.
```

2. Function type context

   The `FunctionType` is an object holds the function type context and used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `FunctionType` APIs to get the parameter or return value types information.

```
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{
    wasmedge.ValType_ExternRef,
    wasmedge.ValType_I32,
    wasmedge.ValType_I64,
  }, []wasmedge.ValType{
    wasmedge.ValType_F32,
    wasmedge.ValType_F64,
  })

plen := functype.GetParametersLength()
// `plen` will be 3.
rlen := functype.GetReturnsLength()
// `rlen` will be 2.
plist := functype.GetParameters()
// `plist` will be `[]wasmedge.ValType{wasmedge.ValType_ExternRef,
wasmedge.ValType_I32, wasmedge.ValType_I64}`.
rlist := functype.GetReturns()
// `rlist` will be `[]wasmedge.ValType{wasmedge.ValType_F32,
wasmedge.ValType_F64}`.

functype.Release()
```

3. Table type context

   The `TableType` is an object holds the table type context and used for `Table` instance creation or getting information from `Table` instances.

```
lim := wasmedge.NewLimit(12)
tabtype := wasmedge.NewTableType(wasmedge.RefType_ExternRef, lim)

rtype := tabtype.GetRefType()
// `rtype` will be `wasmedge.RefType_ExternRef`.
getlim := tabtype.GetLimit()
// `getlim` will be the same value as `lim`.

tabtype.Release()
```

4. Memory type context

   The `MemoryType` is an object holds the memory type context and used for `Memory`

instance creation or getting information from `Memory` instances.

```
lim := wasmedge.NewLimit(1)
memtype := wasmedge.NewMemoryType(lim)

getlim := memtype.GetLimit()
// `getlim` will be the same value as `lim`.

memtype.Release()
```

5. Global type context

   The `GlobalType` is an object holds the global type context and used for `Global` instance creation or getting information from `Global` instances.

```
globtype := wasmedge.NewGlobalType(wasmedge.ValType_F64,
wasmedge.ValMut_Var)

vtype := globtype.GetValType()
// `vtype` will be `wasmedge.ValType_F64`.
vmut := globtype.GetMutability()
// `vmut` will be `wasmedge.ValMut_Var`.

globtype.Release()
```

6. Import type context

   The `ImportType` is an object holds the import type context and used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `ImportType` object. The details about querying `ImportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
imptypelist := ast.ListImports()
// Assume that `imptypelist` is an array listed from the `ast` for the
imports.

for i, imptype := range imptypelist {
  exttype := imptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  modname := imptype.GetModuleName()
  extname := imptype.GetExternalName()
  // Get the module name and external name of the imports.

  extval := imptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

7. Export type context

   The `ExportType` is an object holds the export type context is used for getting the exports information from a AST Module. Developers can get the external type (`function`, `table`, `memory`, or `global`) and external name from an `Export Type` context. The details about querying `ExportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
exptypelist := ast.ListExports()
// Assume that `exptypelist` is an array listed from the `ast` for the
exports.

for i, exptype := range exptypelist {
  exttype := exptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  extname := exptype.GetExternalName()
  // Get the external name of the exports.

  extval := exptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

Async

After calling the asynchronous execution APIs, developers will get the `wasmedge.Async` object. Developers own the object and should call the `(*Async).Release()` API to release it.

1. Get the execution result of the asynchronous execution

   Developers can use the `(*Async).GetResult()` API to block and wait for getting the return values. This function will block and wait for the execution. If the execution has finished, this function will return immediately. If the execution failed, this function will return an error.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution and get the return values.
res, err := async.GetResult()
async.Release()
```

2. Wait for the asynchronous execution with timeout settings

   Besides waiting until the end of execution, developers can set the timeout to wait for.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution with the timeout(ms).
isend := async.WaitFor(1000)
if isend {
  res, err := async.GetResult()
  // ...
} else {
  async.Cancel()
  _, err := async.GetResult()
  // The error message in `err` will be "execution interrupted".
}
async.Release()
```

Configurations

The configuration object, `wasmedge.Configure`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` object to create other runtime objects.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` object.

```
const (
  IMPORT_EXPORT_MUT_GLOBALS         =
Proposal(C.WasmEdge_Proposal_ImportExportMutGlobals)
  NON_TRAP_FLOAT_TO_INT_CONVERSIONS =
Proposal(C.WasmEdge_Proposal_NonTrapFloatToIntConversions)
  SIGN_EXTENSION_OPERATORS          =
Proposal(C.WasmEdge_Proposal_SignExtensionOperators)
  MULTI_VALUE                       =
Proposal(C.WasmEdge_Proposal_MultiValue)
  BULK_MEMORY_OPERATIONS            =
Proposal(C.WasmEdge_Proposal_BulkMemoryOperations)
  REFERENCE_TYPES                   =
Proposal(C.WasmEdge_Proposal_ReferenceTypes)
  SIMD                              = Proposal(C.WasmEdge_Proposal_SIMD)
  TAIL_CALL                         =
Proposal(C.WasmEdge_Proposal_TailCall)
  ANNOTATIONS                       =
Proposal(C.WasmEdge_Proposal_Annotations)
  MEMORY64                          =
Proposal(C.WasmEdge_Proposal_Memory64)
  EXCEPTION_HANDLING                =
Proposal(C.WasmEdge_Proposal_ExceptionHandling)
  EXTENDED_CONST                    =
Proposal(C.WasmEdge_Proposal_ExtendedConst)
  THREADS                           = Proposal(C.WasmEdge_Proposal_Threads)
  FUNCTION_REFERENCES               =
Proposal(C.WasmEdge_Proposal_FunctionReferences)
)
```

Developers can add or remove the proposals into the `Configure` object.

```
// By default, the following proposals have turned on initially:
// * IMPORT_EXPORT_MUT_GLOBALS
// * NON_TRAP_FLOAT_TO_INT_CONVERSIONS
// * SIGN_EXTENSION_OPERATORS
// * MULTI_VALUE
// * BULK_MEMORY_OPERATIONS
// * REFERENCE_TYPES
// * SIMD
// For the current WasmEdge version, the following proposals are supported:
// * TAIL_CALL
// * MULTI_MEMORIES
// * THREADS
// * EXTENDED_CONST
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.SIMD,
wasmedge.BULK_MEMORY_OPERATIONS)
conf.AddConfig(wasmedge.SIMD)
conf.RemoveConfig(wasmedge.REFERENCE_TYPES)
is_bulkmem := conf.HasConfig(wasmedge.BULK_MEMORY_OPERATIONS)
// The `is_bulkmem` will be `true`.
conf.Release()
```

2. Host registrations

This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` objects.

```
const (
  WASI                        =
HostRegistration(C.WasmEdge_HostRegistration_Wasi)
  WasmEdge_PROCESS            =
HostRegistration(C.WasmEdge_HostRegistration_WasmEdge_Process)
  WasiNN                      =
HostRegistration(C.WasmEdge_HostRegistration_WasiNN)
  WasiCrypto_Common           =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Common)
  WasiCrypto_AsymmetricCommon =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_AsymmetricCommon)
  WasiCrypto_Kx               =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Kx)
  WasiCrypto_Signatures       =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Signatures)
  WasiCrypto_Symmetric        =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Symmetric)
)
```

The details will be introduced in the preregistrations of VM context.

```
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.WASI)
conf.AddConfig(wasmedge.WASI)
conf.Release()
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` objects.

```
conf := wasmedge.NewConfigure()

pagesize := conf.GetMaxMemoryPage()
// By default, the maximum memory page size in each memory instances is
65536.
conf.SetMaxMemoryPage(1234)
pagesize = conf.GetMaxMemoryPage()
// `pagesize` will be 1234.

conf.Release()
```

4. Forcibly interpreter mode (`v0.11.2` or upper only)

   If developers want to execute the WASM file or the AOT compiled WASM in interpreter mode forcibly, they can turn on the configuration.

```
conf := wasmedge.NewConfigure()

is_forceinterp := conf.IsForceInterpreter()
// By default, the `is_forceinterp` will be `false`.
conf.SetForceInterpreter(true)
is_forceinterp = conf.IsForceInterpreter()
/* The `is_forceinterp` will be `true`. */

conf.Release()
```

5. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

These configurations are only effective in `Compiler` contexts.

```
conf := wasmedge.NewConfigure()

// By default, the optimization level is O3.
conf.SetCompilerOptimizationLevel(wasmedge.CompilerOptLevel_O2)
// By default, the output format is universal WASM.
conf.SetCompilerOutputFormat(wasmedge.CompilerOutputFormat_Native)
// By default, the dump IR is `false`.
conf.SetCompilerDumpIR(true)
// By default, the generic binary is `false`.
conf.SetCompilerGenericBinary(true)

conf.Release()
```

6. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` objects.

```
conf := wasmedge.NewConfigure()

// By default, the instruction counting is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsInstructionCounting(true)
// By default, the cost measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsTimeMeasuring(true)
// By default, the time measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsCostMeasuring(true)

conf.Release()
```

Statistics

The statistics object, `wasmedge.Statistics`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values

of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` object from the `VM` object, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   stat := wasmedge.NewStatistics()
   // ... After running the WASM functions with the `Statistics` object

   count := stat.GetInstrCount()
   ips := stat.GetInstrPerSecond()
   stat.Release()
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` object. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
stat := wasmedge.NewStatistics()

costtable := []uint64{
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0,
}
// Developers can set the costs of each instruction. The value not covered
will be 0.

WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
stat.SetCostTable()
stat.SetCostLimit(5000000)

// ... After running the WASM functions with the `Statistics` object
cost := stat.GetTotalCost()
stat.Release()
```

Tools Driver

Besides executing the `wasmedge` and `wasmedgec` CLI tools, developers can trigger the WasmEdge CLI tools in WasmEdge-Go. The API arguments are the same as the command line arguments of the CLI tools.

```
package main

import (
  "os"
  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.RunWasmEdgeCLI(os.Args)
}
```

```
package main

import (
  "os"
  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.RunWasmEdgeAOTCompilerCLI(os.Args)
}
```

WasmEdge VM

In this partition, we will introduce the functions of `wasmedge.VM` object and show examples of executing WASM functions.

WASM Execution Example With VM Object

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s (get_local $n)(i32.const 2))
      (return (i32.const 1))
    )
    (return
      (i32.add
        (call $fib (i32.sub (get_local $n)(i32.const 2)))
        (call $fib (i32.sub (get_local $n)(i32.const 1)))
      )
    )
  )
)
```

1. Run WASM functions rapidly

   Create a new Go project first:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Assume that the WASM file `fibonacci.wasm` is copied into the current `wasmedge_test` directory, and create and edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create the configure context and add the WASI support.
  // This step is not necessary unless you need WASI support.
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  // Create VM with the configure.
  vm := wasmedge.NewVMWithConfig(conf)

  res, err := vm.RunWasmFile("fibonacci.wasm", "fib", uint32(21))
  if err == nil {
    fmt.Println("Get fibonacci[21]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
  conf.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK: (the 21 Fibonacci number is 17711 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get fibonacci[21]: 17711
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` object APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create VM.
  vm := wasmedge.NewVM()
  var err error
  var res []interface{}

  // Step 1: Load WASM file.
  err = vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  // Developers can load, validate, and instantiate another WASM module
  // to replace the instantiated one. In this case, the old module will
  // be cleared, but the registered modules are still kept.
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }
```

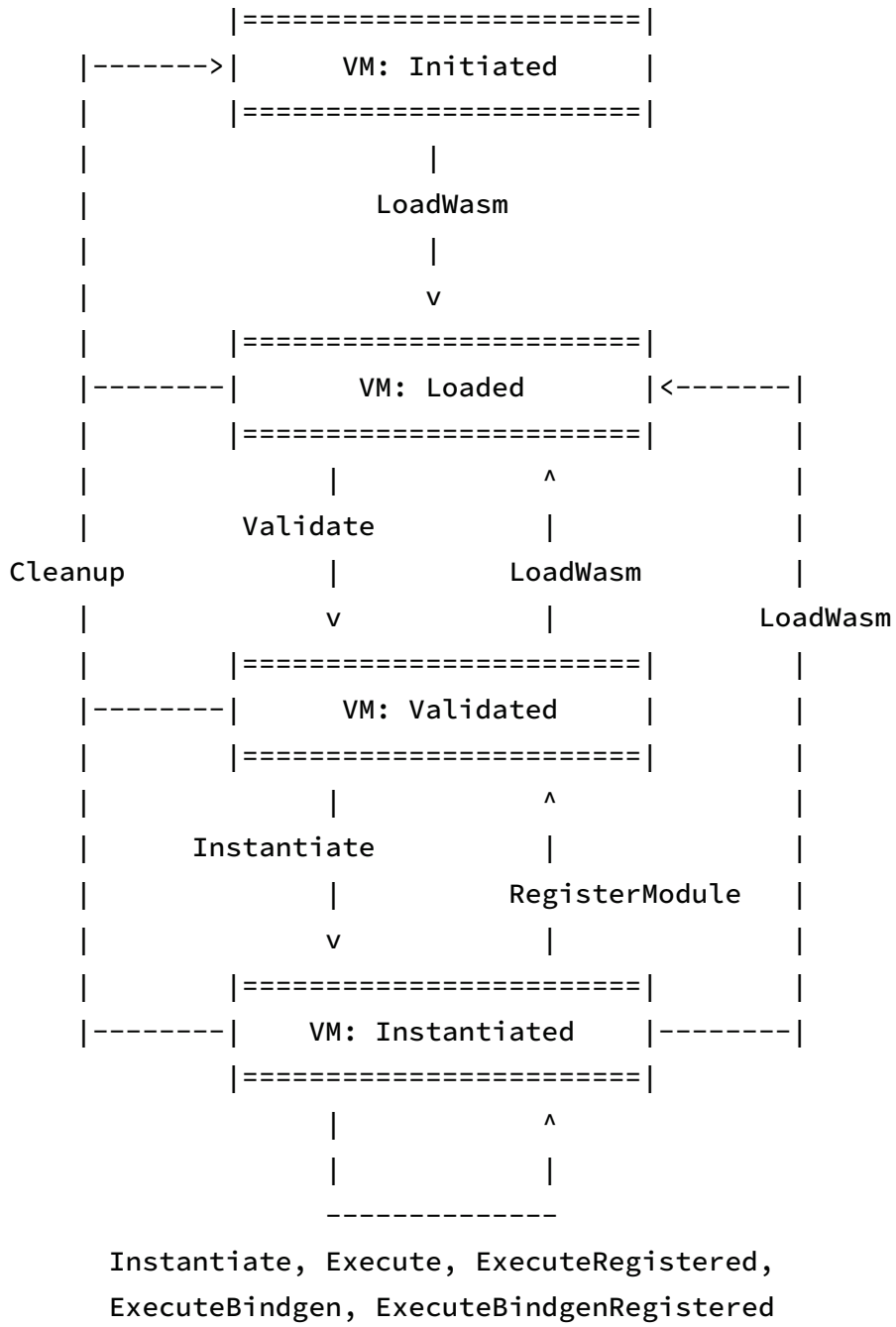
```
  // Step 4: Execute WASM functions. Parameters: (funcname, args...)
  res, err = vm.Execute("fib", uint32(25))
  // Developers can execute functions repeatedly after instantiation.
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

The following graph explains the status of the `VM` object.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or import objects in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation APIs accepts the `Configure` object and the `Store` object. Noticed that if the `VM` created with the outside `Store` object, the `VM` will execute WASM on that `Store` object. If the `Store` object is set into multiple `VM` objects, it may causes data conflict when in execution. The details of the `Store` object will be introduced in Store.

```
conf := wasmedge.NewConfigure()
store := wasmedge.NewStore()

// Create a VM with default configure and store.
vm := wasmedge.NewVM()
vm.Release()

// Create a VM with the specified configure and default store.
vm = wasmedge.NewVMWithConfig(conf)
vm.Release()

// Create a VM with the default configure and specified store.
vm = wasmedge.NewVMWithStore(store)
vm.Release()

// Create a VM with the specified configure and store.
vm = wasmedge.NewVMWithConfigAndStore(conf, store)
vm.Release()

conf.Release()
store.Release()
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` object.

```
conf := wasmedge.NewConfigure(wasmedge.WASI)
// Or you can set the `wasmedge.WASI` into the configure object through
`(*Configure).AddConfig`.
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
wasiconf := conf.GetImportModule(wasmedge.WASI)
// Initialize the WASI.
wasiconf.InitWasi(/* ... ignored */)

conf.Release()
```

And also can create the WASI import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` plugin.

```
conf := wasmedge.NewConfigure(wasmedge.WasmEdge_PROCESS)
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
procconf := conf.GetImportModule(wasmedge.WasmEdge_PROCESS)
// Initialize the WasmEdge_Process.
procconf.InitWasmEdgeProcess(/* ... ignored */)

conf.Release()
```

And also can create the WasmEdge_Process import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

3. WASI-NN proposal

   Developers can turn on the WASI-NN proposal support for VM in the `Configure` object.

   Note: Please check that the dependencies and prerequests are satisfied.

   ```
   conf := wasmedge.NewConfigure(wasmedge.WasiNN)
   vm := wasmedge.NewVMWithConfig(conf)
   vm.Release()

   // The following API can retrieve the pre-registration import objects from
   the VM object.
   // This API will return `nil` if the corresponding pre-registration is not
   set into the configuration.
   nnmodule := conf.GetImportModule(wasmedge.WasiNN)
   conf.Release()
   ```

   And also can create the WASI-NN module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

4. WASI-Crypto proposal

   Developers can turn on the WASI-Crypto proposal support for VM in the `Configure` object.

   Note: Please check that the dependencies and prerequests are satisfied.

```
conf := wasmedge.NewConfigure(wasmedge.WasiCrypto_Common,
wasmedge.WasiCrypto_AsymmetricCommon, wasmedge.WasiCrypto_Kx,
wasmedge.WasiCrypto_Signatures, wasmedge.WasiCrypto_Symmetric)
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
nnmodule := conf.GetImportModule(wasmedge.WasiCrypto_Common)
conf.Release()
```

And also can create the WASI-Crypto module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, the host functions are composed into host modules as `Module` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` object.

```
vm := wasmedge.NewVM()
// You can also create and register the WASI host modules by this API.
wasiobj := wasmedge.NewWasiModule(/* ... ignored ... */)

res := vm.RegisterModule(wasiobj)
// The result status should be checked.

vm.Release()
// The created import objects should be released.
wasiobj.Release()
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM

modules.

1. Register the WASM modules with exported module names

   Unless the import objects have already contained the module names, every WASM module should be named uniquely when registering. The following shows the example.

   Create a new Go project first:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory. Then create and edit the Go file `main.go` as following:

   ```
   package main

   import "github.com/second-state/WasmEdge-go/wasmedge"

   func main() {
     // Create VM.
     vm := wasmedge.NewVM()

     var err error
     err = vm.RegisterWasmFile("module_name", "fibonacci.wasm")
     // Developers can register the WASM module from `[]byte` with the
     // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
     // the `(*VM).RegisterAST` function.
     // The result status should be checked. The error will occur if the
     // WASM module instantiation failed or the module name conflicts.

     vm.Release()
   }
   ```

2. Execute the functions in registered WASM modules

   Edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  var res []interface{}
  var err error
  // Register the WASM module from file into VM with the module name "mod".
  err = vm.RegisterWasmFile("mod", "fibonacci.wasm")
  // Developers can register the WASM module from `[]byte` with the
  // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
  // the `(*VM).RegisterAST` function.
  if err != nil {
    fmt.Println("WASM registration failed:", err.Error())
    return
  }
  // The function "fib" in the "fibonacci.wasm" was exported with the
module
  // name "mod". As the same as host functions, other modules can import
the
  // function `"mod" "fib"`.

  // Execute WASM functions in registered modules.
  // Unlike the execution of functions, the registered functions can be
  // invoked without `(*VM).Instantiate` because the WASM module was
  // instantiated when registering.
  // Developers can also invoke the host functions directly with this API.
  res, err = vm.ExecuteRegistered("mod", "fib", int32(25))
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }
```

```
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Asynchronously run the WASM function from file and get the
`wasmedge.Async` object.
  async := vm.AsyncRunWasmFile("fibonacci.wasm", "fib", uint32(20))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  var err error
  var res []interface{}

  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  // Developers can load the WASM binary from buffer with the
`(*VM).LoadWasmBuffer()` API,
  // or from `wasmedge.AST` object with the `(*VM).LoadWasmAST()` API.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Step 4: Asynchronously execute the WASM function and get the
```

```
`wasmedge.Async` object.
  async := vm.AsyncExecute("fib", uint32(25))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` object supplies the APIs to retrieve the instances.

1. Store

   If the `VM` object is created without assigning a `Store` object, the `VM` context will allocate and own a `Store`.

   ```
   vm := wasmedge.NewVM()
   store := vm.GetStore()
   // The object should __NOT__ be deleted by calling `(*Store).Release`.
   vm.Release()
   ```

   Developers can also create the `VM` object with a `Store` object. In this case, developers should guarantee that the `Store` object cannot be released before the `VM` object. Please refer to the Store Objects for the details about the `Store` APIs.

```
store := wasmedge.NewStore()
vm := wasmedge.NewVMWithStore(store)

storemock := vm.GetStore()
// The internal store context of the `store` and the `storemock` are the
same.

vm.Release()
store.Release()
```

2. List exported functions

   After the WASM module instantiation, developers can use the `(*VM).Execute` function to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types.

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // List the exported functions for the names and function types.
  funcnames, functypes := vm.GetFunctionList()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }
  for _, ftype := range functypes {
    // `ftype` is the `FunctionType` object of the same index in the
```

```
`funcnames` array.
    // Developers should __NOT__ call the `ftype.Release()`.
  }

  vm.Release()
}
```

Then you can build and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Exported function name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` object from the `VM` object and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

   The `VM` object provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
// Assume that a WASM module is instantiated in `vm` which is a
`wasmedge.VM` object.
functype := vm.GetFunctionType("fib")
// Developers can get the function types of functions in the registered
modules via the
// `(*VM).GetFunctionTypeRegistered` API with the function name and the
module name.
// If the function is not found, these APIs will return `nil`.
// Developers should __NOT__ call the `(*FunctionType).Release` function of
the returned object.
```

4. Get the active module

   After the WASM module instantiation, an anonymous module is instantiated and owned by the `VM` object. Developers may need to retrieve it to get the instances beyond the module. Then developers can use the `(*VM).GetActiveModule()` API to get that anonymous module instance. Please refer to the Module instance for the details about the module instance APIs.

```
// Assume that a WASM module is instantiated in `vm` which is a
`wasmedge.VM` object.
mod := vm.GetActiveModule()
// If there's no WASM module instantiated, this API will return `nil`.
// Developers should __NOT__ call the `(*Module).Release` function of the
returned module instance.
```

5. Get the components

   The `VM` object is composed by the `Loader`, `Validator`, and `Executor` objects. For the developers who want to use these objects without creating another instances, these APIs can help developers to get them from the `VM` object. The get objects are owned by the `VM` object, and developers should not call their release functions.

```
loader := vm.GetLoader()
// Developers should __NOT__ call the `(*Loader).Release` function of the
returned object.
validator := vm.GetValidator()
// Developers should __NOT__ call the `(*Validator).Release` function of
the returned object.
executor := vm.GetExecutor()
// Developers should __NOT__ call the `(*Executor).Release` function of the
returned object.
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` object rapidly, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` objects.

Assume that a new Go project is created as following:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level to debug to print the statistics info.
  wasmedge.SetLogDebugLevel()
  // Create the configure object. This is not necessary if developers use the
default configuration.
  conf := wasmedge.NewConfigure()
  // Turn on the runtime instruction counting and time measuring.
  conf.SetStatisticsInstructionCounting(true)
  conf.SetStatisticsTimeMeasuring(true)
  // Create the statistics object. This is not necessary if the statistics in
runtime is not needed.
  stat := wasmedge.NewStatistics()
  // Create the store object. The store object is the WASM runtime structure
core.
  store := wasmedge.NewStore()

  var err error
  var res []interface{}
  var ast *wasmedge.AST
  var mod *wasmedge.Module

  // Create the loader object.
  // For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
  loader := wasmedge.NewLoaderWithConfig(conf)
  // Create the validator object.
  // For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
  validator := wasmedge.NewValidatorWithConfig(conf)
  // Create the executor object.
  // For executor creation with default configuration and without statistics,
you can use `wasmedge.NewExecutor()` instead.
  executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)

  // Load the WASM file or the compiled-WASM file and convert into the AST
module object.
  ast, err = loader.LoadFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }
  // Validate the WASM module.
  err = validator.Validate(ast)
  if err != nil {
```

```
    fmt.Println("Validation FAILED:", err.Error())
    return
  }
  // Instantiate the WASM module and get the output module instance.
  mod, err = executor.Instantiate(store, ast)
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Try to list the exported functions of the instantiated WASM module.
  funcnames := mod.ListFunction()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }

  // Invoke the WASM function.
  funcinst := mod.FindFunction("fib")
  if funcinst == nil {
    fmt.Println("Run FAILED: Function name `fib` not found")
    return
  }
  res, err = executor.Invoke(store, funcinst, int32(30))
  if err == nil {
    fmt.Println("Get fibonacci[30]:", res[0].(int32))
  } else {
    fmt.Println("Run FAILED:", err.Error())
  }

  // Resources deallocations.
  conf.Release()
  stat.Release()
  ast.Release()
  loader.Release()
  validator.Release()
  executor.Release()
  store.Release()
  mod.Release()
}
```

Then you can build and run: (the 18th Fibonacci number is 1346269 in 30-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Exported function name: fib
[2021-11-24 18:53:01.451] [debug]  Execution succeeded.
[2021-11-24 18:53:01.452] [debug]
 ====================  Statistics  ====================
 Total execution time: 556372295 ns
 Wasm instructions execution time: 556372295 ns
 Host functions execution time: 0 ns
 Executed wasm instructions count: 28271634
 Gas costs: 0
 Instructions per second: 50814237
Get fibonacci[30]: 1346269
```

Loader

The `Loader` object loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
var buf []byte
// ... Read the WASM code to the `buf`.

// Developers can adjust settings in the configure object.
conf := wasmedge.NewConfigure()
// Create the loader object.
// For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
loader := wasmedge.NewLoaderWithConfig(conf)
conf.Release()

// Load WASM or compiled-WASM from the file.
ast, err := loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

// Load WASM or compiled-WASM from the buffer
ast, err = loader.LoadBuffer(buf)
if err != nil {
  fmt.Println("Load WASM from buffer FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

loader.Release()
```

Validator

The `Validator` object can validate the WASM module. Every WASM module should be validated before instantiation.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the loader
context.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the validator context.
// For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
validator := wasmedge.NewValidatorWithConfig(conf)

err := validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
}

validator.Release()
```

Executor

The `Executor` object is the executor for both WASM and compiled-WASM. This object should work base on the `Store` object. For the details of the `Store` object, please refer to the next chapter.

1. Instantiate and register an `AST` object as a named `Module` instance

   As the same of registering host modules or importing WASM modules in `VM` objects, developers can instantiate and register an `AST` objects into the `Store` context as a named `Module` instance by the `Executor` APIs. After the registration, the result `Module` instance is exported with the given module name and can be linked when instantiating another module. For the details about the `Module` instances APIs, please refer to the Instances.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Register the loaded WASM `ast` into store with the export module name
"mod".
mod, res := executor.Register(store, ast, "mod")
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
  return
}

// ...

// Resources deallocations.
executor.Release()
stat.Release()
store.Release()
mod.Release()
```

2. Register an existing `Module` instance and export the module name

   Besides instantiating and registering an `AST` object, developers can register an existing `Module` instance into the store with exporting the module name (which is in the `Module` instance already). This case occurs when developers create a `Module` instance for the host functions and want to register it for linking. For the details about the construction of host functions in `Module` instances, please refer to the Host Functions.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Create a module instance for host functions.
mod := wasmedge.NewModule("mod")
// ...
// Create and add the host functions, tables, memories, and globals into
the module instance.
// ...

// Register the module instance into store with the exported module name.
// The export module name is in the module instance already.
res := executor.RegisterImport(store, mod)
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
  return
}

// ...

// Resources deallocations.
executor.Release()
stat.Release()
store.Release()
mod.Release()
```

3. Instantiate an `AST` object to an anonymous `Module` instance

   WASM or compiled-WASM modules should be instantiated before the function invocation. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` object for linking.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Instantiate the WASM module.
mod, err := executor.Instantiate(stpre, ast)
if err != nil {
  fmt.Println("WASM instantiation FAILED:", err.Error())
  return
}

executor.Release()
stat.Release()
store.Release()
mod.Release()
```

4. Invoke functions

   After registering or instantiating and get the result `Module` instance, developers can retrieve the exported `Function` instances from the `Module` instance for invocation. For the details about the `Module` instances APIs, please refer to the Instances. Please refer to the example above for the `Function` instance invocation with the

`(*Executor).Invoke` API.

AST Module

The `AST` object presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST` object.

```
ast := ...
// Assume that a WASM is loaded into an `*wasmedge.AST` object from loader.

// List the imports.
imports := ast.ListImports()
for _, import := range imports {
  fmt.Println("Import:", import.GetModuleName(), import.GetExternalName())
}

// List the exports.
exports := ast.ListExports()
for _, export := range exports {
  fmt.Println("Export:", export.GetExternalName())
}

ast.Release()
```

Store

Store is the runtime structure for the representation of all global state that can be manipulated by WebAssembly programs. The `Store` object in WasmEdge is an object to provide the instance exporting and importing when instantiating WASM modules. Developers can retrieve the named modules from the `Store` context.

```
store := wasmedge.NewStore()

// ...
// Register a WASM module via the executor object.
// ...

// Try to list the registered WASM modules.
modnames := store.ListModule()
// ...

// Find named module by name.
mod := store.FindModule("module")
// If the module with name not found, the `mod` will be `nil`.

store.Release()
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the `Module` instances from the `Store` contexts, and retrieve the other instances from the `Module` instances. A single instance can be allocated by its creation function. Developers can construct instances into an `Module` instance for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed by developers, EXCEPT they are added into an `Module` instance.

1. Module instance

   After instantiating or registering an `AST` object, developers will get a `Module` instance as the result, and have the responsibility to release it when not in use. A `Module` instance can also be created for the host module. Please refer to the host function for the details. `Module` instance provides APIs to list and find the exported instances in the module.

```
// ...
// Instantiate a WASM module via the executor object and get the `mod` as
the output module instance.
// ...

// List the exported instance of the instantiated WASM module.
// Take the function instances for example here.
funcnames := mod.ListFunction()

// Try to find the exported instance of the instantiated WASM module.
// Take the function instances for example here.
funcinst := mod.FindFunction("fib")
// `funcinst` will be `nil` if the function not found.
// The returned instance is owned by the module instance and should __NOT__
be released.
```

2. Function instance

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` objects for host functions and add them into an `Module` instance for registering into a `VM` or a `Store`. Developers can retrieve the `Function Type` from the `Function` objects through the API. For the details of the `Host Function` guide, please refer to the next chapter.

```
funcobj := ...
// `funcobj` is the `*wasmedge.Function` retrieved from the module
instance.
functype := funcobj.GetFunctionType()
// The `funcobj` retrieved from the module instance should __NOT__ be
released.
// The `functype` retrieved from the `funcobj` should __NOT__ be released.

// For the function object creation, please refer to the `Host Function`
guide.
```

3. Table instance

In WasmEdge, developers can create the `Table` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Table` objects supply APIs to control the data in table instances.

```
lim := wasmedge.NewLimitWithMax(10, 20)
// Create the table type with limit and the `FuncRef` element type.
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef, lim)
// Create the table instance with table type.
tabinst := wasmedge.NewTable(tabtype)
// Delete the table type.
tabtype.Release()

gottabtype := tabinst.GetTableType()
// The `gottabtype` got from table instance is owned by the `tabinst`
// and should __NOT__ be released.
reftype := gottabtype.GetRefType()
// The `reftype` will be `wasmedge.RefType_FuncRef`.

var gotdata interface{}
data := wasmedge.NewFuncRef(5)
err := tabinst.SetData(data, 3)
// Set the function index 5 to the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   err = tabinst.SetData(data, 13)

gotdata, err = tabinst.GetData(3)
// Get the FuncRef value of the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   gotdata, err = tabinst.GetData(13)

tabsize := tabinst.GetSize()
// `tabsize` will be 10.
err = tabinst.Grow(6)
// Grow the table size of 6, the table size will be 16.

// The following line will get an "out of bounds table access" error
// because the size (16 + 6) will reach the table limit (20):
//   err = tabinst.Grow(6)

tabinst.Release()
```

4. Memory instance

In WasmEdge, developers can create the `Memory` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Memory` objects supply APIs to control the data in memory instances.

```
lim := wasmedge.NewLimitWithMax(1, 5)
// Create the memory type with limit. The memory page size is 64KiB.
memtype := wasmedge.NewMemoryType(lim)
// Create the memory instance with memory type.
meminst := wasmedge.NewMemory(memtype)
// Delete the memory type.
memtype.Release()

data := []byte("A quick brown fox jumps over the lazy dog")
err := meminst.SetData(data, 0x1000, 10)
// Set the data[0:9] to the memory[4096:4105].

// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   err = meminst.SetData(data, 0xFFFF, 10)

var gotdata []byte
gotdata, err = meminst.GetData(0x1000, 10)
// Get the memory[4096:4105]. The `gotdata` will be `[]byte("A quick br").
// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   gotdata, err = meminst.Getdata(0xFFFF, 10)

pagesize := meminst.GetPageSize()
// `pagesize` will be 1.
err = meminst.GrowPage(2)
// Grow the page size of 2, the page size of the memory instance will be 3.

// The following line will get an "out of bounds memory access" error
// because the size (3 + 3) will reach the memory limit (5):
//   err = meminst.GetPageSize(3)

meminst.Release()
```

5. Global instance

In WasmEdge, developers can create the `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Global` objects supply APIs to control the value in global instances.

```
// Create the global type with value type and mutation.
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I64,
wasmedge.ValMut_Var)
// Create the global instance with value and global type.
globinst := wasmedge.NewGlobal(globtype, uint64(1000))
// Delete the global type.
globtype.Release()

gotglobtype := globinst.GetGlobalType()
// The `gotglobtype` got from global instance is owned by the `globinst`
// and should __NOT__ be released.
valtype := gotglobtype.GetValType()
// The `valtype` will be `wasmedge.ValType_I64`.
valmut := gotglobtype.GetMutability()
// The `valmut` will be `wasmedge.ValMut_Var`.

globinst.SetValue(uint64(888))
// Set the value u64(888) to the global.
// This function will do nothing if the value type mismatched or the
// global mutability is `wasmedge.ValMut_Const`.
gotval := globinst.GetValue()
// The `gotbal` will be `interface{}` which the type is `uint64` and
// the value is 888.

globinst.Release()
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, developers can create the `Function`, `Memory`, `Table`, and `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`.

1. Host function allocation

   Developers can define Go functions with the following function signature as the host

function body:

```
type hostFunctionSignature func(
    data interface{}, callframe *CallingFrame, params []interface{})
([]interface{}, Result)
```

The example of an `add` host function to add 2 `i32` values:

```
func host_add(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}
```

Then developers can create `Function` object with the host function body and function type:

```
// Create a function type: {i32, i32} -> {i32}.
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)

// Create a function context with the function type and host function body.
// The third parameter is the pointer to the additional data.
// Developers should guarantee the life cycle of the data, and it can be
// `nil` if the external data is not needed.
// The last parameter can be 0 if developers do not need the cost
measuring.
func_add := wasmedge.NewFunction(functype, host_add, nil, 0)

// If the function object is not added into an module instance object, it
should be released.
func_add.Release()
functype.Release()
```

2. Calling frame object

   The `wasmedge.CallingFrame` is the object to provide developers to access the module instance of the frame on the top of the calling stack. According to the WASM spec, a frame with the module instance is pushed into the stack when invoking a function. Therefore, the host functions can access the module instance of the top frame to retrieve the memory instances to read/write data.

```
import (
  "encoding/binary"
  "fmt"
)

// Host function body definition.
func LoadOffset(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // Function type: {i32} -> {}
  offset := params[0].(int32)

  // Get the 0th memory instance of the module of the top frame on the
stack.
  mem := callframe.GetMemoryByIndex(0)

  data, err := mem.GetData(uint(offset), 4)
  if err != nil {
    return nil, err
  }
  fmt.Println("u32 at memory[{}]: {}", offset,
binary.LittleEndian.Uint32(data))
  return nil, wasmedge.Result_Success
}
```

Besides using the `(*CallingFrame).GetMemoryByIndex()` API to get the memory instance by index in the module instance, developers can use the `(*CallingFrame).GetModule()` to get the module instance directly. Therefore, developers can retrieve the exported contexts by the `wasmedge.Module` APIs. And also, developers can use the `(*CallingFrame).GetExecutor()` API to get the currently used executor context.

3. User-defined error code of the host functions

   In host functions, WasmEdge-Go provides `wasmedge.Result_Success` to return success, `wasmedge.Result_Terminate` to terminate the WASM execution, and `wasmedge.Result_Fail` to return fail. WasmEdge-Go also provides the usage of returning the user-specified codes. Developers can use the `wasmedge.NewResult()` API to generate the `wasmedge.Result` struct with error code, and use the `(*result).GetCode()` API to get the error code.

> Notice: The error code only supports 24-bit integer (0 ~ 16777216 in `uint32`). The values larger than 24-bit will be truncated.

Create a new Go project first:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Assume that a simple WASM from the WAT is as following:

```
(module
  (type $t0 (func (param i32)))
  (import "extern" "trap" (func $f-trap (type $t0)))
  (func (export "trap") (param i32)
    local.get 0
    call $f-trap)
)
```

And the `main.go` is as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_trap(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x05, 0x01,
    /* function type {i32} -> {} */
    0x60, 0x01, 0x7F, 0x00,
    /* Import section */
    0x02, 0x0F, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "trap" */
    0x04, 0x74, 0x72, 0x61, 0x70,
```

```
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x08, 0x01,
    /* export name: "trap" */
    0x04, 0x74, 0x72, 0x61, 0x70,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x08, 0x01,
    /* code body */
    0x06, 0x00, 0x20, 0x00, 0x10, 0x00, 0x0B,
  }

  // Create the module instance with the module name "extern".
  impmod := wasmedge.NewModule("extern")

  // Create and add a function instance into the module instance with
export name "func-add".
  functype :=
wasmedge.NewFunctionType([]wasmedge.ValType{wasmedge.ValType_I32},
[]wasmedge.ValType{})
  hostfunc := wasmedge.NewFunction(functype, host_trap, nil, 0)
  functype.Release()
  impmod.AddFunction("trap", hostfunc)

  // Register the module instance into VM.
  vm.RegisterImport(impmod)

  _, err := vm.RunWasmBuffer(wasmbuf, "trap", uint32(5566))
  if err != nil {
    fmt.Println("Get the error code:", err.GetCode())
  }

  impmod.Release()
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
[2022-08-26 15:06:40.384] [error] user defined failed: user defined error
code, Code: 0x15be
[2022-08-26 15:06:40.384] [error]     When executing function name: "trap"
Get the error code: 5566
```

4. Construct a module instance with host instances

   Besides creating a `Module` instance by registering or instantiating a WASM module, developers can create a `Module` instance with a module name and add the `Function`, `Memory`, `Table`, and `Global` instances into it with their exporting names.

```
// Host function body definition.
func host_add(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

// Create a module instance with the module name "module".
mod := wasmedge.NewModule("module")

// Create and add a function instance into the module instance with export
name "add".
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)
hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
functype.Release()
mod.AddFunction("add", hostfunc)

// Create and add a table instance into the module instance with export
name "table".
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef
,wasmedge.NewLimitWithMax(10, 20))
hosttab := wasmedge.NewTable(tabtype)
tabtype.Release()
mod.AddTable("table", hosttab)

// Create and add a memory instance into the module instance with export
name "memory".
memtype := wasmedge.NewMemoryType(wasmedge.NewLimitWithMax(1, 2))
hostmem := wasmedge.NewMemory(memtype)
memtype.Release()
```

```
mod.AddMemory("memory", hostmem)

// Create and add a global instance into the module instance with export
name "global".
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I32,
wasmedge.ValMut_Var)
hostglob := wasmedge.NewGlobal(globtype, uint32(666))
globtype.Release()
mod.AddGlobal("global", hostglob)

// The module instances should be released.
// Developers should __NOT__ release the instances added into the module
instance objects.
mod.Release()
```

5. Specified module instance

`wasmedge.NewWasiModule()` API can create and initialize the `WASI` module instance.

`wasmedge.NewWasiNNModule()` API can create and initialize the `wasi_ephemeral_nn` module instance for `WASI-NN` plugin.

`wasmedge.NewWasiCryptoCommonModule()` API can create and initialize the `wasi_ephemeral_crypto_common` module instance for `WASI-Crypto` plugin.

`wasmedge.NewWasiCryptoAsymmetricCommonModule()` API can create and initialize the `wasi_ephemeral_crypto_asymmetric_common` module instance for `WASI-Crypto` plugin.

`wasmedge.NewWasiCryptoKxModule()` API can create and initialize the `wasi_ephemeral_crypto_kx` module instance for `WASI-Crypto` plugin.

`wasmedge.NewWasiCryptoSignaturesModule()` API can create and initialize the `wasi_ephemeral_crypto_signatures` module instance for `WASI-Crypto` plugin.

`wasmedge.NewWasiCryptoSymmetricModule()` API can create and initialize the `wasi_ephemeral_crypto_symmetric` module instance for `WASI-Crypto` plugin.

`wasmedge.NewWasmEdgeProcessModule()` API can create and initialize the `wasmedge_process` module instance for `wasmedge_process` plugin.

Developers can create these module instance objects and register them into the `Store` or `VM` objects rather than adjust the settings in the `Configure` objects.

> Note: For the `WASI-NN` plugin, please check that the dependencies and prerequests are satisfied. Note: For the `WASI-Crypto` plugin, please check that the dependencies and prerequests are satisfied. And the 5 modules are recommended to all be created and registered together.

```
wasiobj := wasmedge.NewWasiModule(
  os.Args[1:],     // The args
  os.Environ(),    // The envs
  []string{".:."}, // The mapping preopens
)
procobj := wasmedge.NewWasmEdgeProcessModule(
  []string{"ls", "echo"}, // The allowed commands
  false,                  // Not to allow all commands
)

// Register the WASI and WasmEdge_Process into the VM object.
vm := wasmedge.NewVM()
vm.RegisterImport(wasiobj)
vm.RegisterImport(procobj)

// ... Execute some WASM functions.

// Get the WASI exit code.
exitcode := wasiobj.WasiGetExitCode()
// The `exitcode` will be 0 if the WASI function "_start" execution has no
error.
// Otherwise, it will return with the related exit code.

vm.Release()
// The import objects should be deleted.
wasiobj.Release()
procobj.Release()
```

6. Example

Assume that there is a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

Assume that edit the Go file `main.go` above:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
```

```
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // Create the module instance with the module name "extern".
  impmod := wasmedge.NewModule("extern")

  // Create and add a function instance into the module instance with
export name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
  functype.Release()
  impmod.AddFunction("func-add", hostfunc)

  // Register the module instance into VM.
  vm.RegisterImport(impmod)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }

  impmod.Release()
```

```
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get the result: 6912
```

7. Host Data Example

   Developers can set a external data object to the `Function` object, and access to the object in the function body. Assume that edit the Go file `main.go` above:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Also set the result to the data.
  *data.(*int32) = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
```

```
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // The additional data to set into the host function.
  var data int32 = 0

  // Create the module instance with the module name "extern".
  impmod := wasmedge.NewImportObject("extern")

  // Create and add a function instance into the module instance with
export name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, &data, 0)
  functype.Release()
  impmod.AddFunction("func-add", hostfunc)

  // Register the module instance into VM.
  vm.RegisterImport(impmod)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
```

```
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  fmt.Println("Data value:", data)

  impmod.Release()
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.11.2
$ go build
$ ./wasmedge_test
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options in Go. WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

The go_WasmAOT example provide a tool for compiling a WASM file.

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

Please refer to the AOT compiler options configuration for details.

WasmEdge Go v0.10.1 API references

The following are the guides to working with the WasmEdge-Go SDK.

Developers can refer to here to upgrade to 0.11.0.

Table of Contents

Getting Started

The WasmEdge-go requires golang version >= 1.16. Please check your golang version before installation. Developers can download golang here.

```
$ go version
go version go1.16.5 linux/amd64
```

WasmEdge Installation

Developers must install the WasmEdge shared library with the same `WasmEdge-go` release or pre-release version.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.10.1
```

For the developers need the `TensorFlow` or `Image` extension for `WasmEdge-go`, please install the `WasmEdge` with extensions:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e tf,image -v 0.10.1
```

Noticed that the `TensorFlow` and `Image` extensions are only for the `Linux` platforms. After installation, developers can use the `source` command to update the include and linking searching path.

Get WasmEdge-go

After the WasmEdge installation, developers can get the `WasmEdge-go` package and build it in your Go project directory.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
go build
```

The WasmEdge-Go version number should match the installed WasmEdge version.

WasmEdge-go Extensions

By default, the `WasmEdge-go` only turns on the basic runtime.

`WasmEdge-go` has the following extensions (on the Linux platforms only):

- Tensorflow
  - This extension supports the host functions in WasmEdge-tensorflow.
  - The `TensorFlow` and `TensorFlow-Lite` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e tensorflow` command.
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflow
    ```

- Tensorflow-Lite (`v0.10.1` or upper only)
  - This extension supports the host functions in WasmEdge-tensorflow with only `TensorFlow-Lite` .
  - The `TensorFlow-Lite` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e tensorflow` command.
  - **THIS TAG CANNOT BE USED WITH THE `tensorflow` TAG.**
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflowlite
    ```

- Image
  - This extension supports the host functions in WasmEdge-image.
  - The `Image` extension when installing `WasmEdge` is required. Please install

`WasmEdge` with the `-e image` command.

- For using this extension, the tag `image` when building is required:

```
go build -tags image
```

Users can also turn on the multiple extensions when building:

```
go build -tags image,tensorflow
```

Example Repository

Developers can refer to the example repository for the WasmEdge-Go examples.

WasmEdge-go Basics

In this partition, we will introduce the utilities and concepts of WasmEdge-go APIs and data structures.

Version

The `Version` related APIs provide developers to check for the installed WasmEdge shared library version.

```
import "github.com/second-state/WasmEdge-go/wasmedge"

verstr := wasmedge.GetVersion() // Will be `string` of WasmEdge version.
vermajor := wasmedge.GetVersionMajor() // Will be `uint` of WasmEdge major
version number.
verminor := wasmedge.GetVersionMinor() // Will be `uint` of WasmEdge minor
version number.
verpatch := wasmedge.GetVersionPatch() // Will be `uint` of WasmEdge patch
version number.
```

Logging Settings

The `wasmedge.SetLogErrorLevel()` and `wasmedge.SetLogDebugLevel()` APIs can set the

logging system to debug level or error level. By default, the error level is set, and the debug info is hidden.

Value Types

In WasmEdge-go, the APIs will automatically do the conversion for the built-in types, and implement the data structure for the reference types.

1. Number types: `i32`, `i64`, `f32`, and `f64`
    - Convert the `uint32` and `int32` to `i32` automatically when passing a value into WASM.
    - Convert the `uint64` and `int64` to `i64` automatically when passing a value into WASM.
    - Convert the `uint` and `int` to `i32` automatically when passing a value into WASM in 32-bit system.
    - Convert the `uint` and `int` to `i64` automatically when passing a value into WASM in 64-bit system.
    - Convert the `float32` to `f32` automatically when passing a value into WASM.
    - Convert the `float64` to `f64` automatically when passing a value into WASM.
    - Convert the `i32` from WASM to `int32` when getting a result.
    - Convert the `i64` from WASM to `int64` when getting a result.
    - Convert the `f32` from WASM to `float32` when getting a result.
    - Convert the `f64` from WASM to `float64` when getting a result.
2. Number type: `v128` for the `SIMD` proposal

    Developers should use the `wasmedge.NewV128()` to generate a `v128` value, and use the `wasmedge.GetV128()` to get the value.

    ```
    val := wasmedge.NewV128(uint64(1234), uint64(5678))
    high, low := val.GetVal()
    // `high` will be uint64(1234), `low` will be uint64(5678)
    ```

3. Reference types: `FuncRef` and `ExternRef` for the `Reference-Types` proposal

```
var funccxt *wasmedge.Function = ... // Create or get function object.
funcref := wasmedge.NewFuncRef(funccxt)
// Create a `FuncRef` with the function object.

num := 1234
// `num` is a `int`.
externref := wasmedge.NewExternRef(&num)
// Create an `ExternRef` which reference to the `num`.
num = 5678
// Modify the `num` to 5678.
numref := externref.GetRef().(*int)
// Get the original reference from the `ExternRef`.
fmt.Println(*numref)
// Will print `5678`.
numref.Release()
// Should call the `Release` method.
```

Results

The `Result` object specifies the execution status. Developers can use the `Error()` function to get the error message.

```
// Assume that `vm` is a `wasmedge.VM` object.
res, err = vm.Execute(...) // Ignore the detail of parameters.
// Assume that `res, err` are the return values for executing a function with
`vm`.
if err != nil {
  fmt.Println("Error message:", err.Error())
}
```

Contexts And Their Life Cycles

The objects, such as `VM`, `Store`, and `Function`, etc., are composed of `Context`s in the WasmEdge shared library. All of the contexts can be created by calling the corresponding `New` APIs, developers should also call the corresponding `Release` functions of the contexts to release the resources. Noticed that it's not necessary to call the `Release` functions for the contexts which are retrieved from other contexts but not created from the `New` APIs.

```
// Create a Configure.
conf := wasmedge.NewConfigure()
// Release the `conf` immediately.
conf.Release()
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `Limit` struct presents the minimum and maximum value data structure.

   ```
   lim1 := wasmedge.NewLimit(12)
   fmt.Println(lim1.HasMax())
   // Will print `false`.
   fmt.Println(lim1.GetMin())
   // Will print `12`.

   lim2 := wasmedge.NewLimitWithMax(15, 50)
   fmt.Println(lim2.HasMax())
   // Will print `true`.
   fmt.Println(lim2.GetMin())
   // Will print `15`.
   fmt.Println(lim2.GetMax())
   // Will print `50`.
   ```

   For the thread proposal, the `Limit` struct also supports the shared memory description. (`v0.10.1` or upper only)

```
lim3 := wasmedge.NewLimitShared(20)
fmt.Println(lim3.HasMax())
// Will print `false`.
fmt.Println(lim3.IsShared())
// Will print `true`.
fmt.Println(lim3.GetMin())
// Will print `20`.

lim4 := wasmedge.NewLimitSharedWithMax(30, 40)
fmt.Println(lim4.HasMax())
// Will print `true`.
fmt.Println(lim4.IsShared())
// Will print `true`.
fmt.Println(lim4.GetMin())
// Will print `30`.
fmt.Println(lim4.GetMax())
// Will print `40`.
```

2. Function type context

   The `FunctionType` is an object holds the function type context and used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `FunctionType` APIs to get the parameter or return value types information.

```
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{
    wasmedge.ValType_ExternRef,
    wasmedge.ValType_I32,
    wasmedge.ValType_I64,
  }, []wasmedge.ValType{
    wasmedge.ValType_F32,
    wasmedge.ValType_F64,
  })

plen := functype.GetParametersLength()
// `plen` will be 3.
rlen := functype.GetReturnsLength()
// `rlen` will be 2.
plist := functype.GetParameters()
// `plist` will be `[]wasmedge.ValType{wasmedge.ValType_ExternRef,
wasmedge.ValType_I32, wasmedge.ValType_I64}`.
rlist := functype.GetReturns()
// `rlist` will be `[]wasmedge.ValType{wasmedge.ValType_F32,
wasmedge.ValType_F64}`.

functype.Release()
```

3. Table type context

   The `TableType` is an object holds the table type context and used for `Table` instance creation or getting information from `Table` instances.

```
lim := wasmedge.NewLimit(12)
tabtype := wasmedge.NewTableType(wasmedge.RefType_ExternRef, lim)

rtype := tabtype.GetRefType()
// `rtype` will be `wasmedge.RefType_ExternRef`.
getlim := tabtype.GetLimit()
// `getlim` will be the same value as `lim`.

tabtype.Release()
```

4. Memory type context

   The `MemoryType` is an object holds the memory type context and used for `Memory`

instance creation or getting information from `Memory` instances.

```
lim := wasmedge.NewLimit(1)
memtype := wasmedge.NewMemoryType(lim)

getlim := memtype.GetLimit()
// `getlim` will be the same value as `lim`.

memtype.Release()
```

5. Global type context

   The `GlobalType` is an object holds the global type context and used for `Global` instance creation or getting information from `Global` instances.

```
globtype := wasmedge.NewGlobalType(wasmedge.ValType_F64,
wasmedge.ValMut_Var)

vtype := globtype.GetValType()
// `vtype` will be `wasmedge.ValType_F64`.
vmut := globtype.GetMutability()
// `vmut` will be `wasmedge.ValMut_Var`.

globtype.Release()
```

6. Import type context

   The `ImportType` is an object holds the import type context and used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `ImportType` object. The details about querying `ImportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
imptypelist := ast.ListImports()
// Assume that `imptypelist` is an array listed from the `ast` for the
imports.

for i, imptype := range imptypelist {
  exttype := imptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  modname := imptype.GetModuleName()
  extname := imptype.GetExternalName()
  // Get the module name and external name of the imports.

  extval := imptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

7. Export type context

   The `ExportType` is an object holds the export type context is used for getting the exports information from a AST Module. Developers can get the external type (`function`, `table`, `memory`, or `global`) and external name from an `Export Type` context. The details about querying `ExportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
exptypelist := ast.ListExports()
// Assume that `exptypelist` is an array listed from the `ast` for the
exports.

for i, exptype := range exptypelist {
  exttype := exptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  extname := exptype.GetExternalName()
  // Get the external name of the exports.

  extval := exptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

Async

After calling the asynchronous execution APIs, developers will get the `wasmedge.Async` object. Developers own the object and should call the `(*Async).Release()` API to release it.

1. Get the execution result of the asynchronous execution

   Developers can use the `(*Async).GetResult()` API to block and wait for getting the return values. This function will block and wait for the execution. If the execution has finished, this function will return immediately. If the execution failed, this function will return an error.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution and get the return values.
res, err := async.GetResult()
async.Release()
```

2. Wait for the asynchronous execution with timeout settings

   Besides waiting until the end of execution, developers can set the timeout to wait for.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution with the timeout(ms).
isend := async.WaitFor(1000)
if isend {
  res, err := async.GetResult()
  // ...
} else {
  async.Cancel()
  _, err := async.GetResult()
  // The error message in `err` will be "execution interrupted".
}
async.Release()
```

Configurations

The configuration object, `wasmedge.Configure`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` object to create other runtime objects.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` object.

```
const (
  IMPORT_EXPORT_MUT_GLOBALS         =
Proposal(C.WasmEdge_Proposal_ImportExportMutGlobals)
  NON_TRAP_FLOAT_TO_INT_CONVERSIONS =
Proposal(C.WasmEdge_Proposal_NonTrapFloatToIntConversions)
  SIGN_EXTENSION_OPERATORS          =
Proposal(C.WasmEdge_Proposal_SignExtensionOperators)
  MULTI_VALUE                       =
Proposal(C.WasmEdge_Proposal_MultiValue)
  BULK_MEMORY_OPERATIONS            =
Proposal(C.WasmEdge_Proposal_BulkMemoryOperations)
  REFERENCE_TYPES                   =
Proposal(C.WasmEdge_Proposal_ReferenceTypes)
  SIMD                              = Proposal(C.WasmEdge_Proposal_SIMD)
  TAIL_CALL                         =
Proposal(C.WasmEdge_Proposal_TailCall)
  ANNOTATIONS                       =
Proposal(C.WasmEdge_Proposal_Annotations)
  MEMORY64                          =
Proposal(C.WasmEdge_Proposal_Memory64)
  THREADS                           = Proposal(C.WasmEdge_Proposal_Threads)
  EXCEPTION_HANDLING                =
Proposal(C.WasmEdge_Proposal_ExceptionHandling)
  FUNCTION_REFERENCES               =
Proposal(C.WasmEdge_Proposal_FunctionReferences)
)
```

Developers can add or remove the proposals into the `Configure` object.

```
// By default, the following proposals have turned on initially:
// * IMPORT_EXPORT_MUT_GLOBALS
// * NON_TRAP_FLOAT_TO_INT_CONVERSIONS
// * SIGN_EXTENSION_OPERATORS
// * MULTI_VALUE
// * BULK_MEMORY_OPERATIONS
// * REFERENCE_TYPES
// * SIMD
// For the current WasmEdge version, the following proposals are supported:
// * TAIL_CALL
// * MULTI_MEMORIES
// * THREADS
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.SIMD,
wasmedge.BULK_MEMORY_OPERATIONS)
conf.AddConfig(wasmedge.SIMD)
conf.RemoveConfig(wasmedge.REFERENCE_TYPES)
is_bulkmem := conf.HasConfig(wasmedge.BULK_MEMORY_OPERATIONS)
// The `is_bulkmem` will be `true`.
conf.Release()
```

2. Host registrations

   This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` objects.

```
const (
  WASI                          =
HostRegistration(C.WasmEdge_HostRegistration_Wasi)
  WasmEdge_PROCESS              =
HostRegistration(C.WasmEdge_HostRegistration_WasmEdge_Process)
  // The follows are `v0.10.1` or upper only.
  WasiNN                        =
HostRegistration(C.WasmEdge_HostRegistration_WasiNN)
  WasiCrypto_Common             =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Common)
  WasiCrypto_AsymmetricCommon =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_AsymmetricCommon)
  WasiCrypto_Kx                 =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Kx)
  WasiCrypto_Signatures         =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Signatures)
  WasiCrypto_Symmetric          =
HostRegistration(C.WasmEdge_HostRegistration_WasiCrypto_Symmetric)
)
```

The details will be introduced in the preregistrations of VM context.

```
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.WASI)
conf.AddConfig(wasmedge.WASI)
conf.Release()
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` objects.

```
conf := wasmedge.NewConfigure()

pagesize := conf.GetMaxMemoryPage()
// By default, the maximum memory page size in each memory instances is
65536.
conf.SetMaxMemoryPage(1234)
pagesize := conf.GetMaxMemoryPage()
// `pagesize` will be 1234.

conf.Release()
```

4. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

These configurations are only effective in `Compiler` contexts.

```
conf := wasmedge.NewConfigure()

// By default, the optimization level is O3.
conf.SetCompilerOptimizationLevel(wasmedge.CompilerOptLevel_O2)
// By default, the output format is universal WASM.
conf.SetCompilerOutputFormat(wasmedge.CompilerOutputFormat_Native)
// By default, the dump IR is `false`.
conf.SetCompilerDumpIR(true)
// By default, the generic binary is `false`.
conf.SetCompilerGenericBinary(true)

conf.Release()
```

5. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` objects.

```
conf := wasmedge.NewConfigure()

// By default, the instruction counting is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsInstructionCounting(true)
// By default, the cost measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsTimeMeasuring(true)
// By default, the time measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsCostMeasuring(true)

conf.Release()
```

Statistics

The statistics object, `wasmedge.Statistics`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values

of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` object from the `VM` object, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   stat := wasmedge.NewStatistics()
   // ... After running the WASM functions with the `Statistics` object

   count := stat.GetInstrCount()
   ips := stat.GetInstrPerSecond()
   stat.Release()
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` object. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
stat := wasmedge.NewStatistics()

costtable := []uint64{
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0,
}
// Developers can set the costs of each instruction. The value not covered
will be 0.

WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
stat.SetCostTable()
stat.SetCostLimit(5000000)

// ... After running the WASM functions with the `Statistics` object
cost := stat.GetTotalCost()
stat.Release()
```

Tools Driver (`v0.10.1` or upper only)

Besides executing the `wasmedge` and `wasmedgec` CLI tools, developers can trigger the WasmEdge CLI tools in WasmEdge-Go. The API arguments are the same as the command line arguments of the CLI tools.

```
package main

import (
  "os"
  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.RunWasmEdgeCLI(os.Args)
}
```

```
package main

import (
  "os"
  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.RunWasmEdgeAOTCompilerCLI(os.Args)
}
```

WasmEdge VM

In this partition, we will introduce the functions of `wasmedge.VM` object and show examples of executing WASM functions.

WASM Execution Example With VM Object

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s (get_local $n)(i32.const 2))
      (return (i32.const 1))
    )
    (return
      (i32.add
        (call $fib (i32.sub (get_local $n)(i32.const 2)))
        (call $fib (i32.sub (get_local $n)(i32.const 1)))
      )
    )
  )
)
```

1. Run WASM functions rapidly

   Create a new Go project first:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Assume that the WASM file `fibonacci.wasm` is copied into the current `wasmedge_test` directory, and create and edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create the configure context and add the WASI support.
  // This step is not necessary unless you need WASI support.
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  // Create VM with the configure.
  vm := wasmedge.NewVMWithConfig(conf)

  res, err := vm.RunWasmFile("fibonacci.wasm", "fib", uint32(21))
  if err == nil {
    fmt.Println("Get fibonacci[21]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
  conf.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK: (the 21 Fibonacci number is 17711 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get fibonacci[21]: 17711
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` object APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create VM.
  vm := wasmedge.NewVM()
  var err error
  var res []interface{}

  // Step 1: Load WASM file.
  err = vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  // Developers can load, validate, and instantiate another WASM module
  // to replace the instantiated one. In this case, the old module will
  // be cleared, but the registered modules are still kept.
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }
```

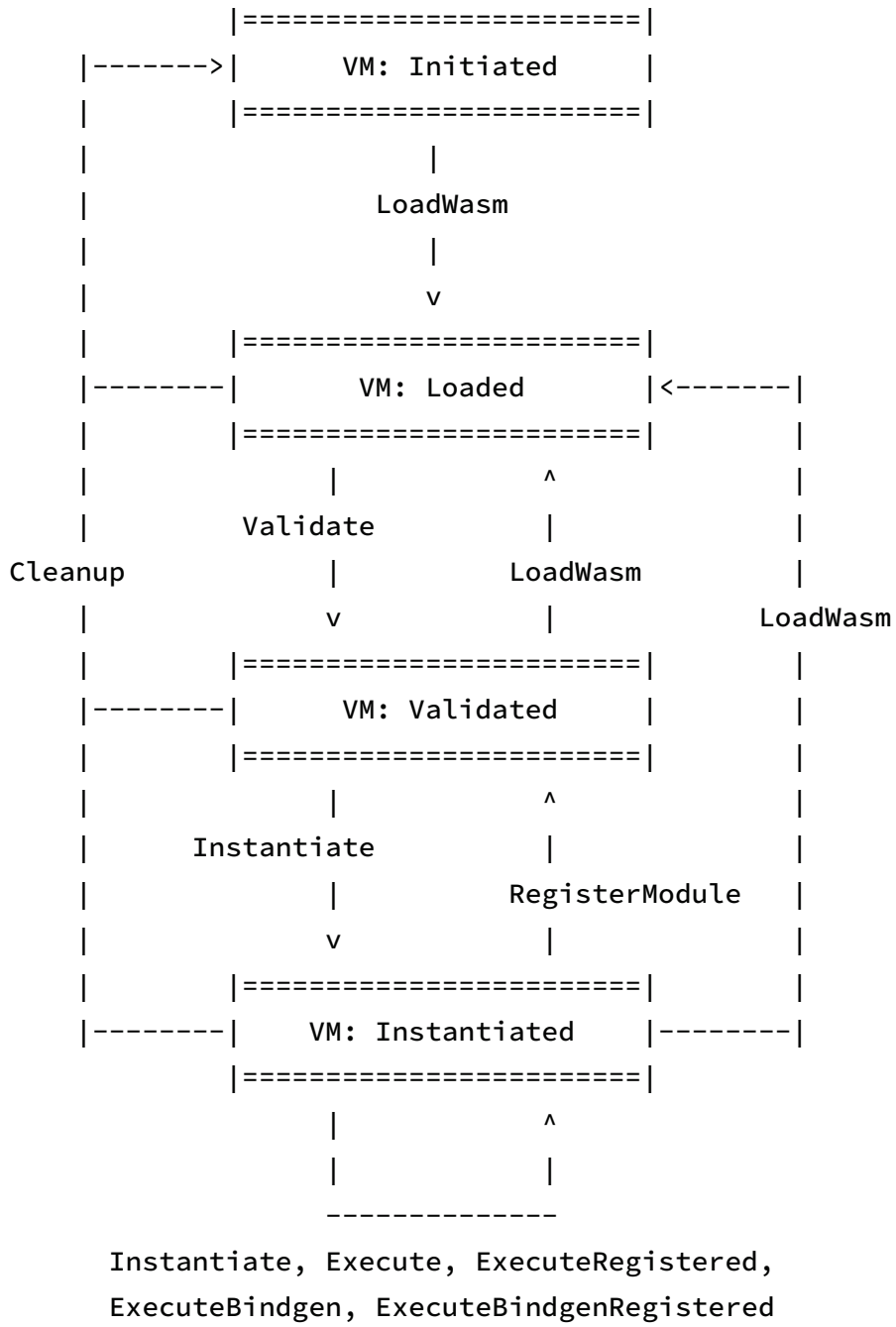
```
  // Step 4: Execute WASM functions. Parameters: (funcname, args...)
  res, err = vm.Execute("fib", uint32(25))
  // Developers can execute functions repeatedly after instantiation.
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

The following graph explains the status of the `VM` object.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or import objects in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation APIs accepts the `Configure` object and the `Store` object. Noticed that if the `VM` created with the outside `Store` object, the `VM` will execute WASM on that `Store` object. If the `Store` object is set into multiple `VM` objects, it may causes data conflict when in execution. The details of the `Store` object will be introduced in Store.

```
conf := wasmedge.NewConfigure()
store := wasmedge.NewStore()

// Create a VM with default configure and store.
vm := wasmedge.NewVM()
vm.Release()

// Create a VM with the specified configure and default store.
vm = wasmedge.NewVMWithConfig(conf)
vm.Release()

// Create a VM with the default configure and specified store.
vm = wasmedge.NewVMWithStore(store)
vm.Release()

// Create a VM with the specified configure and store.
vm = wasmedge.NewVMWithConfigAndStore(conf, store)
vm.Release()

conf.Release()
store.Release()
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` object.

```
conf := wasmedge.NewConfigure(wasmedge.WASI)
// Or you can set the `wasmedge.WASI` into the configure object through
`(*Configure).AddConfig`.
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
wasiconf := conf.GetImportModule(wasmedge.WASI)
// Initialize the WASI.
wasiconf.InitWasi(/* ... ignored */)

conf.Release()
```

And also can create the WASI import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` plugin.

```
conf := wasmedge.NewConfigure(wasmedge.WasmEdge_PROCESS)
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
procconf := conf.GetImportModule(wasmedge.WasmEdge_PROCESS)
// Initialize the WasmEdge_Process.
procconf.InitWasmEdgeProcess(/* ... ignored */)

conf.Release()
```

And also can create the WasmEdge_Process import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

3. WASI-NN proposal (`v0.10.1` or upper only)

   Developers can turn on the WASI-NN proposal support for VM in the `Configure` object.

   Note: Please check that the dependencies and prerequests are satisfied.

   ```
   conf := wasmedge.NewConfigure(wasmedge.WasiNN)
   vm := wasmedge.NewVMWithConfig(conf)
   vm.Release()

   // The following API can retrieve the pre-registration import objects from
   the VM object.
   // This API will return `nil` if the corresponding pre-registration is not
   set into the configuration.
   nnmodule := conf.GetImportModule(wasmedge.WasiNN)
   conf.Release()
   ```

   And also can create the WASI-NN module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

4. WASI-Crypto proposal (`v0.10.1` or upper only)

   Developers can turn on the WASI-Crypto proposal support for VM in the `Configure` object.

   Note: Please check that the dependencies and prerequests are satisfied.

```
conf := wasmedge.NewConfigure(wasmedge.WasiCrypto_Common,
wasmedge.WasiCrypto_AsymmetricCommon, wasmedge.WasiCrypto_Kx,
wasmedge.WasiCrypto_Signatures, wasmedge.WasiCrypto_Symmetric)
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
nnmodule := conf.GetImportModule(wasmedge.WasiCrypto_Common)
conf.Release()
```

And also can create the WASI-Crypto module instance from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, the host functions are composed into host modules as `Module` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` object.

```
vm := wasmedge.NewVM()
// You can also create and register the WASI host modules by this API.
wasiobj := wasmedge.NewWasiModule(/* ... ignored ... */)

res := vm.RegisterModule(wasiobj)
// The result status should be checked.

vm.Release()
// The created import objects should be released.
wasiobj.Release()
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM

modules.

1. Register the WASM modules with exported module names

   Unless the import objects have already contained the module names, every WASM module should be named uniquely when registering. The following shows the example.

   Create a new Go project first:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory. Then create and edit the Go file `main.go` as following:

   ```
   package main

   import "github.com/second-state/WasmEdge-go/wasmedge"

   func main() {
     // Create VM.
     vm := wasmedge.NewVM()

     var err error
     err = vm.RegisterWasmFile("module_name", "fibonacci.wasm")
     // Developers can register the WASM module from `[]byte` with the
     // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
     // the `(*VM).RegisterAST` function.
     // The result status should be checked. The error will occur if the
     // WASM module instantiation failed or the module name conflicts.

     vm.Release()
   }
   ```

2. Execute the functions in registered WASM modules

   Edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  var res []interface{}
  var err error
  // Register the WASM module from file into VM with the module name "mod".
  err = vm.RegisterWasmFile("mod", "fibonacci.wasm")
  // Developers can register the WASM module from `[]byte` with the
  // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
  // the `(*VM).RegisterAST` function.
  if err != nil {
    fmt.Println("WASM registration failed:", err.Error())
    return
  }
  // The function "fib" in the "fibonacci.wasm" was exported with the
module
  // name "mod". As the same as host functions, other modules can import
the
  // function `"mod" "fib"`.

  // Execute WASM functions in registered modules.
  // Unlike the execution of functions, the registered functions can be
  // invoked without `(*VM).Instantiate` because the WASM module was
  // instantiated when registering.
  // Developers can also invoke the host functions directly with this API.
  res, err = vm.ExecuteRegistered("mod", "fib", int32(25))
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }
```

```
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Asynchronously run the WASM function from file and get the
`wasmedge.Async` object.
  async := vm.AsyncRunWasmFile("fibonacci.wasm", "fib", uint32(20))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  var err error
  var res []interface{}

  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  // Developers can load the WASM binary from buffer with the
`(*VM).LoadWasmBuffer()` API,
  // or from `wasmedge.AST` object with the `(*VM).LoadWasmAST()` API.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Step 4: Asynchronously execute the WASM function and get the
```

```
`wasmedge.Async` object.
  async := vm.AsyncExecute("fib", uint32(25))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` object supplies the APIs to retrieve the instances.

1. Store

   If the `VM` object is created without assigning a `Store` object, the `VM` context will allocate and own a `Store`.

   ```
   vm := wasmedge.NewVM()
   store := vm.GetStore()
   // The object should __NOT__ be deleted by calling `(*Store).Release`.
   vm.Release()
   ```

   Developers can also create the `VM` object with a `Store` object. In this case, developers should guarantee that the `Store` object cannot be released before the `VM` object. Please refer to the Store Objects for the details about the `Store` APIs.

```
store := wasmedge.NewStore()
vm := wasmedge.NewVMWithStore(store)

storemock := vm.GetStore()
// The internal store context of the `store` and the `storemock` are the
same.

vm.Release()
store.Release()
```

2. List exported functions

   After the WASM module instantiation, developers can use the `(*VM).Execute` function to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types.

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // List the exported functions for the names and function types.
  funcnames, functypes := vm.GetFunctionList()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }
  for _, ftype := range functypes {
    // `ftype` is the `FunctionType` object of the same index in the
```

```
`funcnames` array.
    // Developers should __NOT__ call the `ftype.Release()`.
  }

  vm.Release()
}
```

Then you can build and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Exported function name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` object from the `VM` object and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

   The `VM` object provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
// Assume that a WASM module is instantiated in `vm` which is a
`wasmedge.VM` object.
functype := vm.GetFunctionType("fib")
// Developers can get the function types of functions in the registered
modules via the
// `(*VM).GetFunctionTypeRegistered` API with the function name and the
module name.
// If the function is not found, these APIs will return `nil`.
// Developers should __NOT__ call the `(*FunctionType).Release` function of
the returned object.
```

4. Get the active module

   After the WASM module instantiation, an anonymous module is instantiated and owned by the `VM` object. Developers may need to retrieve it to get the instances beyond the module. Then developers can use the `(*VM).GetActiveModule()` API to get that anonymous module instance. Please refer to the Module instance for the details about the module instance APIs.

```
// Assume that a WASM module is instantiated in `vm` which is a
`wasmedge.VM` object.
mod := vm.GetActiveModule()
// If there's no WASM module instantiated, this API will return `nil`.
// Developers should __NOT__ call the `(*Module).Release` function of the
returned module instance.
```

5. Get the components (`v0.10.1` or upper only)

   The `VM` object is composed by the `Loader`, `Validator`, and `Executor` objects. For the developers who want to use these objects without creating another instances, these APIs can help developers to get them from the `VM` object. The get objects are owned by the `VM` object, and developers should not call their release functions.

```
loader := vm.GetLoader()
// Developers should __NOT__ call the `(*Loader).Release` function of the
returned object.
validator := vm.GetValidator()
// Developers should __NOT__ call the `(*Validator).Release` function of
the returned object.
executor := vm.GetExecutor()
// Developers should __NOT__ call the `(*Executor).Release` function of the
returned object.
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` object rapidly, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` objects.

Assume that a new Go project is created as following:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level to debug to print the statistics info.
  wasmedge.SetLogDebugLevel()
  // Create the configure object. This is not necessary if developers use the
default configuration.
  conf := wasmedge.NewConfigure()
  // Turn on the runtime instruction counting and time measuring.
  conf.SetStatisticsInstructionCounting(true)
  conf.SetStatisticsTimeMeasuring(true)
  // Create the statistics object. This is not necessary if the statistics in
runtime is not needed.
  stat := wasmedge.NewStatistics()
  // Create the store object. The store object is the WASM runtime structure
core.
  store := wasmedge.NewStore()

  var err error
  var res []interface{}
  var ast *wasmedge.AST
  var mod *wasmedge.Module

  // Create the loader object.
  // For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
  loader := wasmedge.NewLoaderWithConfig(conf)
  // Create the validator object.
  // For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
  validator := wasmedge.NewValidatorWithConfig(conf)
  // Create the executor object.
  // For executor creation with default configuration and without statistics,
you can use `wasmedge.NewExecutor()` instead.
  executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)

  // Load the WASM file or the compiled-WASM file and convert into the AST
module object.
  ast, err = loader.LoadFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }
  // Validate the WASM module.
  err = validator.Validate(ast)
  if err != nil {
```

```
    fmt.Println("Validation FAILED:", err.Error())
    return
  }
  // Instantiate the WASM module and get the output module instance.
  mod, err = executor.Instantiate(store, ast)
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Try to list the exported functions of the instantiated WASM module.
  funcnames := mod.ListFunction()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }

  // Invoke the WASM function.
  funcinst := mod.FindFunction("fib")
  if funcinst == nil {
    fmt.Println("Run FAILED: Function name `fib` not found")
    return
  }
  res, err = executor.Invoke(store, funcinst, int32(30))
  if err == nil {
    fmt.Println("Get fibonacci[30]:", res[0].(int32))
  } else {
    fmt.Println("Run FAILED:", err.Error())
  }

  // Resources deallocations.
  conf.Release()
  stat.Release()
  ast.Release()
  loader.Release()
  validator.Release()
  executor.Release()
  store.Release()
  mod.Release()
}
```

Then you can build and run: (the 18th Fibonacci number is 1346269 in 30-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Exported function name: fib
[2021-11-24 18:53:01.451] [debug]  Execution succeeded.
[2021-11-24 18:53:01.452] [debug]
 ====================  Statistics  ====================
 Total execution time: 556372295 ns
 Wasm instructions execution time: 556372295 ns
 Host functions execution time: 0 ns
 Executed wasm instructions count: 28271634
 Gas costs: 0
 Instructions per second: 50814237
Get fibonacci[30]: 1346269
```

Loader

The `Loader` object loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
var buf []byte
// ... Read the WASM code to the `buf`.

// Developers can adjust settings in the configure object.
conf := wasmedge.NewConfigure()
// Create the loader object.
// For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
loader := wasmedge.NewLoaderWithConfig(conf)
conf.Release()

// Load WASM or compiled-WASM from the file.
ast, err := loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

// Load WASM or compiled-WASM from the buffer
ast, err = loader.LoadBuffer(buf)
if err != nil {
  fmt.Println("Load WASM from buffer FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

loader.Release()
```

Validator

The `Validator` object can validate the WASM module. Every WASM module should be validated before instantiation.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the loader
context.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the validator context.
// For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
validator := wasmedge.NewValidatorWithConfig(conf)

err := validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
}

validator.Release()
```

Executor

The `Executor` object is the executor for both WASM and compiled-WASM. This object should work base on the `Store` object. For the details of the `Store` object, please refer to the next chapter.

1. Instantiate and register an `AST` object as a named `Module` instance

   As the same of registering host modules or importing WASM modules in `VM` objects, developers can instantiate and register an `AST` objects into the `Store` context as a named `Module` instance by the `Executor` APIs. After the registration, the result `Module` instance is exported with the given module name and can be linked when instantiating another module. For the details about the `Module` instances APIs, please refer to the Instances.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Register the loaded WASM `ast` into store with the export module name
"mod".
mod, res := executor.Register(store, ast, "mod")
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
  return
}

// ...

// Resources deallocations.
executor.Release()
stat.Release()
store.Release()
mod.Release()
```

2. Register an existing `Module` instance and export the module name

   Besides instantiating and registering an `AST` object, developers can register an existing `Module` instance into the store with exporting the module name (which is in the `Module` instance already). This case occurs when developers create a `Module` instance for the host functions and want to register it for linking. For the details about the construction of host functions in `Module` instances, please refer to the Host Functions.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Create a module instance for host functions.
mod := wasmedge.NewModule("mod")
// ...
// Create and add the host functions, tables, memories, and globals into
the module instance.
// ...

// Register the module instance into store with the exported module name.
// The export module name is in the module instance already.
res := executor.RegisterImport(store, mod)
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
  return
}

// ...

// Resources deallocations.
executor.Release()
stat.Release()
store.Release()
mod.Release()
```

3. Instantiate an `AST` object to an anonymous `Module` instance

   WASM or compiled-WASM modules should be instantiated before the function invocation. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` object for linking.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Instantiate the WASM module.
mod, err := executor.Instantiate(stpre, ast)
if err != nil {
  fmt.Println("WASM instantiation FAILED:", err.Error())
  return
}

executor.Release()
stat.Release()
store.Release()
mod.Release()
```

4. Invoke functions

   After registering or instantiating and get the result `Module` instance, developers can retrieve the exported `Function` instances from the `Module` instance for invocation. For the details about the `Module` instances APIs, please refer to the Instances. Please refer to the example above for the `Function` instance invocation with the

`(*Executor).Invoke` API.

AST Module

The `AST` object presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST` object.

```
ast := ...
// Assume that a WASM is loaded into an `*wasmedge.AST` object from loader.

// List the imports.
imports := ast.ListImports()
for _, import := range imports {
  fmt.Println("Import:", import.GetModuleName(), import.GetExternalName())
}

// List the exports.
exports := ast.ListExports()
for _, export := range exports {
  fmt.Println("Export:", export.GetExternalName())
}

ast.Release()
```

Store

Store is the runtime structure for the representation of all global state that can be manipulated by WebAssembly programs. The `Store` object in WasmEdge is an object to provide the instance exporting and importing when instantiating WASM modules. Developers can retrieve the named modules from the `Store` context.

```
store := wasmedge.NewStore()

// ...
// Register a WASM module via the executor object.
// ...

// Try to list the registered WASM modules.
modnames := store.ListModule()
// ...

// Find named module by name.
mod := store.FindModule("module")
// If the module with name not found, the `mod` will be `nil`.

store.Release()
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the `Module` instances from the `Store` contexts, and retrieve the other instances from the `Module` instances. A single instance can be allocated by its creation function. Developers can construct instances into an `Module` instance for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed by developers, EXCEPT they are added into an `Module` instance.

1. Module instance

   After instantiating or registering an `AST` object, developers will get a `Module` instance as the result, and have the responsibility to release it when not in use. A `Module` instance can also be created for the host module. Please refer to the host function for the details. `Module` instance provides APIs to list and find the exported instances in the module.

```
// ...
// Instantiate a WASM module via the executor object and get the `mod` as
the output module instance.
// ...

// List the exported instance of the instantiated WASM module.
// Take the function instances for example here.
funcnames := mod.ListFunction()

// Try to find the exported instance of the instantiated WASM module.
// Take the function instances for example here.
funcinst := mod.FindFunction("fib")
// `funcinst` will be `nil` if the function not found.
// The returned instance is owned by the module instance and should __NOT__
be released.
```

2. Function instance

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` objects for host functions and add them into an `Module` instance for registering into a `VM` or a `Store`. Developers can retrieve the `Function Type` from the `Function` objects through the API. For the details of the `Host Function` guide, please refer to the next chapter.

```
funcobj := ...
// `funcobj` is the `*wasmedge.Function` retrieved from the module
instance.
functype := funcobj.GetFunctionType()
// The `funcobj` retrieved from the module instance should __NOT__ be
released.
// The `functype` retrieved from the `funcobj` should __NOT__ be released.

// For the function object creation, please refer to the `Host Function`
guide.
```

3. Table instance

In WasmEdge, developers can create the `Table` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Table` objects supply APIs to control the data in table instances.

```
lim := wasmedge.NewLimitWithMax(10, 20)
// Create the table type with limit and the `FuncRef` element type.
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef, lim)
// Create the table instance with table type.
tabinst := wasmedge.NewTable(tabtype)
// Delete the table type.
tabtype.Release()

gottabtype := tabinst.GetTableType()
// The `gottabtype` got from table instance is owned by the `tabinst`
// and should __NOT__ be released.
reftype := gottabtype.GetRefType()
// The `reftype` will be `wasmedge.RefType_FuncRef`.

var gotdata interface{}
data := wasmedge.NewFuncRef(5)
err := tabinst.SetData(data, 3)
// Set the function index 5 to the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   err = tabinst.SetData(data, 13)

gotdata, err = tabinst.GetData(3)
// Get the FuncRef value of the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   gotdata, err = tabinst.GetData(13)

tabsize := tabinst.GetSize()
// `tabsize` will be 10.
err = tabinst.Grow(6)
// Grow the table size of 6, the table size will be 16.

// The following line will get an "out of bounds table access" error
// because the size (16 + 6) will reach the table limit (20):
//   err = tabinst.Grow(6)

tabinst.Release()
```

4. Memory instance

In WasmEdge, developers can create the `Memory` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Memory` objects supply APIs to control the data in memory instances.

```
lim := wasmedge.NewLimitWithMax(1, 5)
// Create the memory type with limit. The memory page size is 64KiB.
memtype := wasmedge.NewMemoryType(lim)
// Create the memory instance with memory type.
meminst := wasmedge.NewMemory(memtype)
// Delete the memory type.
memtype.Release()

data := []byte("A quick brown fox jumps over the lazy dog")
err := meminst.SetData(data, 0x1000, 10)
// Set the data[0:9] to the memory[4096:4105].

// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   err = meminst.SetData(data, 0xFFFF, 10)

var gotdata []byte
gotdata, err = meminst.GetData(0x1000, 10)
// Get the memory[4096:4105]. The `gotdata` will be `[]byte("A quick br").
// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   gotdata, err = meminst.Getdata(0xFFFF, 10)

pagesize := meminst.GetPageSize()
// `pagesize` will be 1.
err = meminst.GrowPage(2)
// Grow the page size of 2, the page size of the memory instance will be 3.

// The following line will get an "out of bounds memory access" error
// because the size (3 + 3) will reach the memory limit (5):
//   err = meminst.GetPageSize(3)

meminst.Release()
```

5. Global instance

In WasmEdge, developers can create the `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Global` objects supply APIs to control the value in global instances.

```
// Create the global type with value type and mutation.
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I64,
wasmedge.ValMut_Var)
// Create the global instance with value and global type.
globinst := wasmedge.NewGlobal(globtype, uint64(1000))
// Delete the global type.
globtype.Release()

gotglobtype := globinst.GetGlobalType()
// The `gotglobtype` got from global instance is owned by the `globinst`
// and should __NOT__ be released.
valtype := gotglobtype.GetValType()
// The `valtype` will be `wasmedge.ValType_I64`.
valmut := gotglobtype.GetMutability()
// The `valmut` will be `wasmedge.ValMut_Var`.

globinst.SetValue(uint64(888))
// Set the value u64(888) to the global.
// This function will do nothing if the value type mismatched or the
// global mutability is `wasmedge.ValMut_Const`.
gotval := globinst.GetValue()
// The `gotbal` will be `interface{}` which the type is `uint64` and
// the value is 888.

globinst.Release()
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, developers can create the `Function`, `Memory`, `Table`, and `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`.

1. Host function allocation

   Developers can define Go functions with the following function signature as the host

function body:

```
type hostFunctionSignature func(
    data interface{}, mem *Memory, params []interface{}) ([]interface{},
Result)
```

The example of an `add` host function to add 2 `i32` values:

```
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}
```

Then developers can create `Function` object with the host function body and function type:

```
// Create a function type: {i32, i32} -> {i32}.
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)

// Create a function context with the function type and host function body.
// The third parameter is the pointer to the additional data.
// Developers should guarantee the life cycle of the data, and it can be
// `nil` if the external data is not needed.
// The last parameter can be 0 if developers do not need the cost
measuring.
func_add := wasmedge.NewFunction(functype, host_add, nil, 0)

// If the function object is not added into an module instance object, it
should be released.
func_add.Release()
functype.Release()
```

2. Construct a module instance with host instances

   Besides creating a `Module` instance by registering or instantiating a WASM module, developers can create a `Module` instance with a module name and add the `Function`, `Memory`, `Table`, and `Global` instances into it with their exporting names.

```
// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

// Create a module instance with the module name "module".
mod := wasmedge.NewModule("module")

// Create and add a function instance into the module instance with export
name "add".
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)
hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
functype.Release()
mod.AddFunction("add", hostfunc)

// Create and add a table instance into the module instance with export
name "table".
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef
,wasmedge.NewLimitWithMax(10, 20))
hosttab := wasmedge.NewTable(tabtype)
tabtype.Release()
mod.AddTable("table", hosttab)

// Create and add a memory instance into the module instance with export
name "memory".
memtype := wasmedge.NewMemoryType(wasmedge.NewLimitWithMax(1, 2))
hostmem := wasmedge.NewMemory(memtype)
memtype.Release()
```

```
mod.AddMemory("memory", hostmem)

// Create and add a global instance into the module instance with export
name "global".
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I32,
wasmedge.ValMut_Var)
hostglob := wasmedge.NewGlobal(globtype, uint32(666))
globtype.Release()
mod.AddGlobal("global", hostglob)

// The module instances should be released.
// Developers should __NOT__ release the instances added into the module
instance objects.
mod.Release()
```

3. Specified module instance

`wasmedge.NewWasiModule()` API can create and initialize the `WASI` module instance.

`wasmedge.NewWasiNNModule()` API can create and initialize the `wasi_ephemeral_nn` module instance for `WASI-NN` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasiCryptoCommonModule()` API can create and initialize the `wasi_ephemeral_crypto_common` module instance for `WASI-Crypto` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasiCryptoAsymmetricCommonModule()` API can create and initialize the `wasi_ephemeral_crypto_asymmetric_common` module instance for `WASI-Crypto` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasiCryptoKxModule()` API can create and initialize the `wasi_ephemeral_crypto_kx` module instance for `WASI-Crypto` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasiCryptoSignaturesModule()` API can create and initialize the `wasi_ephemeral_crypto_signatures` module instance for `WASI-Crypto` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasiCryptoSymmetricModule()` API can create and initialize the `wasi_ephemeral_crypto_symmetric` module instance for `WASI-Crypto` plugin (`v0.10.1` or upper only).

`wasmedge.NewWasmEdgeProcessModule()` API can create and initialize the

`wasmedge_process` module instance for `wasmedge_process` plugin.

Developers can create these module instance objects and register them into the `Store` or `VM` objects rather than adjust the settings in the `Configure` objects.

Note: For the `WASI-NN` plugin, please check that the dependencies and prerequests are satisfied. Note: For the `WASI-Crypto` plugin, please check that the dependencies and prerequests are satisfied. And the 5 modules are recommended to all be created and registered together.

```
wasiobj := wasmedge.NewWasiModule(
  os.Args[1:],     // The args
  os.Environ(),    // The envs
  []string{".:."}, // The mapping preopens
)
procobj := wasmedge.NewWasmEdgeProcessModule(
  []string{"ls", "echo"}, // The allowed commands
  false,                  // Not to allow all commands
)

// Register the WASI and WasmEdge_Process into the VM object.
vm := wasmedge.NewVM()
vm.RegisterImport(wasiobj)
vm.RegisterImport(procobj)

// ... Execute some WASM functions.

// Get the WASI exit code.
exitcode := wasiobj.WasiGetExitCode()
// The `exitcode` will be 0 if the WASI function "_start" execution has no
error.
// Otherwise, it will return with the related exit code.

vm.Release()
// The import objects should be deleted.
wasiobj.Release()
procobj.Release()
```

4. Example

Create a new Go project first:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Assume that there is a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

Create and edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
```

```
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // Create the module instance with the module name "extern".
  impmod := wasmedge.NewModule("extern")

  // Create and add a function instance into the module instance with
export name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
  functype.Release()
  impmod.AddFunction("func-add", hostfunc)

  // Register the module instance into VM.
  vm.RegisterImport(impmod)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }

  impmod.Release()
```

```
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get the result: 6912
```

5. Host Data Example

   Developers can set a external data object to the `Function` object, and access to the object in the function body. Assume that edit the Go file `main.go` above:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Also set the result to the data.
  *data.(*int32) = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
```

```
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // The additional data to set into the host function.
  var data int32 = 0

  // Create the module instance with the module name "extern".
  impmod := wasmedge.NewImportObject("extern")

  // Create and add a function instance into the module instance with
export name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, &data, 0)
  functype.Release()
  impmod.AddFunction("func-add", hostfunc)

  // Register the module instance into VM.
  vm.RegisterImport(impmod)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
```

```
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  fmt.Println("Data value:", data)

  impmod.Release()
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.10.1
$ go build
$ ./wasmedge_test
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options in Go. WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

The go_WasmAOT example provide a tool for compiling a WASM file.

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

Please refer to the AOT compiler options configuration for details.

Upgrade to WasmEdge-Go v0.11.0

Due to the WasmEdge-Go API breaking changes, this document shows the guideline of programming with WasmEdge-Go API to upgrade from the `v0.10.1` to the `v0.11.0` version.

Concepts

1. Supported the user-defined error code in host functions.

   Developers can use the new API `wasmedge.NewResult()` to generate a `wasmedge.Result` struct with `wasmedge.ErrCategory_UserLevel` and the error code. With this support, developers can specify the host function error code when failed by themselves. For the examples to specify the user-defined error code, please refer to the example below.

2. Calling frame for the host function extension

   In the previous versions, host functions only pass the memory instance into the function body. For supporting the WASM multiple memories proposal and providing the recursive invocation in host functions, the new object `wasmedge.CallingFrame` replaced the memory instance in the second argument of the host function definition. For the examples of the new host function definition, please refer to the example below.

User Defined Error Code In Host Functions

Assume that we want to specify that the host function failed in the versions before `v0.10.1`:

```
// Host function body definition.
func FaildFunc(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  return nil, wasmedge.Result_Fail
}
```

When the execution is finished, developers will get the `wasmedge.Result` struct if error occurred. If developers call the `(*Result).GetCode()` with the returned error, they will get the value `2`. If developers call the `(*Result).Error()` with the returned error, they will get the error string `"generic runtime error"`.

For the versions after `v0.11.0`, developers can specify the error code within 24-bit (smaller than `16777216`) size.

```
// Host function body definition.
func FaildFunc(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // This will create a trap in WASM with the error code.
  return nil, wasmedge.NewResult(wasmedge.ErrCategory_UserLevel, 12345678)
}
```

Therefore when developers call the `(*Result).GetCode()` with the returned error, they will get the error code `12345678`. Noticed that if developers call the `(*Result).Error()`, they will always get the string `"user defined error code"`.

Calling Frame In Host Functions

When implementing the host functions, developers usually use the input memory instance to load or store data. In the WasmEdge versions before `v0.10.1`, the argument before the input and return value list of the host function definition is the memory instance object, so that developers can access the data in the memory instance.

```
import (
  "encoding/binary"
  "fmt"
)

// Host function body definition.
func LoadOffset(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // Function type: {i32} -> {}
  offset := params[0].(int32)
  data, err := mem.GetData(uint(offset), 4)
  if err != nil {
    return nil, err
  }
  fmt.Println("u32 at memory[{}]: {}", offset,
binary.LittleEndian.Uint32(data))
  return nil, wasmedge.Result_Success
}
```

The input memory instance is the one that belongs to the module instance on the top calling frame of the stack. However, after applying the WASM multiple memories proposal, there may be more than 1 memory instance in a WASM module. Furthermore, there may be requests for accessing the module instance on the top frame of the stack to get the

exported WASM functions, such as recursive invocation in host functions. To support these, the `wasmedge.CallingFrame` is designed to replace the memory instance input of the host function.

In the WasmEdge versions after `v0.11.0`, the host function definitions are changed:

```
type hostFunctionSignature func(data interface{}, callframe
*wasmedge.CallingFrame, params []interface{}) ([]interface{}, wasmedge.Result)
```

Developers need to change to use the `wasmedge.CallingFrame` related APIs to access the memory instance:

```
import (
  "encoding/binary"
  "fmt"
)

// Host function body definition.
func LoadOffset(data interface{}, callframe *wasmedge.CallingFrame, params
[]interface{}) ([]interface{}, wasmedge.Result) {
  // Function type: {i32} -> {}
  offset := params[0].(int32)

  // Get the 0th memory instance of the module of the top frame on the stack.
  mem := callframe.GetMemoryByIndex(0)

  data, err := mem.GetData(uint(offset), 4)
  if err != nil {
    return nil, err
  }
  fmt.Println("u32 at memory[{}]: {}", offset,
binary.LittleEndian.Uint32(data))
  return nil, wasmedge.Result_Success
}
```

The `(*CallingFrame).GetModule()` API can help developers to get the module instance of the top frame on the stack. With the module instance context, developers can use the module instance-related APIs to get its contents.

The `(*CallingFrame).GetExecutor()` API can help developers to get the currently used executor context. Therefore developers can use the executor to recursively invoke other WASM functions without creating a new executor context.

WasmEdge Go v0.9.1 API Documentation

The following are the guides to working with the WasmEdge-Go SDK at WasmEdge version `0.9.1` and WasmEdge-Go version `v0.9.2`.

Please install WasmEdge 0.9.1 to use this Go package.

WasmEdge-Go v0.9.1 is retracted. Please use WasmEdge-Go v0.9.2 instead.

Developers can refer here to upgrade to v0.10.0.

Table of Contents

Getting Started

The WasmEdge-go requires golang version >= 1.15. Please check your golang version before installation. Developers can download golang here.

```
$ go version
go version go1.16.5 linux/amd64
```

WasmEdge Installation

Developers must install the WasmEdge shared library with the same `WasmEdge-go` release or pre-release version.

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -v 0.9.1
```

For the developers need the `TensorFlow` or `Image` extension for `WasmEdge-go`, please install the `WasmEdge` with extensions:

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- -e tf,image -v 0.9.1
```

Noticed that the `TensorFlow` and `Image` extensions are only for the `Linux` platforms. After installation, developers can use the `source` command to update the include and linking searching path.

Get WasmEdge-go

After the WasmEdge installation, developers can get the `WasmEdge-go` package and build it in your Go project directory.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
go build
```

WasmEdge-go Extensions

By default, the `WasmEdge-go` only turns on the basic runtime.

`WasmEdge-go` has the following extensions (on the Linux platforms only):

- Tensorflow
  - This extension supports the host functions in WasmEdge-tensorflow.
  - The `TensorFlow` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e tensorflow` command.
  - For using this extension, the tag `tensorflow` when building is required:

    ```
    go build -tags tensorflow
    ```

- Image
  - This extension supports the host functions in WasmEdge-image.
  - The `Image` extension when installing `WasmEdge` is required. Please install `WasmEdge` with the `-e image` command.
  - For using this extension, the tag `image` when building is required:

    ```
    go build -tags image
    ```

Users can also turn on the multiple extensions when building:

```
go build -tags image,tensorflow
```

Example of Embedding A Function with wasmedge-bindgen

In this example, we will demonstrate how to call a few simple WebAssembly functions with wasmedge-bindgen from a Golang app. The functions are written in Rust, and require complex call parameters and return values.

While the WebAssembly only supports a few simple data types out of the box. It does not support types such as string and array. In order to pass rich types in Golang to WebAssembly, the compiler needs to convert them to simple integers. For example, it converts a string into an integer memory address and an integer length. The `#[wasmedge_bindgen]` macro does this conversion automatically, combining it with Golang's `wasmedge-bindgen` package to auto-generate the correct code to pass call parameters from Golang to WebAssembly.

```
use wasmedge_bindgen::*;
use wasmedge_bindgen_macro::*;
use num_integer::lcm;
use sha3::{Digest, Sha3_256, Keccak256};
use serde::{Serialize, Deserialize};

#[derive(Serialize, Deserialize, Debug)]
struct Point {
  x: f32,
  y: f32
}

#[derive(Serialize, Deserialize, Debug)]
struct Line {
  points: Vec<Point>,
  valid: bool,
  length: f32,
  desc: String
}

#[wasmedge_bindgen]
pub fn create_line(p1: String, p2: String, desc: String) -> String {
  let point1: Point = serde_json::from_str(p1.as_str()).unwrap();
  let point2: Point = serde_json::from_str(p2.as_str()).unwrap();
  let length = ((point1.x - point2.x) * (point1.x - point2.x) + (point1.y -
point2.y) * (point1.y - point2.y)).sqrt();

  let valid = if length == 0.0 { false } else { true };

  let line = Line { points: vec![point1, point2], valid: valid, length: length,
desc: desc };

  return serde_json::to_string(&line).unwrap();
}

#[wasmedge_bindgen]
pub fn say(s: String) -> String {
  let r = String::from("hello ");
  return r + s.as_str();
}

#[wasmedge_bindgen]
pub fn obfusticate(s: String) -> String {
  (&s).chars().map(|c| {
    match c {
      'A' ..= 'M' | 'a' ..= 'm' => ((c as u8) + 13) as char,
      'N' ..= 'Z' | 'n' ..= 'z' => ((c as u8) - 13) as char,
      _ => c
    }
  }).collect()
}
```

```
#[wasmedge_bindgen]
pub fn lowest_common_multiple(a: i32, b: i32) -> i32 {
  return lcm(a, b);
}

#[wasmedge_bindgen]
pub fn sha3_digest(v: Vec<u8>) -> Vec<u8> {
  return Sha3_256::digest(&v).as_slice().to_vec();
}

#[wasmedge_bindgen]
pub fn keccak_digest(s: Vec<u8>) -> Vec<u8> {
  return Keccak256::digest(&s).as_slice().to_vec();
}
```

First, compile the Rust source code into WebAssembly bytecode functions.

```
rustup target add wasm32-wasi
cd rust_bindgen_funcs
cargo build --target wasm32-wasi --release
# The output WASM will be target/wasm32-wasi/release
/rust_bindgen_funcs_lib.wasm
```

The Golang source code to run the WebAssembly function in WasmEdge is as follows. The `bg.Execute()` function calls the WebAssembly function and passes the parameters with the `wasmedge-bindgen` supporting.

```
package main

import (
  "fmt"
  "os"

  "github.com/second-state/WasmEdge-go/wasmedge"
  bindgen "github.com/second-state/wasmedge-bindgen/host/go"
)

func main() {
  // Expected Args[0]: program name (./bindgen_funcs)
  // Expected Args[1]: wasm file (rust_bindgen_funcs_lib.wasm))

  // Set not to print debug info
  wasmedge.SetLogErrorLevel()

  // Create configure
  var conf = wasmedge.NewConfigure(wasmedge.WASI)

  // Create VM with configure
  var vm = wasmedge.NewVMWithConfig(conf)

  // Init WASI
  var wasi = vm.GetImportObject(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping preopens
  )

  // Load and validate the wasm
  vm.LoadWasmFile(os.Args[1])
  vm.Validate()

  // Instantiate the bindgen and vm
  bg := bindgen.Instantiate(vm)

  // create_line: string, string, string -> string (inputs are JSON
stringified)
  res, err := bg.Execute("create_line", "{\"x\":2.5,\"y\":7.8}", "{\"x\":2.5,
\"y\":5.8}", "A thin red line")
  if err == nil {
    fmt.Println("Run bindgen -- create_line:", res[0].(string))
  } else {
    fmt.Println("Run bindgen -- create_line FAILED", err)
  }

  // say: string -> string
  res, err = bg.Execute("say", "bindgen funcs test")
  if err == nil {
    fmt.Println("Run bindgen -- say:", res[0].(string))
```

```
  } else {
    fmt.Println("Run bindgen -- say FAILED")
  }

  // obfusticate: string -> string
  res, err = bg.Execute("obfusticate", "A quick brown fox jumps over the lazy
dog")
  if err == nil {
    fmt.Println("Run bindgen -- obfusticate:", res[0].(string))
  } else {
    fmt.Println("Run bindgen -- obfusticate FAILED")
  }

  // lowest_common_multiple: i32, i32 -> i32
  res, err = bg.Execute("lowest_common_multiple", int32(123), int32(2))
  if err == nil {
    fmt.Println("Run bindgen -- lowest_common_multiple:", res[0].(int32))
  } else {
    fmt.Println("Run bindgen -- lowest_common_multiple FAILED")
  }

  // sha3_digest: array -> array
  res, err = bg.Execute("sha3_digest", []byte("This is an important message"))
  if err == nil {
    fmt.Println("Run bindgen -- sha3_digest:", res[0].([]byte))
  } else {
    fmt.Println("Run bindgen -- sha3_digest FAILED")
  }

  // keccak_digest: array -> array
  res, err = bg.Execute("keccak_digest", []byte("This is an important
message"))
  if err == nil {
    fmt.Println("Run bindgen -- keccak_digest:", res[0].([]byte))
  } else {
    fmt.Println("Run bindgen -- keccak_digest FAILED")
  }

  bg.Release()
  vm.Release()
  conf.Release()
}
```

Next, build the Golang application with the WasmEdge Golang SDK.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
go get github.com/second-state/wasmedge-bindgen@v0.1.12
go build
```

Run the Golang application and it will run the WebAssembly functions embedded in the WasmEdge runtime.

```
$ ./bindgen_funcs rust_bindgen_funcs/target/wasm32-wasi/release
/rust_bindgen_funcs_lib.wasm
Run bindgen -- create_line: {"points":[{"x":2.5,"y":7.8},
{"x":2.5,"y":5.8}],"valid":true,"length":2.0,"desc":"A thin red line"}
Run bindgen -- say: hello bindgen funcs test
Run bindgen -- obfusticate: N dhvpx oebja sbk whzcf bire gur ynml qbt
Run bindgen -- lowest_common_multiple: 246
Run bindgen -- sha3_digest: [87 27 231 209 189 105 251 49 159 10 211 250 15 159
154 181 43 218 26 141 56 199 25 45 60 10 20 163 54 211 195 203]
Run bindgen -- keccak_digest: [126 194 241 200 151 116 227 33 216 99 159 22 107
3 177 169 216 191 114 156 174 193 32 159 246 228 245 133 52 75 55 27]
```

Example of Embedding A Full WASI Program

Note: You can use the latest Rust compiler to create a standalone WasmEdge application with a `main.rs` functions and then embed it into a Golang application.

Besides functions, the WasmEdge Golang SDK can also embed standalone WebAssembly applications — i.e. a Rust application with a `main()` function compiled into WebAssembly.

Our demo Rust application reads from a file.

```
use std::env;
use std::fs::File;
use std::io::{self, BufRead};

fn main() {
  // Get the argv.
  let args: Vec<String> = env::args().collect();
  if args.len() <= 1 {
    println!("Rust: ERROR - No input file name.");
    return;
  }

  // Open the file.
  println!("Rust: Opening input file \"{}\"...", args[1]);
  let file = match File::open(&args[1]) {
    Err(why) => {
      println!("Rust: ERROR - Open file \"{}\" failed: {}", args[1], why);
      return;
    },
    Ok(file) => file,
  };

  // Read lines.
  let reader = io::BufReader::new(file);
  let mut texts:Vec<String> = Vec::new();
  for line in reader.lines() {
    if let Ok(text) = line {
      texts.push(text);
    }
  }
  println!("Rust: Read input file \"{}\" succeeded.", args[1]);

  // Get stdin to print lines.
  println!("Rust: Please input the line number to print the line of file.");
  let stdin = io::stdin();
  for line in stdin.lock().lines() {
    let input = line.unwrap();
    match input.parse::<usize>() {
      Ok(n) => if n > 0 && n <= texts.len() {
        println!("{}", texts[n - 1]);
      } else {
        println!("Rust: ERROR - Line \"{}\" is out of range.", n);
      },
      Err(e) => println!("Rust: ERROR - Input \"{}\" is not an integer: {}",
input, e),
    }
  }
  println!("Rust: Process end.");
}
```

Use the `rustwasmc` tool to compile the application into WebAssembly.

```
cd rust_readfile
rustwasmc build
# The output file will be at `pkg/rust_readfile.wasm`.
```

Or you can compile the application into WebAssembly directly by `cargo`:

```
cd rust_readfile
# Need to add the `wasm32-wasi` target.
rustup target add wasm32-wasi
cargo build --release --target=wasm32-wasi
# The output wasm will be at `target/wasm32-wasi/release/rust_readfile.wasm`.
```

The Golang source code to run the WebAssembly function in WasmEdge is as follows.

```
package main

import (
  "os"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  wasmedge.SetLogErrorLevel()

  var conf = wasmedge.NewConfigure(wasmedge.REFERENCE_TYPES)
  conf.AddConfig(wasmedge.WASI)
  var vm = wasmedge.NewVMWithConfig(conf)
  var wasi = vm.GetImportObject(wasmedge.WASI)
  wasi.InitWasi(
    os.Args[1:],     // The args
    os.Environ(),    // The envs
    []string{".:."}, // The mapping directories
  )

  // Instantiate and run WASM "_start" function, which refers to the main()
function
  vm.RunWasmFile(os.Args[1], "_start")

  vm.Release()
  conf.Release()
}
```

Next, build the Golang application with the WasmEdge Golang SDK.

```
go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
go build
```

Run the Golang application.

```
$ ./read_file rust_readfile/pkg/rust_readfile.wasm file.txt
Rust: Opening input file "file.txt"...
Rust: Read input file "file.txt" succeeded.
Rust: Please input the line number to print the line of file.
# Input "5" and press Enter.
5
# The output will be the 5th line of `file.txt`:
abcDEF___!@#$%^
# To terminate the program, send the EOF (Ctrl + D).
^D
# The output will print the terminate message:
Rust: Process end.
```

For more examples, please refer to the example repository.

WasmEdge-go Basics

In this partition, we will introduce the utilities and concepts of WasmEdge-go APIs and data structures.

Version

The `Version` related APIs provide developers to check for the installed WasmEdge shared library version.

```
import "github.com/second-state/WasmEdge-go/wasmedge"

verstr := wasmedge.GetVersion() // Will be `string` of WasmEdge version.
vermajor := wasmedge.GetVersionMajor() // Will be `uint` of WasmEdge major
version number.
verminor := wasmedge.GetVersionMinor() // Will be `uint` of WasmEdge minor
version number.
verpatch := wasmedge.GetVersionPatch() // Will be `uint` of WasmEdge patch
version number.
```

Logging Settings

The `wasmedge.SetLogErrorLevel()` and `wasmedge.SetLogDebugLevel()` APIs can set the logging system to debug level or error level. By default, the error level is set, and the debug

info is hidden.

Value Types

In WasmEdge-go, the APIs will automatically do the conversion for the built-in types, and implement the data structure for the reference types.

1. Number types: `i32`, `i64`, `f32`, and `f64`
    - Convert the `uint32` and `int32` to `i32` automatically when passing a value into WASM.
    - Convert the `uint64` and `int64` to `i64` automatically when passing a value into WASM.
    - Convert the `uint` and `int` to `i32` automatically when passing a value into WASM in 32-bit system.
    - Convert the `uint` and `int` to `i64` automatically when passing a value into WASM in 64-bit system.
    - Convert the `float32` to `f32` automatically when passing a value into WASM.
    - Convert the `float64` to `f64` automatically when passing a value into WASM.
    - Convert the `i32` from WASM to `int32` when getting a result.
    - Convert the `i64` from WASM to `int64` when getting a result.
    - Convert the `f32` from WASM to `float32` when getting a result.
    - Convert the `f64` from WASM to `float64` when getting a result.
2. Number type: `v128` for the `SIMD` proposal

    Developers should use the `wasmedge.NewV128()` to generate a `v128` value, and use the `wasmedge.GetV128()` to get the value.

    ```
    val := wasmedge.NewV128(uint64(1234), uint64(5678))
    high, low := val.GetVal()
    // `high` will be uint64(1234), `low` will be uint64(5678)
    ```

3. Reference types: `FuncRef` and `ExternRef` for the `Reference-Types` proposal

```
funcref := wasmedge.NewFuncRef(10)
// Create a `FuncRef` with function index 10.

num := 1234
// `num` is a `int`.
externref := wasmedge.NewExternRef(&num)
// Create an `ExternRef` which reference to the `num`.
num = 5678
// Modify the `num` to 5678.
numref := externref.GetRef().(*int)
// Get the original reference from the `ExternRef`.
fmt.Println(*numref)
// Will print `5678`.
numref.Release()
// Should call the `Release` method.
```

Results

The `Result` object specifies the execution status. Developers can use the `Error()` function to get the error message.

```
// Assume that `vm` is a `wasmedge.VM` object.
res, err = vm.Execute(...) // Ignore the detail of parameters.
// Assume that `res, err` are the return values for executing a function with
`vm`.
if err != nil {
  fmt.Println("Error message:", err.Error())
}
```

Contexts And Their Life Cycles

The objects, such as `VM`, `Store`, and `Function`, etc., are composed of `Context`s in the WasmEdge shared library. All of the contexts can be created by calling the corresponding `New` APIs, developers should also call the corresponding `Release` functions of the contexts to release the resources. Noticed that it's not necessary to call the `Release` functions for the contexts which are retrieved from other contexts but not created from the `New` APIs.

```
// Create a Configure.
conf := wasmedge.NewConfigure()
// Release the `conf` immediately.
conf.Release()
```

The details of other contexts will be introduced later.

WASM Data Structures

The WASM data structures are used for creating instances or can be queried from instance contexts. The details of instances creation will be introduced in the Instances.

1. Limit

   The `Limit` struct presents the minimum and maximum value data structure.

   ```
   lim1 := wasmedge.NewLimit(12)
   fmt.Println(lim1.HasMax())
   // Will print `false`.
   fmt.Println(lim1.GetMin())
   // Will print `12`.

   lim2 := wasmedge.NewLimitWithMax(15, 50)
   fmt.Println(lim2.HasMax())
   // Will print `true`.
   fmt.Println(lim2.GetMin())
   // Will print `15`.
   fmt.Println(lim2.GetMax())
   // Will print `50`.
   ```

2. Function type context

   The `FunctionType` is an object holds the function type context and used for the `Function` creation, checking the value types of a `Function` instance, or getting the function type with function name from VM. Developers can use the `FunctionType` APIs to get the parameter or return value types information.

```
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{
    wasmedge.ValType_ExternRef,
    wasmedge.ValType_I32,
    wasmedge.ValType_I64,
  }, []wasmedge.ValType{
    wasmedge.ValType_F32,
    wasmedge.ValType_F64,
  })

plen := functype.GetParametersLength()
// `plen` will be 3.
rlen := functype.GetReturnsLength()
// `rlen` will be 2.
plist := functype.GetParameters()
// `plist` will be `[]wasmedge.ValType{wasmedge.ValType_ExternRef,
wasmedge.ValType_I32, wasmedge.ValType_I64}`.
rlist := functype.GetReturns()
// `rlist` will be `[]wasmedge.ValType{wasmedge.ValType_F32,
wasmedge.ValType_F64}`.

functype.Release()
```

3. Table type context

   The `TableType` is an object holds the table type context and used for `Table` instance creation or getting information from `Table` instances.

```
lim := wasmedge.NewLimit(12)
tabtype := wasmedge.NewTableType(wasmedge.RefType_ExternRef, lim)

rtype := tabtype.GetRefType()
// `rtype` will be `wasmedge.RefType_ExternRef`.
getlim := tabtype.GetLimit()
// `getlim` will be the same value as `lim`.

tabtype.Release()
```

4. Memory type context

   The `MemoryType` is an object holds the memory type context and used for `Memory`

instance creation or getting information from `Memory` instances.

```
lim := wasmedge.NewLimit(1)
memtype := wasmedge.NewMemoryType(lim)

getlim := memtype.GetLimit()
// `getlim` will be the same value as `lim`.

memtype.Release()
```

5. Global type context

   The `GlobalType` is an object holds the global type context and used for `Global` instance creation or getting information from `Global` instances.

```
globtype := wasmedge.NewGlobalType(wasmedge.ValType_F64,
wasmedge.ValMut_Var)

vtype := globtype.GetValType()
// `vtype` will be `wasmedge.ValType_F64`.
vmut := globtype.GetMutability()
// `vmut` will be `wasmedge.ValMut_Var`.

globtype.Release()
```

6. Import type context

   The `ImportType` is an object holds the import type context and used for getting the imports information from a AST Module. Developers can get the external type (`function` , `table` , `memory` , or `global`), import module name, and external name from an `ImportType` object. The details about querying `ImportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
imptypelist := ast.ListImports()
// Assume that `imptypelist` is an array listed from the `ast` for the
imports.

for i, imptype := range imptypelist {
  exttype := imptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  modname := imptype.GetModuleName()
  extname := imptype.GetExternalName()
  // Get the module name and external name of the imports.

  extval := imptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

7. Export type context

   The `ExportType` is an object holds the export type context is used for getting the exports information from a AST Module. Developers can get the external type (`function`, `table`, `memory`, or `global`) and external name from an `Export Type` context. The details about querying `ExportType` objects will be introduced in the AST Module.

```
var ast *wasmedge.AST = ...
// Assume that `ast` is returned by the `Loader` for the result of loading
a WASM file.
exptypelist := ast.ListExports()
// Assume that `exptypelist` is an array listed from the `ast` for the
exports.

for i, exptype := range exptypelist {
  exttype := exptype.GetExternalType()
  // The `exttype` must be one of `wasmedge.ExternType_Function`,
`wasmedge.ExternType_Table`,
  // wasmedge.ExternType_Memory`, or `wasmedge.ExternType_Global`.

  extname := exptype.GetExternalName()
  // Get the external name of the exports.

  extval := exptype.GetExternalValue()
  // The `extval` is the type of `interface{}` which indicates one of
`*wasmedge.FunctionType`,
  // `*wasmedge.TableType`, `*wasmedge.MemoryType`, or
`*wasmedge.GlobalType`.
}
```

Async

After calling the asynchronous execution APIs, developers will get the `wasmedge.Async` object. Developers own the object and should call the `(*Async).Release()` API to release it.

1. Get the execution result of the asynchronous execution

   Developers can use the `(*Async).GetResult()` API to block and wait for getting the return values. This function will block and wait for the execution. If the execution has finished, this function will return immediately. If the execution failed, this function will return an error.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution and get the return values.
res, err := async.GetResult()
async.Release()
```

2. Wait for the asynchronous execution with timeout settings

   Besides waiting until the end of execution, developers can set the timeout to wait for.

```
async := ... // Ignored. Asynchronous execute a function.

// Blocking and waiting for the execution with the timeout(ms).
isend := async.WaitFor(1000)
if isend {
  res, err := async.GetResult()
  // ...
} else {
  async.Cancel()
  _, err := async.GetResult()
  // The error message in `err` will be "execution interrupted".
}
async.Release()
```

Configurations

The configuration object, `wasmedge.Configure`, manages the configurations for `Loader`, `Validator`, `Executor`, `VM`, and `Compiler`. Developers can adjust the settings about the proposals, VM host pre-registrations (such as `WASI`), and AOT compiler options, and then apply the `Configure` object to create other runtime objects.

1. Proposals

   WasmEdge supports turning on or off the WebAssembly proposals. This configuration is effective in any contexts created with the `Configure` object.

```
const (
  IMPORT_EXPORT_MUT_GLOBALS         =
Proposal(C.WasmEdge_Proposal_ImportExportMutGlobals)
  NON_TRAP_FLOAT_TO_INT_CONVERSIONS =
Proposal(C.WasmEdge_Proposal_NonTrapFloatToIntConversions)
  SIGN_EXTENSION_OPERATORS          =
Proposal(C.WasmEdge_Proposal_SignExtensionOperators)
  MULTI_VALUE                       =
Proposal(C.WasmEdge_Proposal_MultiValue)
  BULK_MEMORY_OPERATIONS            =
Proposal(C.WasmEdge_Proposal_BulkMemoryOperations)
  REFERENCE_TYPES                   =
Proposal(C.WasmEdge_Proposal_ReferenceTypes)
  SIMD                              = Proposal(C.WasmEdge_Proposal_SIMD)
  TAIL_CALL                         =
Proposal(C.WasmEdge_Proposal_TailCall)
  ANNOTATIONS                       =
Proposal(C.WasmEdge_Proposal_Annotations)
  MEMORY64                          =
Proposal(C.WasmEdge_Proposal_Memory64)
  THREADS                           = Proposal(C.WasmEdge_Proposal_Threads)
  EXCEPTION_HANDLING                =
Proposal(C.WasmEdge_Proposal_ExceptionHandling)
  FUNCTION_REFERENCES               =
Proposal(C.WasmEdge_Proposal_FunctionReferences)
)
```

Developers can add or remove the proposals into the `Configure` object.

```
// By default, the following proposals have turned on initially:
// * IMPORT_EXPORT_MUT_GLOBALS
// * NON_TRAP_FLOAT_TO_INT_CONVERSIONS
// * SIGN_EXTENSION_OPERATORS
// * MULTI_VALUE
// * BULK_MEMORY_OPERATIONS
// * REFERENCE_TYPES
// * SIMD
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.SIMD,
wasmedge.BULK_MEMORY_OPERATIONS)
conf.AddConfig(wasmedge.SIMD)
conf.RemoveConfig(wasmedge.REFERENCE_TYPES)
is_bulkmem := conf.HasConfig(wasmedge.BULK_MEMORY_OPERATIONS)
// The `is_bulkmem` will be `true`.
conf.Release()
```

2. Host registrations

   This configuration is used for the `VM` context to turn on the `WASI` or `wasmedge_process` supports and only effective in `VM` objects.

```
const (
  WASI             = HostRegistration(C.WasmEdge_HostRegistration_Wasi)
  WasmEdge_PROCESS =
HostRegistration(C.WasmEdge_HostRegistration_WasmEdge_Process)
)
```

   The details will be introduced in the preregistrations of VM context.

```
conf := wasmedge.NewConfigure()
// Developers can also pass the proposals as parameters:
// conf := wasmedge.NewConfigure(wasmedge.WASI)
conf.AddConfig(wasmedge.WASI)
conf.Release()
```

3. Maximum memory pages

   Developers can limit the page size of memory instances by this configuration. When

growing the page size of memory instances in WASM execution and exceeding the limited size, the page growing will fail. This configuration is only effective in the `Executor` and `VM` objects.

```
conf := wasmedge.NewConfigure()

pagesize := conf.GetMaxMemoryPage()
// By default, the maximum memory page size in each memory instances is
65536.
conf.SetMaxMemoryPage(1234)
pagesize := conf.GetMaxMemoryPage()
// `pagesize` will be 1234.

conf.Release()
```

4. AOT compiler options

   The AOT compiler options configure the behavior about optimization level, output format, dump IR, and generic binary.

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

These configurations are only effective in `Compiler` contexts.

```
conf := wasmedge.NewConfigure()

// By default, the optimization level is O3.
conf.SetCompilerOptimizationLevel(wasmedge.CompilerOptLevel_O2)
// By default, the output format is universal WASM.
conf.SetCompilerOutputFormat(wasmedge.CompilerOutputFormat_Native)
// By default, the dump IR is `false`.
conf.SetCompilerDumpIR(true)
// By default, the generic binary is `false`.
conf.SetCompilerGenericBinary(true)

conf.Release()
```

5. Statistics options

   The statistics options configure the behavior about instruction counting, cost measuring, and time measuring in both runtime and AOT compiler. These configurations are effective in `Compiler`, `VM`, and `Executor` objects.

```
conf := wasmedge.NewConfigure()

// By default, the instruction counting is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsInstructionCounting(true)
// By default, the cost measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsTimeMeasuring(true)
// By default, the time measurement is `false` when running a compiled-WASM or a pure-WASM.
conf.SetStatisticsCostMeasuring(true)

conf.Release()
```

Statistics

The statistics object, `wasmedge.Statistics`, provides the instruction counter, cost summation, and cost limitation at runtime.

Before using statistics, the statistics configuration must be set. Otherwise, the return values

of calling statistics are undefined behaviour.

1. Instruction counter

   The instruction counter can help developers to profile the performance of WASM running. Developers can retrieve the `Statistics` object from the `VM` object, or create a new one for the `Executor` creation. The details will be introduced in the next partitions.

   ```
   stat := wasmedge.NewStatistics()
   // ... After running the WASM functions with the `Statistics` object

   count := stat.GetInstrCount()
   ips := stat.GetInstrPerSecond()
   stat.Release()
   ```

2. Cost table

   The cost table is to accumulate the cost of instructions with their weights. Developers can set the cost table array (the indices are the byte code value of instructions, and the values are the cost of instructions) into the `Statistics` object. If the cost limit value is set, the execution will return the `cost limit exceeded` error immediately when exceeds the cost limit in runtime.

```
stat := wasmedge.NewStatistics()

costtable := []uint64{
  0, 0,
  10, /* 0x02: Block */
  11, /* 0x03: Loop */
  12, /* 0x04: If */
  12, /* 0x05: Else */
  0, 0, 0, 0, 0, 0,
  20, /* 0x0C: Br */
  21, /* 0x0D: Br_if */
  22, /* 0x0E: Br_table */
  0,
}
// Developers can set the costs of each instruction. The value not covered
will be 0.

WasmEdge_StatisticsSetCostTable(StatCxt, CostTable, 16);
stat.SetCostTable()
stat.SetCostLimit(5000000)

// ... After running the WASM functions with the `Statistics` object
cost := stat.GetTotalCost()
stat.Release()
```

WasmEdge VM

In this partition, we will introduce the functions of `wasmedge.VM` object and show examples of executing WASM functions.

WASM Execution Example With VM Object

The following shows the example of running the WASM for getting the Fibonacci. This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

```
(module
 (export "fib" (func $fib))
 (func $fib (param $n i32) (result i32)
  (if
   (i32.lt_s (get_local $n)(i32.const 2))
   (return (i32.const 1))
  )
  (return
   (i32.add
    (call $fib (i32.sub (get_local $n)(i32.const 2)))
    (call $fib (i32.sub (get_local $n)(i32.const 1)))
   )
  )
 )
)
```

1. Run WASM functions rapidly

   Create a new Go project first:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Assume that the WASM file `fibonacci.wasm` is copied into the current `wasmedge_test` directory, and create and edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create the configure context and add the WASI support.
  // This step is not necessary unless you need WASI support.
  conf := wasmedge.NewConfigure(wasmedge.WASI)
  // Create VM with the configure.
  vm := wasmedge.NewVMWithConfig(conf)

  res, err := vm.RunWasmFile("fibonacci.wasm", "fib", uint32(21))
  if err == nil {
    fmt.Println("Get fibonacci[21]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
  conf.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK: (the 21 Fibonacci number is 17711 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get fibonacci[21]: 17711
```

2. Instantiate and run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with

`VM` object APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level.
  wasmedge.SetLogErrorLevel()

  // Create VM.
  vm := wasmedge.NewVM()
  var err error
  var res []interface{}

  // Step 1: Load WASM file.
  err = vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  // Developers can load, validate, and instantiate another WASM module
  // to replace the instantiated one. In this case, the old module will
  // be cleared, but the registered modules are still kept.
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }
```

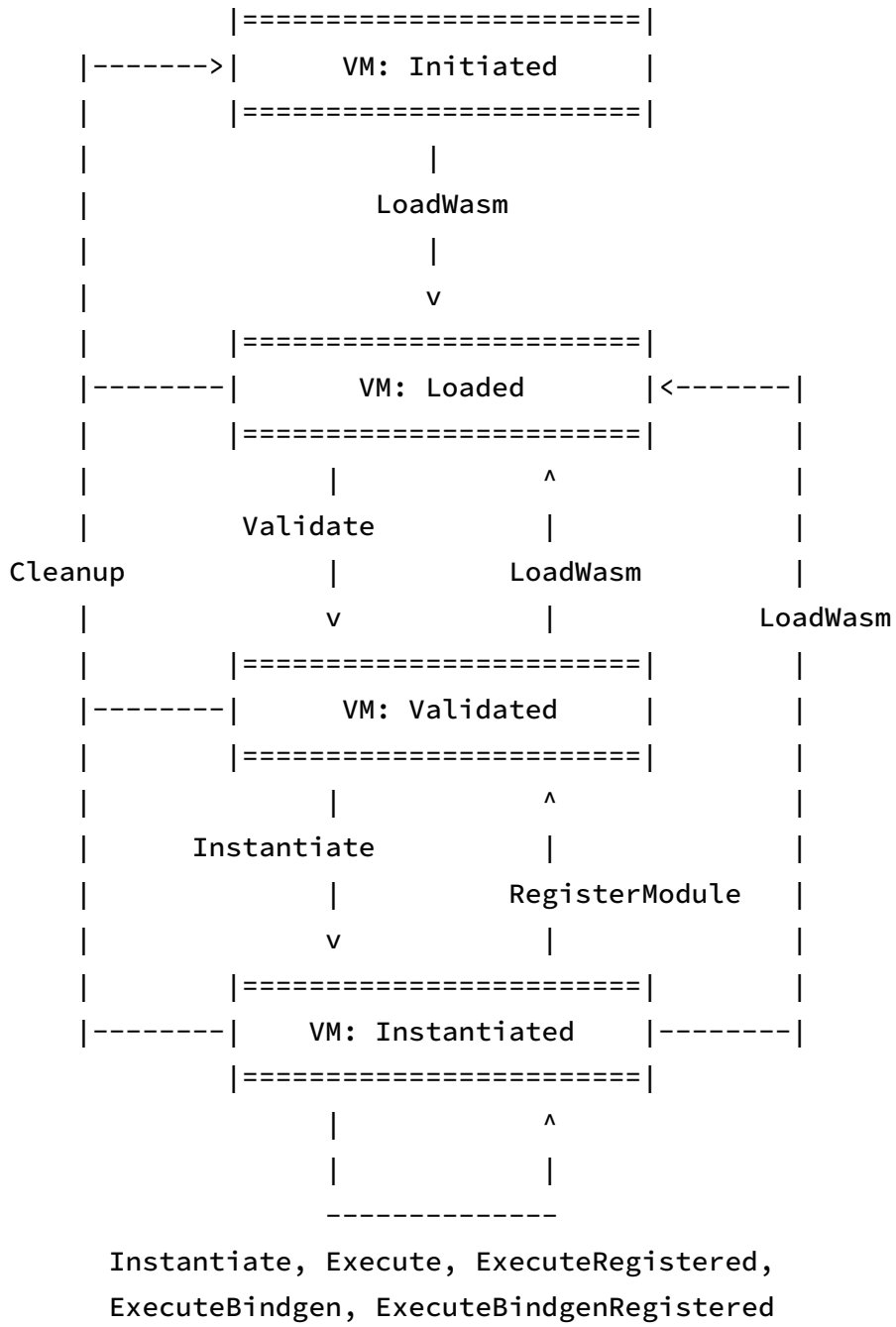
```
  // Step 4: Execute WASM functions. Parameters: (funcname, args...)
  res, err = vm.Execute("fib", uint32(25))
  // Developers can execute functions repeatedly after instantiation.
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

The following graph explains the status of the `VM` object.



The status of the `VM` context would be `Inited` when created. After loading WASM successfully, the status will be `Loaded`. After validating WASM successfully, the status will be `Validated`. After instantiating WASM successfully, the status will be `Instantiated`, and developers can invoke functions. Developers can register WASM or import objects in any status, but they should instantiate WASM again. Developers can also load WASM in any status, and they should validate and instantiate the WASM module before function invocation. When in the `Instantiated` status, developers can instantiate the WASM module again to reset the old WASM runtime structures.

VM Creations

The `VM` creation APIs accepts the `Configure` object and the `Store` object. Noticed that if the `VM` created with the outside `Store` object, the `VM` will execute WASM on that `Store` object. If the `Store` object is set into multiple `VM` objects, it may causes data conflict when in execution. The details of the `Store` object will be introduced in Store.

```
conf := wasmedge.NewConfigure()
store := wasmedge.NewStore()

// Create a VM with default configure and store.
vm := wasmedge.NewVM()
vm.Release()

// Create a VM with the specified configure and default store.
vm = wasmedge.NewVMWithConfig(conf)
vm.Release()

// Create a VM with the default configure and specified store.
vm = wasmedge.NewVMWithStore(store)
vm.Release()

// Create a VM with the specified configure and store.
vm = wasmedge.NewVMWithConfigAndStore(conf, store)
vm.Release()

conf.Release()
store.Release()
```

Preregistrations

WasmEdge provides the following built-in pre-registrations.

1. WASI (WebAssembly System Interface)

   Developers can turn on the WASI support for VM in the `Configure` object.

```
conf := wasmedge.NewConfigure(wasmedge.WASI)
// Or you can set the `wasmedge.WASI` into the configure object through
`(*Configure).AddConfig`.
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
wasiconf := conf.GetImportObject(wasmedge.WASI)
// Initialize the WASI.
wasiconf.InitWasi(/* ... ignored */)

conf.Release()
```

And also can create the WASI import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

2. WasmEdge_Process

   This pre-registration is for the process interface for WasmEdge on `Rust` sources. After turning on this pre-registration, the VM will support the `wasmedge_process` host functions.

```
conf := wasmedge.NewConfigure(wasmedge.WasmEdge_PROCESS)
vm := wasmedge.NewVMWithConfig(conf)
vm.Release()

// The following API can retrieve the pre-registration import objects from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not
set into the configuration.
procconf := conf.GetImportObject(wasmedge.WasmEdge_PROCESS)
// Initialize the WasmEdge_Process.
procconf.InitWasmEdgeProcess(/* ... ignored */)

conf.Release()
```

   And also can create the WasmEdge_Process import object from API. The details will be introduced in the Host Functions and the Host Module Registrations.

Host Module Registrations

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, the host functions are composed into host modules as `ImportObject` objects with module names. Please refer to the Host Functions in WasmEdge Runtime for the details. In this chapter, we show the example for registering the host modules into a `VM` object.

```
vm := wasmedge.NewVM()
// You can also create and register the WASI host modules by this API.
wasiobj := wasmedge.NewWasiImportObject(/* ... ignored ... */)

res := vm.RegisterImport(wasiobj)
// The result status should be checked.

vm.Release()
// The created import objects should be released.
wasiobj.Release()
```

WASM Registrations And Executions

In WebAssembly, the instances in WASM modules can be exported and can be imported by other WASM modules. WasmEdge VM provides APIs for developers to register and export any WASM modules, and execute the functions or host functions in the registered WASM modules.

1. Register the WASM modules with exported module names

   Unless the import objects have already contained the module names, every WASM module should be named uniquely when registering. The following shows the example.

   Create a new Go project first:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Assume that the WASM file `fibonacci.wasm` is copied into the current directory. Then create and edit the Go file `main.go` as following:

```
package main

import "github.com/second-state/WasmEdge-go/wasmedge"

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  var err error
  err = vm.RegisterWasmFile("module_name", "fibonacci.wasm")
  // Developers can register the WASM module from `[]byte` with the
  // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
  // the `(*VM).RegisterAST` function.
  // The result status should be checked. The error will occur if the
  // WASM module instantiation failed or the module name conflicts.

  vm.Release()
}
```

2. Execute the functions in registered WASM modules

   Edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  var res []interface{}
  var err error
  // Register the WASM module from file into VM with the module name "mod".
  err = vm.RegisterWasmFile("mod", "fibonacci.wasm")
  // Developers can register the WASM module from `[]byte` with the
  // `(*VM).RegisterWasmBuffer` function, or from `AST` object with
  // the `(*VM).RegisterAST` function.
  if err != nil {
    fmt.Println("WASM registration failed:", err.Error())
    return
  }
  // The function "fib" in the "fibonacci.wasm" was exported with the
module
  // name "mod". As the same as host functions, other modules can import
the
  // function `"mod" "fib"`.

  // Execute WASM functions in registered modules.
  // Unlike the execution of functions, the registered functions can be
  // invoked without `(*VM).Instantiate` because the WASM module was
  // instantiated when registering.
  // Developers can also invoke the host functions directly with this API.
  res, err = vm.ExecuteRegistered("mod", "fib", int32(25))
  if err == nil {
    fmt.Println("Get fibonacci[25]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }
```

```
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get fibonacci[25]: 121393
```

Asynchronous Execution

1. Asynchronously run WASM functions rapidly

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Asynchronously run the WASM function from file and get the
`wasmedge.Async` object.
  async := vm.AsyncRunWasmFile("fibonacci.wasm", "fib", uint32(20))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 20th Fibonacci number is 10946 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get the result: 10946
```

2. Instantiate and asynchronously run WASM functions manually

   Besides the above example, developers can run the WASM functions step-by-step with `VM` context APIs:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  var err error
  var res []interface{}

  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  // Developers can load the WASM binary from buffer with the
`(*VM).LoadWasmBuffer()` API,
  // or from `wasmedge.AST` object with the `(*VM).LoadWasmAST()` API.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Step 4: Asynchronously execute the WASM function and get the
```

```
`wasmedge.Async` object.
  async := vm.AsyncExecute("fib", uint32(25))

  // Block and wait for the execution and get the results.
  res, err := async.GetResult()
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  async.Release()
  vm.Release()
}
```

Then you can build and run: (the 25th Fibonacci number is 121393 in 0-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get the result: 121393
```

Instance Tracing

Sometimes the developers may have requirements to get the instances of the WASM runtime. The `VM` object supplies the APIs to retrieve the instances.

1. Store

   If the `VM` object is created without assigning a `Store` object, the `VM` context will allocate and own a `Store`.

   ```
   vm := wasmedge.NewVM()
   store := vm.GetStore()
   // The object should __NOT__ be deleted by calling `(*Store).Release`.
   vm.Release()
   ```

   Developers can also create the `VM` object with a `Store` object. In this case, developers should guarantee that the `Store` object cannot be released before the `VM` object. Please refer to the Store Objects for the details about the `Store` APIs.

```
store := wasmedge.NewStore()
vm := wasmedge.NewVMWithStore(store)

storemock := vm.GetStore()
// The internal store context of the `store` and the `storemock` are the
same.

vm.Release()
store.Release()
```

2. List exported functions

   After the WASM module instantiation, developers can use the `(*VM).Execute` function to invoke the exported WASM functions. For this purpose, developers may need information about the exported WASM function list. Please refer to the Instances in runtime for the details about the function types.

   Assume that a new Go project is created as following:

   ```
   mkdir wasmedge_test && cd wasmedge_test
   go mod init wasmedge_test
   ```

   Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Create VM.
  vm := wasmedge.NewVM()

  // Step 1: Load WASM file.
  err := vm.LoadWasmFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }

  // Step 2: Validate the WASM module.
  err = vm.Validate()
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
    return
  }

  // Step 3: Instantiate the WASM module.
  err = vm.Instantiate()
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // List the exported functions for the names and function types.
  funcnames, functypes := vm.GetFunctionList()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }
  for _, ftype := range functypes {
    // `ftype` is the `FunctionType` object of the same index in the
```

```
`funcnames` array.
    // Developers should __NOT__ call the `ftype.Release()`.
  }

  vm.Release()
}
```

Then you can build and run: (the only exported function in `fibonacci.wasm` is `fib`)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Exported function name: fib
```

If developers want to get the exported function names in the registered WASM modules, please retrieve the `Store` object from the `VM` object and refer to the APIs of Store Contexts to list the registered functions by the module name.

3. Get function types

   The `VM` object provides APIs to find the function type by function name. Please refer to the Instances in runtime for the details about the function types.

```
// Assume that a WASM module is instantiated in `vm` which is a
`wasmedge.VM` object.
functype := vm.GetFunctionType("fib")
// Developers can get the function types of functions in the registered
modules via the
// `(*VM).GetFunctionTypeRegistered` API with the function name and the
module name.
// If the function is not found, these APIs will return `nil`.
// Developers should __NOT__ call the `(*FunctionType).Release` function of
the returned object.
```

WasmEdge Runtime

In this partition, we will introduce the objects of WasmEdge runtime manually.

WASM Execution Example Step-By-Step

Besides the WASM execution through the `VM` object rapidly, developers can execute the WASM functions or instantiate WASM modules step-by-step with the `Loader`, `Validator`, `Executor`, and `Store` objects.

Assume that a new Go project is created as following:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Then assume that the WASM file `fibonacci.wasm` is copied into the current directory, and create and edit a Go file `main.go`:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

func main() {
  // Set the logging level to debug to print the statistics info.
  wasmedge.SetLogDebugLevel()
  // Create the configure object. This is not necessary if developers use the
default configuration.
  conf := wasmedge.NewConfigure()
  // Turn on the runtime instruction counting and time measuring.
  conf.SetStatisticsInstructionCounting(true)
  conf.SetStatisticsTimeMeasuring(true)
  // Create the statistics object. This is not necessary if the statistics in
runtime is not needed.
  stat := wasmedge.NewStatistics()
  // Create the store object. The store object is the WASM runtime structure
core.
  store := wasmedge.NewStore()

  var err error
  var res []interface{}
  var ast *wasmedge.AST

  // Create the loader object.
  // For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
  loader := wasmedge.NewLoaderWithConfig(conf)
  // Create the validator object.
  // For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
  validator := wasmedge.NewValidatorWithConfig(conf)
  // Create the executor object.
  // For executor creation with default configuration and without statistics,
you can use `wasmedge.NewExecutor()` instead.
  executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)

  // Load the WASM file or the compiled-WASM file and convert into the AST
module object.
  ast, err = loader.LoadFile("fibonacci.wasm")
  if err != nil {
    fmt.Println("Load WASM from file FAILED:", err.Error())
    return
  }
  // Validate the WASM module.
  err = validator.Validate(ast)
  if err != nil {
    fmt.Println("Validation FAILED:", err.Error())
```

```
    return
  }
  // Instantiate the WASM module into the Store object.
  err = executor.Instantiate(store, ast)
  if err != nil {
    fmt.Println("Instantiation FAILED:", err.Error())
    return
  }

  // Try to list the exported functions of the instantiated WASM module.
  funcnames := store.ListFunction()
  for _, fname := range funcnames {
    fmt.Println("Exported function name:", fname)
  }

  // Invoke the WASM function.
  res, err = executor.Invoke(store, "fib", int32(30))
  if err == nil {
    fmt.Println("Get fibonacci[30]:", res[0].(int32))
  } else {
    fmt.Println("Run failed:", err.Error())
  }

  // Resources deallocations.
  conf.Release()
  stat.Release()
  ast.Release()
  loader.Release()
  validator.Release()
  executor.Release()
  store.Release()
}
```

Then you can build and run: (the 18th Fibonacci number is 1346269 in 30-based index)

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Exported function name: fib
[2021-11-24 18:53:01.451] [debug]  Execution succeeded.
[2021-11-24 18:53:01.452] [debug]
 ====================  Statistics  ====================
 Total execution time: 556372295 ns
 Wasm instructions execution time: 556372295 ns
 Host functions execution time: 0 ns
 Executed wasm instructions count: 28271634
 Gas costs: 0
 Instructions per second: 50814237
Get fibonacci[30]: 1346269
```

Loader

The `Loader` object loads the WASM binary from files or buffers. Both the WASM and the compiled-WASM from the WasmEdge AOT Compiler are supported.

```
var buf []byte
// ... Read the WASM code to the `buf`.

// Developers can adjust settings in the configure object.
conf := wasmedge.NewConfigure()
// Create the loader object.
// For loader creation with default configuration, you can use
`wasmedge.NewLoader()` instead.
loader := wasmedge.NewLoaderWithConfig(conf)
conf.Release()

// Load WASM or compiled-WASM from the file.
ast, err := loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

// Load WASM or compiled-WASM from the buffer
ast, err = loader.LoadBuffer(buf)
if err != nil {
  fmt.Println("Load WASM from buffer FAILED:", err.Error())
} else {
  // The output AST object should be released.
  ast.Release()
}

loader.Release()
```

Validator

The `Validator` object can validate the WASM module. Every WASM module should be validated before instantiation.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the loader
context.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the validator context.
// For validator creation with default configuration, you can use
`wasmedge.NewValidator()` instead.
validator := wasmedge.NewValidatorWithConfig(conf)

err := validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
}

validator.Release()
```

Executor

The `Executor` object is the executor for both WASM and compiled-WASM. This object should work base on the `Store` object. For the details of the `Store` object, please refer to the next chapter.

1. Register modules

   As the same of registering host modules or importing WASM modules in `VM` objects, developers can register `ImportObject` or `AST` objects into the `Store` object by the `Executor` APIs. For the details of import objects, please refer to the Host Functions).

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Register the loaded WASM `ast` into store with the export module name
"mod".
res := executor.RegisterModule(store, ast, "mod")
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
  return
}

// Assume that the `impobj` is the `*wasmedge.ImportObject` for host
functions.
impobj := ...
err = executor.RegisterImport(store, impobj)
if err != nil {
  fmt.Println("Import object registration FAILED:", err.Error())
  return
}

executor.Release()
stat.Release()
store.Release()
impobj.Release()
```

2. Instantiate modules

WASM or compiled-WASM modules should be instantiated before the function invocation. Note that developers can only instantiate one module into the `Store` object, and in that case, the old instantiated module will be cleaned. Before instantiating a WASM module, please check the import section for ensuring the imports are registered into the `Store` object.

```
// ...
// Assume that the `ast` is the output `*wasmedge.AST` object from the
loader
// and has passed the validation.
// Assume that the `conf` is the `*wasmedge.Configure` object.

// Create the statistics object. This step is not necessary if the
statistics
// is not needed.
stat := wasmedge.NewStatistics()
// Create the executor object.
// For executor creation with default configuration and without statistics,
// you can use `wasmedge.NewExecutor()` instead.
executor := wasmedge.NewExecutorWithConfigAndStatistics(conf, stat)
// Create the store object. The store is the WASM runtime structure core.
store := wasmedge.NewStore()

// Instantiate the WASM module.
err := executor.Instantiate(stpre, ast)
if err != nil {
  fmt.Println("WASM instantiation FAILED:", err.Error())
  return
}

executor.Release()
stat.Release()
store.Release()
```

3. Invoke functions

As the same as function invocation via the `VM` object, developers can invoke the functions of the instantiated or registered modules. The APIs, `(*Executor).Invoke` and `(*Executor).InvokeRegistered`, are similar as the APIs of the `VM` object. Please refer to the VM context workflows for details.

AST Module

The `AST` object presents the loaded structure from a WASM file or buffer. Developer will get this object after loading a WASM file or buffer from Loader. Before instantiation, developers can also query the imports and exports of an `AST` object.

```
ast := ...
// Assume that a WASM is loaded into an `*wasmedge.AST` object from loader.

// List the imports.
imports := ast.ListImports()
for _, import := range imports {
  fmt.Println("Import:", import.GetModuleName(), import.GetExternalName())
}

// List the exports.
exports := ast.ListExports()
for _, export := range exports {
  fmt.Println("Export:", export.GetExternalName())
}

ast.Release()
```

Store

Store is the runtime structure for the representation of all instances of `Function` s, `Table` s, `Memory` s, and `Global` s that have been allocated during the lifetime of the abstract machine. The `Store` object in WasmEdge-go provides APIs to list the exported instances with their names or find the instances by exported names. For adding instances into `Store` objects, please instantiate or register WASM modules or `ImportObject` objects via the `Executor` APIs.

1. List instances

```
store := wasmedge.NewStore()
// ...
// Instantiate a WASM module via the `*wasmedge.Executor` object.
// ...

// Try to list the exported functions of the instantiated WASM module.
// Take the function instances for example here.
funcnames := store.ListFunction()
for _, name := range funcnames {
  fmt.Println("Exported function name:", name)
}

store.Release()
```

Developers can list the function instance exported names of the registered modules via the `(*Store).ListFunctionRegistered()` API with the module name.

2. Find instances

```
store := wasmedge.NewStore()
// ...
// Instantiate a WASM module via the `*wasmedge.Executor` object.
// ...

// Try to find the exported functions of the instantiated WASM module.
// Take the function instances for example here.
funcobj := store.FindFunction("fib")
// `funcobj` will be `nil` if the function not found.

store.Release()
```

Developers can retrieve the exported function instances of the registered modules via the `(*Store).FindFunctionRegistered` API with the module name.

3. List registered modules

With the module names, developers can list the exported instances of the registered modules with their names.

```
store := wasmedge.NewStore()
// ...
// Instantiate a WASM module via the `*wasmedge.Executor` object.
// ...

// Try to list the registered WASM modules.
modnames := store.ListModule()
for _, name := range modnames {
  fmt.Println("Registered module names:", name)
}

store.Release()
```

Instances

The instances are the runtime structures of WASM. Developers can retrieve the instances from the `Store` objects. The `Store` objects will allocate instances when a WASM module or an `ImportObject` is registered or instantiated through the `Executor`. A single instance can be allocated by its creation function. Developers can construct instances into an `ImportObject` for registration. Please refer to the Host Functions for details. The instances created by their creation functions should be destroyed, EXCEPT they are added into an `ImportObject` object.

1. Function instance

   Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge, developers can create the `Function` objects for host functions and add them into an `ImportObject` object for registering into a `VM` or a `Store`. For both host functions and the functions get from `Store`, developers can retrieve the `FunctionType` from the `Function` objects. For the details of the `Host Function` guide, please refer to the next chapter.

   ```
   funcinst := ...
   // `funcobj` is the `*wasmedge.Function` retrieved from the store object.
   functype := funcobj.GetFunctionType()
   // The `funcobj` retrieved from the store object should __NOT__ be
   released.
   // The `functype` retrieved from the `funcobj` should __NOT__ be released.
   ```

2. Table instance

   In WasmEdge, developers can create the `Table` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Table` objects supply APIs to control the data in table instances.

```
lim := wasmedge.NewLimitWithMax(10, 20)
// Create the table type with limit and the `FuncRef` element type.
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef, lim)
// Create the table instance with table type.
tabinst := wasmedge.NewTable(tabtype)
// Delete the table type.
tabtype.Release()

gottabtype := tabinst.GetTableType()
// The `gottabtype` got from table instance is owned by the `tabinst`
// and should __NOT__ be released.
reftype := gottabtype.GetRefType()
// The `reftype` will be `wasmedge.RefType_FuncRef`.

var gotdata interface{}
data := wasmedge.NewFuncRef(5)
err := tabinst.SetData(data, 3)
// Set the function index 5 to the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   err = tabinst.SetData(data, 13)

gotdata, err = tabinst.GetData(3)
// Get the FuncRef value of the table[3].

// The following line will get an "out of bounds table access" error
// because the position (13) is out of the table size (10):
//   gotdata, err = tabinst.GetData(13)

tabsize := tabinst.GetSize()
// `tabsize` will be 10.
err = tabinst.Grow(6)
// Grow the table size of 6, the table size will be 16.

// The following line will get an "out of bounds table access" error
// because the size (16 + 6) will reach the table limit (20):
//   err = tabinst.Grow(6)

tabinst.Release()
```

3. Memory instance

In WasmEdge, developers can create the `Memory` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Memory` objects supply APIs to control the data in memory instances.

```
lim := wasmedge.NewLimitWithMax(1, 5)
// Create the memory type with limit. The memory page size is 64KiB.
memtype := wasmedge.NewMemoryType(lim)
// Create the memory instance with memory type.
meminst := wasmedge.NewMemory(memtype)
// Delete the memory type.
memtype.Release()

data := []byte("A quick brown fox jumps over the lazy dog")
err := meminst.SetData(data, 0x1000, 10)
// Set the data[0:9] to the memory[4096:4105].

// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   err = meminst.SetData(data, 0xFFFF, 10)

var gotdata []byte
gotdata, err = meminst.GetData(0x1000, 10)
// Get the memory[4096:4105]. The `gotdata` will be `[]byte("A quick br").
// The following line will get an "out of bounds memory access" error
// because [65535:65544] is out of 1 page size (65536):
//   gotdata, err = meminst.Getdata(0xFFFF, 10)

pagesize := meminst.GetPageSize()
// `pagesize` will be 1.
err = meminst.GrowPage(2)
// Grow the page size of 2, the page size of the memory instance will be 3.

// The following line will get an "out of bounds memory access" error
// because the size (3 + 3) will reach the memory limit (5):
//   err = meminst.GetPageSize(3)

meminst.Release()
```

4. Global instance

In WasmEdge, developers can create the `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`. The `Global` objects supply APIs to control the value in global instances.

```
// Create the global type with value type and mutation.
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I64,
wasmedge.ValMut_Var)
// Create the global instance with value and global type.
globinst := wasmedge.NewGlobal(globtype, uint64(1000))
// Delete the global type.
globtype.Release()

gotglobtype := globinst.GetGlobalType()
// The `gotglobtype` got from global instance is owned by the `globinst`
// and should __NOT__ be released.
valtype := gotglobtype.GetValType()
// The `valtype` will be `wasmedge.ValType_I64`.
valmut := gotglobtype.GetMutability()
// The `valmut` will be `wasmedge.ValMut_Var`.

globinst.SetValue(uint64(888))
// Set the value u64(888) to the global.
// This function will do nothing if the value type mismatched or the
// global mutability is `wasmedge.ValMut_Const`.
gotval := globinst.GetValue()
// The `gotbal` will be `interface{}` which the type is `uint64` and
// the value is 888.

globinst.Release()
```

Host Functions

Host functions are functions outside WebAssembly and passed to WASM modules as imports. In WasmEdge-go, developers can create the `Function`, `Memory`, `Table`, and `Global` objects and add them into an `ImportObject` object for registering into a `VM` or a `Store`.

1. Host function allocation

   Developers can define Go functions with the following function signature as the host

function body:

```
type hostFunctionSignature func(
    data interface{}, mem *Memory, params []interface{}) ([]interface{},
Result)
```

The example of an `add` host function to add 2 `i32` values:

```
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}
```

Then developers can create `Function` object with the host function body and function type:

```
// Create a function type: {i32, i32} -> {i32}.
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)

// Create a function context with the function type and host function body.
// The third parameter is the pointer to the additional data.
// Developers should guarantee the life cycle of the data, and it can be
// `nil` if the external data is not needed.
// The last parameter can be 0 if developers do not need the cost
measuring.
func_add := wasmedge.NewFunction(functype, host_add, nil, 0)

// If the function object is not added into an import object object, it
should be released.
func_add.Release()
functype.Release()
```

2. Import object object

   The `ImportObject` object holds an exporting module name and the instances. Developers can add the `Function`, `Memory`, `Table`, and `Global` instances with their exporting names.

```
// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

// Create the import object with the module name "module".
impobj := wasmedge.NewImportObject("module")

// Create and add a function instance into the import object with export
name "add".
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)
hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
functype.Release()
impobj.AddFunction("add", hostfunc)

// Create and add a table instance into the import object with export name
"table".
tabtype := wasmedge.NewTableType(wasmedge.RefType_FuncRef
,wasmedge.NewLimitWithMax(10, 20))
hosttab := wasmedge.NewTable(tabtype)
tabtype.Release()
impobj.AddTable("table", hosttab)

// Create and add a memory instance into the import object with export name
"memory".
memtype := wasmedge.NewMemoryType(wasmedge.NewLimitWithMax(1, 2))
hostmem := wasmedge.NewMemory(memtype)
memtype.Release()
```

```
impobj.AddMemory("memory", hostmem)

// Create and add a global instance into the import object with export name
"global".
globtype := wasmedge.NewGlobalType(wasmedge.ValType_I32,
wasmedge.ValMut_Var)
hostglob := wasmedge.NewGlobal(globtype, uint32(666))
globtype.Release()
impobj.AddGlobal("global", hostglob)

// The import objects should be released.
// Developers should __NOT__ release the instances added into the import
object objects.
impobj.Release()
```

3. Specified import object

`wasmedge.NewWasiImportObject()` API can create and initialize the `WASI` import object. `wasmedge.NewWasmEdgeProcessImportObject()` API can create and initialize the `wasmedge_process` import object. Developers can create these import object objects and register them into the `Store` or `VM` objects rather than adjust the settings in the `Configure` objects.

```
wasiobj := wasmedge.NewWasiImportObject(
  os.Args[1:],     // The args
  os.Environ(),    // The envs
  []string{".:."}, // The mapping preopens
)
procobj := wasmedge.NewWasmEdgeProcessImportObject(
  []string{"ls", "echo"}, // The allowed commands
  false,                  // Not to allow all commands
)

// Register the WASI and WasmEdge_Process into the VM object.
vm := wasmedge.NewVM()
vm.RegisterImport(wasiobj)
vm.RegisterImport(procobj)

// ... Execute some WASM functions.

// Get the WASI exit code.
exitcode := wasiobj.WasiGetExitCode()
// The `exitcode` will be 0 if the WASI function "_start" execution has no
error.
// Otherwise, it will return with the related exit code.

vm.Release()
// The import objects should be deleted.
wasiobj.Release()
procobj.Release()
```

4. Example

Create a new Go project first:

```
mkdir wasmedge_test && cd wasmedge_test
go mod init wasmedge_test
```

Assume that there is a simple WASM from the WAT as following:

```
(module
  (type $t0 (func (param i32 i32) (result i32)))
  (import "extern" "func-add" (func $f-add (type $t0)))
  (func (export "addTwo") (param i32 i32) (result i32)
    local.get 0
    local.get 1
    call $f-add)
)
```

Create and edit the Go file `main.go` as following:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
```

```
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // Create the import object with the module name "extern".
  impobj := wasmedge.NewImportObject("extern")

  // Create and add a function instance into the import object with export
name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
  functype.Release()
  impobj.AddFunction("func-add", hostfunc)

  // Register the import object into VM.
  vm.RegisterImport(impobj)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }

  impobj.Release()
```

```
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get the result: 6912
```

5. Host Data Example

   Developers can set a external data object to the function object, and access to the object in the function body. Assume that edit the Go file `main.go` above:

```
package main

import (
  "fmt"

  "github.com/second-state/WasmEdge-go/wasmedge"
)

// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Also set the result to the data.
  *data.(*int32) = res

  // Return
  return returns, wasmedge.Result_Success
}

func main() {
  // Create the VM object.
  vm := wasmedge.NewVM()

  // The WASM module buffer.
  wasmbuf := []byte{
    /* WASM header */
    0x00, 0x61, 0x73, 0x6D, 0x01, 0x00, 0x00, 0x00,
    /* Type section */
    0x01, 0x07, 0x01,
    /* function type {i32, i32} -> {i32} */
    0x60, 0x02, 0x7F, 0x7F, 0x01, 0x7F,
    /* Import section */
    0x02, 0x13, 0x01,
    /* module name: "extern" */
```

```
    0x06, 0x65, 0x78, 0x74, 0x65, 0x72, 0x6E,
    /* extern name: "func-add" */
    0x08, 0x66, 0x75, 0x6E, 0x63, 0x2D, 0x61, 0x64, 0x64,
    /* import desc: func 0 */
    0x00, 0x00,
    /* Function section */
    0x03, 0x02, 0x01, 0x00,
    /* Export section */
    0x07, 0x0A, 0x01,
    /* export name: "addTwo" */
    0x06, 0x61, 0x64, 0x64, 0x54, 0x77, 0x6F,
    /* export desc: func 0 */
    0x00, 0x01,
    /* Code section */
    0x0A, 0x0A, 0x01,
    /* code body */
    0x08, 0x00, 0x20, 0x00, 0x20, 0x01, 0x10, 0x00, 0x0B,
  }

  // The additional data to set into the host function.
  var data int32 = 0

  // Create the import object with the module name "extern".
  impobj := wasmedge.NewImportObject("extern")

  // Create and add a function instance into the import object with export
name "func-add".
  functype := wasmedge.NewFunctionType(
    []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
    []wasmedge.ValType{wasmedge.ValType_I32},
  )
  hostfunc := wasmedge.NewFunction(functype, host_add, &data, 0)
  functype.Release()
  impobj.AddFunction("func-add", hostfunc)

  // Register the import object into VM.
  vm.RegisterImport(impobj)

  res, err := vm.RunWasmBuffer(wasmbuf, "addTwo", uint32(1234),
uint32(5678))
  if err == nil {
```

```
    fmt.Println("Get the result:", res[0].(int32))
  } else {
    fmt.Println("Error message:", err.Error())
  }
  fmt.Println("Data value:", data)

  impobj.Release()
  vm.Release()
}
```

Then you can build and run the Golang application with the WasmEdge Golang SDK:

```
$ go get github.com/second-state/WasmEdge-go/wasmedge@v0.9.2
$ go build
$ ./wasmedge_test
Get the result: 6912
Data value: 6912
```

WasmEdge AOT Compiler

In this partition, we will introduce the WasmEdge AOT compiler and the options in Go. WasmEdge runs the WASM files in interpreter mode, and WasmEdge also supports the AOT (ahead-of-time) mode running without modifying any code. The WasmEdge AOT (ahead-of-time) compiler compiles the WASM files for running in AOT mode which is much faster than interpreter mode. Developers can compile the WASM files into the compiled-WASM files in shared library format for universal WASM format for the AOT mode execution.

Compilation Example

The go_WasmAOT example provide a tool for compiling a WASM file.

Compiler Options

Developers can set options for AOT compilers such as optimization level and output format:

```
const (
  // Disable as many optimizations as possible.
  CompilerOptLevel_O0 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O0)
  // Optimize quickly without destroying debuggability.
  CompilerOptLevel_O1 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O1)
  // Optimize for fast execution as much as possible without triggering
significant incremental compile time or code size growth.
  CompilerOptLevel_O2 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O2)
  // Optimize for fast execution as much as possible.
  CompilerOptLevel_O3 =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_O3)
  // Optimize for small code size as much as possible without triggering
significant incremental compile time or execution time slowdowns.
  CompilerOptLevel_Os =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Os)
  // Optimize for small code size as much as possible.
  CompilerOptLevel_Oz =
CompilerOptimizationLevel(C.WasmEdge_CompilerOptimizationLevel_Oz)
)

const (
  // Native dynamic library format.
  CompilerOutputFormat_Native =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Native)
  // WebAssembly with AOT compiled codes in custom section.
  CompilerOutputFormat_Wasm =
CompilerOutputFormat(C.WasmEdge_CompilerOutputFormat_Wasm)
)
```

Please refer to the AOT compiler options configuration for details.

Upgrade to WasmEdge-Go v0.10.0

Due to the WasmEdge-Go API breaking changes, this document shows the guideline of programming with WasmEdge-Go API to upgrade from the `v0.9.2` to the `v0.10.0` version.

Due to the `v0.9.1` is retracted, we use the version `v0.9.2` here.

Concepts

1. Merged the `ImportObject` into the `Module`.

   The `ImportObject` struct which is for the host functions is merged into `Module`. Developers can use the related APIs to construct host modules.

   - `wasmedge.NewImportObject()` is changed to `wasmedge.NewModule()`.
   - `(*wasmedge.ImportObject).Release()` is changed to `(*wasmedge.Module).Release()`.
   - `(*wasmedge.ImportObject).AddFunction()` is changed to `(*wasmedge.Module).AddFunction()`.
   - `(*wasmedge.ImportObject).AddTable()` is changed to `(*wasmedge.Module).AddTable()`.
   - `(*wasmedge.ImportObject).AddMemory()` is changed to `(*wasmedge.Module).AddMemory()`.
   - `(*wasmedge.ImportObject).AddGlobal()` is changed to `(*wasmedge.Module).AddGlobal()`.
   - `(*wasmedge.ImportObject).NewWasiImportObject()` is changed to `(*wasmedge.Module).NewWasiModule()`.
   - `(*wasmedge.ImportObject).NewWasmEdgeProcessImportObject()` is changed to `(*wasmedge.Module).NewWasmEdgeProcessModule()`.
   - `(*wasmedge.ImportObject).InitWASI()` is changed to `(*wasmedge.Module).InitWASI()`.
   - `(*wasmedge.ImportObject).InitWasmEdgeProcess()` is changed to `(*wasmedge.Module).InitWasmEdgeProcess()`.
   - `(*wasmedge.ImportObject).WasiGetExitCode()` is changed to `(*wasmedge.Module).WasiGetExitCode`.
   - `(*wasmedge.VM).RegisterImport()` is changed to `(*wasmedge.VM).RegisterModule()`.
   - `(*wasmedge.VM).GetImportObject()` is changed to

`(*wasmedge.VM).GetImportModule()`.

For the new host function examples, please refer to the example below.

2. Used the pointer to `Function` instead of the index in the `FuncRef` value type.

   For the better performance and security, the `FuncRef` related APIs used the `*wasmedge.Function` for the parameters and returns.

   - `wasmedge.NewFuncRef()` is changed to use the `*Function` as it's argument.
   - Added `(wasmedge.FuncRef).GetRef()` to retrieve the `*Function`.

3. Supported multiple anonymous WASM module instantiation.

   In the version before `v0.9.2`, WasmEdge only supports 1 anonymous WASM module to be instantiated at one time. If developers instantiate a new WASM module, the old one will be replaced. After the `v0.10.0` version, developers can instantiate multiple anonymous WASM module by `Executor` and get the `Module` instance. But for the source code using the `VM` APIs, the behavior is not changed. For the new examples of instantiating multiple anonymous WASM modules, please refer to the example below.

4. Behavior changed of `Store`.

   The `Function`, `Table`, `Memory`, and `Global` instances retrievement from the `Store` is moved to the `Module` instance. The `Store` only manage the module linking when instantiation and the named module searching after the `v0.10.0` version.

   - `(*wasmedge.Store).ListFunction()` and `(*wasmedge.Store).ListFunctionRegistered()` is replaced by `(*wasmedge.Module).ListFunction()`.
   - `(*wasmedge.Store).ListTable()` and `(*wasmedge.Store).ListTableRegistered()` is replaced by `(*wasmedge.Module).ListTable()`.
   - `(*wasmedge.Store).ListMemory()` and `(*wasmedge.Store).ListMemoryRegistered()` is replaced by `(*wasmedge.Module).ListMemory()`.
   - `(*wasmedge.Store).ListGlobal()` and `(*wasmedge.Store).ListGlobalRegistered()` is replaced by `(*wasmedge.Module).ListGlobal()`.
   - `(*wasmedge.Store).FindFunction()` and `(*wasmedge.Store).FindFunctionRegistered()` is replaced by `(*wasmedge.Module).FindFunction()`.

- `(*wasmedge.Store).FindTable()` and `(*wasmedge.Store).FindTableRegistered()` is replaced by `(*wasmedge.Module).FindTable()`.
- `(*wasmedge.Store).FindMemory()` and `(*wasmedge.Store).FindMemoryRegistered()` is replaced by `(*wasmedge.Module).FindMemory()`.
- `(*wasmedge.Store).FindGlobal()` and `(*wasmedge.Store).FindGlobalRegistered()` is replaced by `(*wasmedge.Module).FindGlobal()`.

For the new examples of retrieving instances, please refer to the example below.

5. The `Module`-based resource management.

   Except the creation of `Module` instance for the host functions, the `Executor` will output a `Module` instance after instantiation. No matter the anonymous or named modules, developers have the responsibility to destroy them by `(*wasmedge.Module).Release()` API. The `Store` will link to the named `Module` instance after registering. After the destroyment of a `Module` instance, the `Store` will unlink to that automatically; after the destroyment of the `Store`, the all `Module` instances the `Store` linked to will unlink to that `Store` automatically.

WasmEdge-Go VM changes

The `VM` APIs are basically not changed, except the `ImportObject` related APIs.

The following is the example of WASI initialization in WasmEdge-Go `v0.9.2`:

```
conf := wasmedge.NewConfigure(wasmedge.WASI)
vm := wasmedge.NewVMWithConfig(conf)

// The following API can retrieve the pre-registration import objects from the
VM object.
// This API will return `nil` if the corresponding pre-registration is not set
into the configuration.
wasiobj := vm.GetImportObject(wasmedge.WASI)
// Initialize the WASI.
wasiobj.InitWasi(
  os.Args[1:],     // The args
  os.Environ(),    // The envs
  []string{".:."}, // The mapping preopens
)

// ...

vm.Release()
conf.Release()
```

Developers can change to use the WasmEdge-Go `v0.10.0` as follows, with only replacing the `ImportObject` into `Module`:

```
conf := wasmedge.NewConfigure(wasmedge.WASI)
vm := wasmedge.NewVMWithConfig(conf)

// The following API can retrieve the pre-registration module instances from
the VM object.
// This API will return `nil` if the corresponding pre-registration is not set
into the configuration.
wasiobj := vm.GetImportModule(wasmedge.WASI)
// Initialize the WASI.
wasiobj.InitWasi(
  os.Args[1:],     // The args
  os.Environ(),    // The envs
  []string{".:."}, // The mapping preopens
)

// ...

vm.Release()
conf.Release()
```

The `VM` provides a new API for getting the current instantiated anonymous `Module` instance. For example, if developer want to get the exported `Global` instance:

```
// Assume that a WASM module is instantiated in `vm`, and exports the
"global_i32".
store := vm.GetStore()

globinst := store.FindGlobal("global_i32")
```

After the WasmEdge-Go `v0.10.0`, developers can use the `(*wasmedge.VM).GetActiveModule()` to get the module instance:

```
// Assume that a WASM module is instantiated in `vm`, and exports the
"global_i32".
mod := vm.GetActiveModule()

// The example of retrieving the global instance.
globinst := mod.FindGlobal("global_i32")
```

WasmEdge Executor changes

`Executor` helps to instantiate a WASM module, register a WASM module into `Store` with module name, register the host modules with host functions, or invoke functions.

1. WASM module instantiation

   In WasmEdge-Go `v0.9.2` version, developers can instantiate a WASM module by the `Executor` API:

   ```
   var ast *wasmedge.AST
   // Assume that `ast` is a loaded WASM from file or buffer and has passed
   the validation.
   // Assume that `executor` is a `*wasmedge.Executor`.
   // Assume that `store` is a `*wasmedge.Store`.
   err := executor.Instantiate(store, ast)
   if err != nil {
     fmt.Println("Instantiation FAILED:", err.Error())
   }
   ```

   Then the WASM module is instantiated into an anonymous module instance and handled by the `Store`. If a new WASM module is instantiated by this API, the old instantiated module instance will be cleaned. After the WasmEdge-Go `v0.10.0` version, the instantiated anonymous module will be outputted and handled by caller,

and not only 1 anonymous module instance can be instantiated. Developers have the responsibility to release the outputted module instances.

```
var ast1 *wasmedge.AST
var ast2 *wasmedge.AST
// Assume that `ast1` and `ast2` are loaded WASMs from different files or
buffers,
// and have both passed the validation.
// Assume that `executor` is a `*wasmedge.Executor`.
// Assume that `store` is a `*wasmedge.Store`.
mod1, err1 := executor.Instantiate(store, ast1)
if err1 != nil {
  fmt.Println("Instantiation FAILED:", err1.Error())
}
mod2, err2 := executor.Instantiate(store, ast2)
if err2 != nil {
  fmt.Println("Instantiation FAILED:", err2.Error())
}
mod1.Release()
mod2.Release()
```

2. WASM module registration with module name

   When instantiating and registering a WASM module with module name, developers can use the `(*wasmedge.Executor).RegisterModule()` API before WasmEdge-Go `v0.9.2`.

```
var ast *wasmedge.AST
// Assume that `ast` is a loaded WASM from file or buffer and has passed
the validation.
// Assume that `executor` is a `*wasmedge.Executor`.
// Assume that `store` is a `*wasmedge.Store`.

// Register the WASM module into store with the export module name "mod".
err := executor.RegisterModule(store, ast, "mod")
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
}
```

   The same feature is implemented in WasmEdge-Go `v0.10.0`, but in different API `(*wasmedge.Executor).Register()`:

```
var ast *wasmedge.AST
// Assume that `ast` is a loaded WASM from file or buffer and has passed
the validation.
// Assume that `executor` is a `*wasmedge.Executor`.
// Assume that `store` is a `*wasmedge.Store`.

// Register the WASM module into store with the export module name "mod".
mod, err := executor.Register(store, ast, "mod")
if err != nil {
  fmt.Println("WASM registration FAILED:", err.Error())
}
mod.Release()
```

Developers have the responsibility to release the outputted module instances.

3. Host module registration

In WasmEdge-Go `v0.9.2`, developers can create an `ImportObject` and register into `Store`.

```
// Create the import object with the export module name.
impobj := wasmedge.NewImportObject("module")

// ...
// Add the host functions, tables, memories, and globals into the import
object.

// The import object has already contained the export module name.
err := executor.RegisterImport(store, impobj)
if err != nil {
  fmt.Println("Import object registration FAILED:", err.Error())
}
```

After WasmEdge-Go `v0.10.0`, developers should use the `Module` instance instead:

```
// Create the module instance with the export module name.
impmod := wasmedge.NewModule("module")

// ...
// Add the host functions, tables, memories, and globals into the module
instance.

// The module instance has already contained the export module name.
err := executor.RegisterImport(store, impmod)
if err != nil {
  fmt.Println("Module instance registration FAILED:", err.Error())
}
```

Developers have the responsibility to release the created module instances.

4. WASM function invocation

   This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat. In WasmEdge-Go `v0.9.2` version, developers can invoke a WASM function with the export function name:

```
// Create the store object. The store object holds the instances.
store := wasmedge.NewStore()
// Error.
var err error
// AST object.
var ast *wasmedge.AST
// Return values.
var res []interface{}

// Create the loader object.
loader := wasmedge.NewLoader()
// Create the validator object.
validator := wasmedge.NewValidator()
// Create the executor object.
executor := wasmedge.NewExecutor()

// Load the WASM file or the compiled-WASM file and convert into the AST
object.
ast, err = loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
  return
}
// Validate the WASM module.
err = validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
  return
}
// Instantiate the WASM module into the Store object.
err = executor.Instantiate(store, ast)
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}
// Invoke the function which is exported with the function name "fib".
res, err = executor.Invoke(store, "fib", int32(30))
if err == nil {
  fmt.Println("Get fibonacci[30]:", res[0].(int32))
} else {
```

```
  fmt.Println("Run failed:", err.Error())
}

ast.Release()
loader.Release()
validator.Release()
executor.Release()
store.Release()
```

After the WasmEdge-Go `v0.10.0`, developers should retrieve the `Function` instance by function name first.

```
// ...
// Ignore the unchanged steps before validation. Please refer to the sample
code above.

var mod *wasmedge.Module
// Instantiate the WASM module and get the output module instance.
mod, err = executor.Instantiate(store, ast)
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}
// Retrieve the function instance by name.
funcinst := mod.FindFunction("fib")
if funcinst == nil {
  fmt.Println("Run FAILED: Function name `fib` not found")
  return
}
res, err = executor.Invoke(store, funcinst, int32(30))
if err == nil {
  fmt.Println("Get fibonacci[30]:", res[0].(int32))
} else {
  fmt.Println("Run FAILED:", err.Error())
}

ast.Release()
mod.Release()
loader.Release()
validator.Release()
executor.Release()
store.Release()
```

Instances retrievement

This example uses the fibonacci.wasm, and the corresponding WAT file is at fibonacci.wat.

Before the WasmEdge-Go `v0.9.2` versions, developers can retrieve all exported instances of named or anonymous modules from `Store`:

```
// Create the store object. The store object holds the instances.
store := wasmedge.NewStore()
// Error.
var err error
// AST object.
var ast *wasmedge.AST

// Create the loader object.
loader := wasmedge.NewLoader()
// Create the validator object.
validator := wasmedge.NewValidator()
// Create the executor object.
executor := wasmedge.NewExecutor()

// Load the WASM file or the compiled-WASM file and convert into the AST
object.
ast, err = loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
  return
}
// Validate the WASM module.
err = validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
  return
}
// Example: register and instantiate the WASM module with the module name
"module_fib".
err = executor.RegisterModule(store, ast, "module_fib")
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}
// Example: Instantiate the WASM module into the Store object.
err = executor.Instantiate(store, ast)
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}

// Now, developers can retrieve the exported instances from the store.
// Take the exported functions as example. This WASM exports the function
"fib".
// Find the function "fib" from the instantiated anonymous module.
func1 := store.FindFunction("fib")
// Find the function "fib" from the registered module "module_fib".
func2 := store.FindFunctionRegistered("module_fib", "fib")

ast.Release()
store.Release()
loader.Release()
```

```
validator.Release()
executor.Release()
```

After the WasmEdge-Go `v0.10.0`, developers can instantiate several anonymous `Module` instances, and should retrieve the exported instances from named or anonymous `Module` instances:

```
// Create the store object. The store is the object to link the modules for
imports and exports.
store := wasmedge.NewStore()
// Error.
var err error
// AST object.
var ast *wasmedge.AST
// Module instances.
var namedmod *wasmedge.Module
var anonymousmod *wasmedge.Module

// Create the loader object.
loader := wasmedge.NewLoader()
// Create the validator object.
validator := wasmedge.NewValidator()
// Create the executor object.
executor := wasmedge.NewExecutor()

// Load the WASM file or the compiled-WASM file and convert into the AST
object.
ast, err = loader.LoadFile("fibonacci.wasm")
if err != nil {
  fmt.Println("Load WASM from file FAILED:", err.Error())
  return
}
// Validate the WASM module.
err = validator.Validate(ast)
if err != nil {
  fmt.Println("Validation FAILED:", err.Error())
  return
}
// Example: register and instantiate the WASM module with the module name
"module_fib".
namedmod, err = executor.Register(store, ast, "module_fib")
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}
// Example: Instantiate the WASM module and get the output module instance.
anonymousmod, err = executor.Instantiate(store, ast)
if err != nil {
  fmt.Println("Instantiation FAILED:", err.Error())
  return
}

// Now, developers can retrieve the exported instances from the module
instances.
// Take the exported functions as example. This WASM exports the function
"fib".
// Find the function "fib" from the instantiated anonymous module.
func1 := anonymousmod.FindFunction("fib")
// Find the function "fib" from the registered module "module_fib".
```

```
func2 := namedmod.FindFunction("fib")
// Or developers can get the named module instance from the store:
gotmod := store.FindModule("module_fib")
func3 := gotmod.FindFunction("fib")

namedmod.Release()
anonymousmod.Release()
ast.Release()
store.Release()
loader.Release()
validator.Release()
executor.Release()
```

Host functions

The difference of host functions are the replacement of `ImportObject` struct.

```
// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

// ...

// Create an import object with the module name "module".
impobj := wasmedge.NewImportObject("module")

// Create and add a function instance into the import object with export name
"add".
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)
hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
// The third parameter is the pointer to the additional data object.
// Developers should guarantee the life cycle of the data, and it can be `nil`
// if the external data is not needed.
functype.Release()
impobj.AddFunction("add", hostfunc)

// The import object should be released.
// Developers should __NOT__ release the instances added into the import
objects.
impobj.Release()
```

Developers can use the `Module` struct to upgrade to WasmEdge `v0.10.0` easily.

```
// Host function body definition.
func host_add(data interface{}, mem *wasmedge.Memory, params []interface{})
([]interface{}, wasmedge.Result) {
  // add: i32, i32 -> i32
  res := params[0].(int32) + params[1].(int32)

  // Set the returns
  returns := make([]interface{}, 1)
  returns[0] = res

  // Return
  return returns, wasmedge.Result_Success
}

// ...

// Create a module instance with the module name "module".
mod := wasmedge.NewModule("module")

// Create and add a function instance into the module instance with export name
"add".
functype := wasmedge.NewFunctionType(
  []wasmedge.ValType{wasmedge.ValType_I32, wasmedge.ValType_I32},
  []wasmedge.ValType{wasmedge.ValType_I32},
)
hostfunc := wasmedge.NewFunction(functype, host_add, nil, 0)
// The third parameter is the pointer to the additional data object.
// Developers should guarantee the life cycle of the data, and it can be `nil`
// if the external data is not needed.
functype.Release()
mod.AddFunction("add", hostfunc)

// The module instances should be released.
// Developers should __NOT__ release the instances added into the module
instance objects.
mod.Release()
```

WasmEdge Node.js SDK

In this tutorial, we will show you how to incorporate the WebAssembly functions written in Rust into Node.js applications on the server via the WasmEdge Node.js SDK. This approach combines Rust's **performance**, WebAssembly's **security and portability**, and JavaScript's **ease-of-use**. A typical application works like this.

- The host application is a Node.js web application written in JavaScript. It makes WebAssembly function calls.
- The WebAssembly application is written in Rust. It runs inside the WasmEdge Runtime, and is called from the Node.js web application.

Fork this Github repository to start coding!

Prerequisites

To set up a high-performance Node.js environment with Rust and WebAssembly, you will need the following:

- A modern Linux distribution, such as Ubuntu Server 20.04 LTS
- Rust language
- Node.js
- The WasmEdge Runtime for Node.js
- The rustwasmc compiler toolchain

Docker

The easiest way to get started is to use Docker to build a dev environment. Just clone this template project to your computer and run the following Docker commands.

```
# Get the code
git clone https://github.com/second-state/wasmedge-nodejs-starter
cd wasmedge-nodejs-starter

# Run Docker container
docker pull wasmedge/appdev_x86_64:0.8.2
docker run -p 3000:3000 --rm -it -v $(pwd):/app wasmedge/appdev_x86_64:0.8.2

# In docker
cd /app
```

That's it! You are now ready to compile and run the code.

Manual setup without Docker

The commands are as follows.

```
# Install Rust
curl --proto '=https' --tlsv1.2 -sSf https://sh.rustup.rs | sh
source $HOME/.cargo/env
rustup override set 1.50.0

# Install Node.js and npm
curl -sL https://deb.nodesource.com/setup_14.x |  bash
sudo apt-get install -y nodejs npm

# Install rustwasmc toolchain
npm install -g rustwasmc # Append --unsafe-perm if permission denied

# OS dependencies for WasmEdge
sudo apt-get update
sudo apt-get -y upgrade
sudo apt install -y build-essential curl wget git vim libboost-all-dev llvm-dev
liblld-10-dev

# Install the nodejs addon for WasmEdge
npm install wasmedge-core
npm install wasmedge-extensions
```

> The WasmEdge Runtime depends on the latest version of `libstdc++`. Ubuntu 20.04 LTS already has the latest libraries. If you are running an older Linux distribution, you have several options to upgrade.

Next, clone the example source code repository.

```
git clone https://github.com/second-state/wasmedge-nodejs-starter
cd wasmedge-nodejs-starter
```

Hello World

The first example is a hello world to show you how various parts of the application fit together.

WebAssembly program in Rust

In this example, our Rust program appends the input string after “hello”. Below is the content of the Rust program `src/lib.rs`. You can define multiple external functions in this library file, and all of them will be available to the host JavaScript app via WebAssembly. Just remember to annotate each function with `#[wasm_bindgen]` so that rustwasmc knows to generate the correct JavaScript to Rust interface for it when you build it.

```
use wasm_bindgen::prelude::*;

#[wasm_bindgen]
pub fn say(s: String) -> String {
  let r = String::from("hello ");
  return r + &s;
}
```

Next, you can compile the Rust source code into WebAssembly bytecode and generate the accompanying JavaScript module for the Node.js host environment.

```
rustwasmc build
```

The result are files in the `pkg/` directory. the `.wasm` file is the WebAssembly bytecode program, and the `.js` files are for the JavaScript module.

The Node.js host application

Next, go to the `node` folder and examine the JavaScript program `app.js`. With the generated `wasmedge_nodejs_starter_lib.js` module, it is very easy to write JavaScript to call WebAssembly functions. Below is the node application `app.js`. It simply imports the `say()` function from the generated module. The node application takes the `name`

parameter from incoming an HTTP GET request, and responds with "hello `name`".

```
const { say } = require('../pkg/wasmedge_nodejs_starter_lib.js');

const http = require('http');
const url = require('url');
const hostname = '127.0.0.1';
const port = 3000;

const server = http.createServer((req, res) => {
  const queryObject = url.parse(req.url,true).query;
  res.statusCode = 200;
  res.setHeader('Content-Type', 'text/plain');
  res.end(say(queryObject['name']));
});

server.listen(port, hostname, () => {
  console.log(`Server running at http://${hostname}:${port}/`);
});
```

Start the Node.js application server as follows.

```
$ node node/app.js
Server running at http://127.0.0.1:3000/
```

Then, you can test it from another terminal window.

```
$ curl http://127.0.0.1:3000/?name=Wasm
hello Wasm
```

A complete web application

The next example shows a web application that computes the roots for quadratic equations. Please checkout the full source code here.

The user enters the values for `a`, `b`, `c` on the web form, and the web application calls the web service at `/solve` to compute the roots for the quadratic equation.

```
a*X^2 + b*X + c = 0
```

The roots for `X` are displayed in the area below the input form.

Calling a Rust function in Node.js

Solve the Quadratic equation

3 X^2 + 4 X + -5 = 0 Solve

The roots are [0.7862997,-2.119633]

The HTML file contains the client side JavaScript to submit the web form to `/solve`, and put result into the `#roots` HTML element on the page.

```
$(function() {
  var options = {
    target: '#roots',
    url: "/solve",
    type: "post"
  };
  $('#solve').ajaxForm(options);
});
```

The Node.js application behind the `/solve` URL endpoint is as follows. It reads the data from the input form, passes them into the `solve` function as an array, and puts the return value in the HTTP response.

```
app.post('/solve', function (req, res) {
  var a = parseFloat(req.body.a);
  var b = parseFloat(req.body.b);
  var c = parseFloat(req.body.c);
  res.send(solve([a, b, c]))
})
```

The `solve` function is written in Rust and runs inside the WasmEdge Runtime. While the call arguments in the JavaScript side is an array of values, the Rust function receives a JSON object that encapsulates the array. In the Rust code, we first decode the JSON, perform the computation, and return the result values in a JSON string.

```
#[wasm_bindgen]
pub fn solve(params: &str) -> String {
  let ps: (f32, f32, f32) = serde_json::from_str(&params).unwrap();
  let discriminant: f32 = (ps.1 * ps.1) - (4. * ps.0 * ps.2);
  let mut solution: (f32, f32) = (0., 0.);
  if discriminant >= 0. {
    solution.0 = (((-1.) * ps.1) + discriminant.sqrt()) / (2. * ps.0);
    solution.1 = (((-1.) * ps.1) - discriminant.sqrt()) / (2. * ps.0);
    return serde_json::to_string(&solution).unwrap();
  } else {
    return String::from("not real numbers");
  }
}
```

Let's try it.

```
rustwasmc build
npm install express # The application requires the Express framework in Node.js

node node/server.js
```

From the web browser, go to `http://ip-addr:8080/` to access this application. Note: If you are using Docker, make sure that the Docker container port 8080 is mapped to the host port 8080.

That's it for the quadratic equation example.

More examples

Besides passing string values between Rust and JavaScript, the `rustwasmc` tool supports the following data types.

- Rust call parameters can be any combo of `i32`, `String`, `&str`, `Vec<u8>`, and `&[u8]`
- Return value can be `i32` or `String` or `Vec<u8>` or void
- For complex data types, such as structs, you could use JSON strings to pass data.

> With JSON support, you can call Rust functions with any number of input parameters and return any number of return values of any type.

The Rust program `src/lib.rs` in the functions example demonstrates how to pass in call arguments in various supported types, and return values.

```
#[wasm_bindgen]
pub fn obfusticate(s: String) -> String {
  (&s).chars().map(|c| {
    match c {
      'A' ..= 'M' | 'a' ..= 'm' => ((c as u8) + 13) as char,
      'N' ..= 'Z' | 'n' ..= 'z' => ((c as u8) - 13) as char,
      _ => c
    }
  }).collect()
}

#[wasm_bindgen]
pub fn lowest_common_denominator(a: i32, b: i32) -> i32 {
  let r = lcm(a, b);
  return r;
}

#[wasm_bindgen]
pub fn sha3_digest(v: Vec<u8>) -> Vec<u8> {
  return Sha3_256::digest(&v).as_slice().to_vec();
}

#[wasm_bindgen]
pub fn keccak_digest(s: &[u8]) -> Vec<u8> {
  return Keccak256::digest(s).as_slice().to_vec();
}
```

Perhaps the most interesting is the `create_line()` function. It takes two JSON strings, each representing a `Point` struct, and returns a JSON string representing a `Line` struct. Notice that both the `Point` and `Line` structs are annotated with `Serialize` and `Deserialize` so that the Rust compiler automatically generates necessary code to support their conversion to and from JSON strings.

```
use wasm_bindgen::prelude::*;
use serde::{Serialize, Deserialize};

#[derive(Serialize, Deserialize, Debug)]
struct Point {
  x: f32,
  y: f32
}

#[derive(Serialize, Deserialize, Debug)]
struct Line {
  points: Vec<Point>,
  valid: bool,
  length: f32,
  desc: String
}

#[wasm_bindgen]
pub fn create_line (p1: &str, p2: &str, desc: &str) -> String {
  let point1: Point = serde_json::from_str(p1).unwrap();
  let point2: Point = serde_json::from_str(p2).unwrap();
  let length = ((point1.x - point2.x) * (point1.x - point2.x) + (point1.y -
point2.y) * (point1.y - point2.y)).sqrt();

  let valid = if length == 0.0 { false } else { true };
  let line = Line { points: vec![point1, point2], valid: valid, length: length,
desc: desc.to_string() };
  return serde_json::to_string(&line).unwrap();
}

#[wasm_bindgen]
pub fn say(s: &str) -> String {
  let r = String::from("hello ");
  return r + s;
}
```

Next, let's examine the JavaScript program `app.js`. It shows how to call the Rust functions. As you can see `String` and `&str` are simply strings in JavaScript, `i32` are numbers, and `Vec<u8>` or `&[8]` are JavaScript `Uint8Array`. JavaScript objects need to go through `JSON.stringify()` or `JSON.parse()` before being passed into or returned from Rust functions.

```
const { say, obfusticate, lowest_common_denominator, sha3_digest,
keccak_digest, create_line } = require('./functions_lib.js');

var util = require('util');
const encoder = new util.TextEncoder();
console.hex = (d) => console.log((Object(d).buffer instanceof ArrayBuffer ? new
Uint8Array(d.buffer) : typeof d === 'string' ? (new util.TextEncoder('utf-
8')).encode(d) : new Uint8ClampedArray(d)).reduce((p, c, i, a) => p + (i % 16
=== 0 ? i.toString(16).padStart(6, 0) + '  ' : ' ') +
c.toString(16).padStart(2, 0) + (i === a.length - 1 || i % 16 === 15 ?  '
'.repeat((15 - i % 16) * 3) + Array.from(a).splice(i - i % 16, 16).reduce((r,
v) => r + (v > 31 && v < 127 || v > 159 ? String.fromCharCode(v) : '.'), '  ')
+ '\n' : ''), ''));

console.log( say("WasmEdge") );
console.log( obfusticate("A quick brown fox jumps over the lazy dog") );
console.log( lowest_common_denominator(123, 2) );
console.hex( sha3_digest(encoder.encode("This is an important message")) );
console.hex( keccak_digest(encoder.encode("This is an important message")) );

var p1 = {x:1.5, y:3.8};
var p2 = {x:2.5, y:5.8};
var line = JSON.parse(create_line(JSON.stringify(p1), JSON.stringify(p2), "A
thin red line"));
console.log( line );
```

After running `rustwasmc` to build the Rust library, running `app.js` in Node.js environment produces the following output.

```
$ rustwasmc build
... Building the wasm file and JS shim file in pkg/ ...

$ node node/app.js
hello WasmEdge
N dhvpx oebja sbk whzcf bire gur ynml qbt
246
000000  57 1b e7 d1 bd 69 fb 31 9f 0a d3 fa 0f 9f 9a b5  W.çÑ½iû1..Óú...µ
000010  2b da 1a 8d 38 c7 19 2d 3c 0a 14 a3 36 d3 c3 cb  +Ú..8Ç.-<..£6ÓÃË

000000  7e c2 f1 c8 97 74 e3 21 d8 63 9f 16 6b 03 b1 a9  ~ÂñÈ.tã!Øc..k.±©
000010  d8 bf 72 9c ae c1 20 9f f6 e4 f5 85 34 4b 37 1b  Ø¿r.®Á .öäõ.4K7.

{ points: [ { x: 1.5, y: 3.8 }, { x: 2.5, y: 5.8 } ],
  valid: true,
  length: 2.2360682,
  desc: 'A thin red line' }
```

WasmEdge Rust SDK

Introduction

`WasmEdge` supports embedding into Rust applications via WasmEdge Rust SDK. WasmEdge Rust SDK consists of three crates:

- wasmedge-sdk crate. It defines a group of safe, ergonomic high-level APIs, which are used to build up business applications.
  - API documentation
- wasmedge-sys crate. It defines a group of low-level Rust APIs, which simply wrap WasmEdge C-API and provide the safe counterparts. It is not recommended to use it directly to build up application.
  - API documentation
- wasmedge-types crate. The data structures that are commonly used in `wasmedge-sdk` and `wasmedge-sys` are defined in this crate.
  - API documentation

Versioning Table

The following table provides the versioning information about each release of `wasmedge-sdk` crate and its dependencies.

wasmedge-sdk	WasmEdge lib	wasmedge-sys	wasmedge-types	wasmedge-macro
0.5.0	0.11.1	0.10	0.3.0	0.1.0
0.4.0	0.11.0	0.9	0.2.1	-
0.3.0	0.10.1	0.8	0.2	-
0.1.0	0.10.0	0.7	0.1	-

Build

To use `wasmedge-sdk` in your project, you should finish the following two steps before building your project:

- First, deploy `WasmEdge` library on your local system.

  You can reference the versioning table and download `WasmEdge` library from WasmEdge Releases Page. After download the `WasmEdge` library, you can choose one of the following three ways to specify the locations of the required files:

  - By default location

    For those who do not want to define environment variables, you can put the downloaded `WasmEdge` binary package in the default location `$HOME/.wasmedge/`. The directory structure of the default location should looks like below:

```
// $HOME/.wasmedge/ on Ubuntu-20.04
.
├── bin
│   ├── wasmedge
│   └── wasmedgec
├── include
│   └── wasmedge
│       ├── enum.inc
│       ├── enum_configure.h
│       ├── enum_errcode.h
│       ├── enum_types.h
│       ├── int128.h
│       ├── version.h
│       └── wasmedge.h
└── lib64
    ├── libwasmedge.so
    └── wasmedge
        └── libwasmedgePluginWasmEdgeProcess.so

5 directories, 11 files


// $HOME/.wasmedge/ on macOS-12
.
├── bin
│   ├── wasmedge
│   └── wasmedgec
├── include
│   └── wasmedge
│       ├── enum.inc
│       ├── enum_configure.h
│       ├── enum_errcode.h
│       ├── enum_types.h
│       ├── int128.h
│       ├── version.h
│       └── wasmedge.h
└── lib
    └── libwasmedge.dylib

4 directories, 10 files
```

- By specifying `WASMEDGE_INCLUDE_DIR` and `WASMEDGE_LIB_DIR`.

  If you choose to use install.sh to install WasmEdge Runtime on your local system, please use `WASMEDGE_INCLUDE_DIR` and `WASMEDGE_LIB_DIR` to specify the paths to the `include` and `lib` directories respectively. For example, use the following commands to specify the paths after using `bash install.sh --path=$HOME/wasmedge-install` to install WasmEdge Runtime on Ubuntu 20.04:

  ```
  export WASMEDGE_INCLUDE_DIR=$HOME/wasmedge-install/include
  export WASMEDGE_LIB_DIR=$HOME/wasmedge-install/lib
  ```

- By specifying `WASMEDGE_BUILD_DIR`

  You can choose this way if you'd like to use the latest code in the `master` branch of the `WasmEdge` github repo. For example,

  - Suppose that you `git clone` WasmEdge repo in your local directory, for example, `~/workspace/me/WasmEdge`, and follow the instructions to build WasmEdge native library. After that, you should find the generated `include` and `lib` directories in `~/workspace/me/WasmEdge/build`.
  - Then, set `WASMEDGE_BUILD_DIR` environment variable to specify the `build` directory.

    ```
    root@0a877562f39e:~/workspace/me/WasmEdge# export
    WASMEDGE_BUILD_DIR=/root/workspace/me/WasmEdge/build
    ```

- Second, after deploy the `WasmEdge` library on your local system, copy/paste the following code into the `Cargo.toml` file of your project. Now, you can use `cargo build` command to build your project.

```
[dependencies]
wasmedge-sdk = "0.4"
```

`wasmedge-sys` crate

`wasmedge-sys` serves as a wrapper layer of `WasmEdge` C-API, and provides a group of safe low-level Rust interfaces. For those who are interested in using `wasmedge-sys` in their projects, you should also deploy the `WasmEdge` library on your local system as described in

the wasmedge-sdk crate section. Then, copy/paste the following code in the `Cargo.toml` file of your project. For details, please refer to README.

```
[dependencies]
wasmedge-sys = "0.9"
```

Enable WasmEdge Plugins

If you'd like to enable WasmEdge Plugins (currently, only available on Linux platform), please use `WASMEDGE_PLUGIN_PATH` environment variable to specify the path to the directory containing the plugins. For example, use the following commands to specify the path on Ubuntu 20.04:

```
export WASMEDGE_PLUGIN_PATH=$HOME/.wasmedge/lib/wasmedge
```

Docker image

For those who would like to dev in Docker environment, you can reference the Use Docker section of this book, which details how to use Docker for `WasmEdge` application development.

Examples

For helping you get familiar with WasmEdge Rust bindings, the following quick examples demonstrate how to use the APIs defined in `wasmedge-sdk` and `wasmedge-sys`, respectively. In addition, we'll add more examples continuously. Please file issues here and let us know if you have any problems with the API usage.

`wasmedge-sdk` Examples

- [wasmedge-sdk] Hello World!
- [wasmedge-sdk] Memory manipulation

- [wasmedge-sdk] Table and FuncRef
- More examples

`wasmedge-sys` Examples

- [wasmedge-sys] Run a WebAssembly function with WasmEdge low-level APIs
- [wasmedge-sys] Compute Fibonacci numbers concurrently
- [wasmedge-sys] The usage of WasmEdge module instances
- More examples

Hello World

In this example, we'll use a wasm module, in which a function `run` is exported and it will call a function `say_hello` from an import module named `env`. The imported function `say_hello` has no inputs and outputs, and only prints a greeting message out.

The code in the following example is verified on

- wasmedge-sdk v0.5.0
- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Let's start off by getting all imports right away so you can follow along

```
// please add this feature if you're using rust of version < 1.63
// #![feature(explicit_generic_args_with_impl_trait)]

#![feature(never_type)]

use wasmedge_sdk::{
    error::HostFuncError, host_function, params, wat2wasm, Caller, Executor,
ImportObjectBuilder,
    Module, Store, WasmValue,
};
```

Step 1: Define a native function and Create an ImportObject

First, let's define a native function named `say_hello_world` that prints out `Hello, World!`.

```
#[host_function]
fn say_hello(caller: &Caller, _args: Vec<WasmValue>) -> Result<Vec<WasmValue>,
HostFuncError> {
    println!("Hello, world!");

    Ok(vec![])
}
```

To use the native function as an import function in the `WasmEdge` runtime, we need an

`ImportObject`. `wasmedge-sdk` defines a ImportObjectBuilder, which provides a group of chaining methods used to create an `ImportObject`. Let's see how to do it.

```
// create an import module
let import = ImportObjectBuilder::new()
    .with_func::<(), (), !>("say_hello", say_hello, None)?
    .build("env")?;
```

Now, we have an import module named `env` which holds a host function `say_hello`. As you may notice, the names we used for the import module and the host function are exactly the same as the ones appearing in the wasm module. You can find the wasm module in Step 2.

Step 2: Load a wasm module

Now, let's load a wasm module. `wasmedge-sdk` defines two methods in `Module`:

- from_file loads a wasm module from a file, and meanwhile, validates the loaded wasm module.
- from_bytes loads a wasm module from an array of in-memory bytes, and meanwhile, validates the loaded wasm module.

Here we choose `Module::from_bytes` method to load our wasm module from an array of in-memory bytes.

```
let wasm_bytes = wat2wasm(
    br#"
(module
    ;; First we define a type with no parameters and no results.
    (type $no_args_no_rets_t (func (param) (result)))

    ;; Then we declare that we want to import a function named "env"
"say_hello" with
    ;; that type signature.
    (import "env" "say_hello" (func $say_hello (type $no_args_no_rets_t)))

    ;; Finally we create an entrypoint that calls our imported function.
    (func $run (type $no_args_no_rets_t)
    (call $say_hello))
    ;; And mark it as an exported function named "run".
    (export "run" (func $run)))
"#,
)?;

// loads a wasm module from the given in-memory bytes and returns a compiled
module
let module = Module::from_bytes(None, &wasm_bytes)?;
```

Step 3: Register import module and compiled module

To register a compiled module, we need to check if it has dependency on some import modules. In the wasm module this statement `(import "env" "say_hello" (func $say_hello (type $no_args_no_rets_t)))` tells us that it depends on an import module named `env`. Therefore, we need to register the import module first before registering the compiled wasm module.

```
// loads a wasm module from the given in-memory bytes
let module = Module::from_bytes(None, &wasm_bytes)?;

// create an executor
let mut executor = Executor::new(None, None)?;

// create a store
let mut store = Store::new()?;

// register the module into the store
store.register_import_module(&mut executor, &import)?;

// register the compiled module into the store and get an module instance
let extern_instance = store.register_named_module(&mut executor, "extern",
&module)?;
```

In the code above we use Executor and Store to register the import module and the compiled module. `wasmedge-sdk` also provides alternative APIs to do the same thing: Vm::register_import_module and Vm::register_module_from_bytes.

Step 4: Run the exported function

Now we are ready to run the exported function.

```
// get the exported function "run"
let run = extern_instance
    .func("run")
    .ok_or_else(|| anyhow::Error::msg("Not found exported function named
'run'."))?;

// run host function
run.call(&mut executor, params!())?;
```

In this example we created an instance of `Executor`, hence, we have two choices to call a function instance:

- Func::call
- Executor::run_func

Any one of these two methods requires that you have to get a function instance.

In addition, Vm defines a group of methods which can invoke host function in different ways. For details, please reference Vm.

The complete example can be found in hello_world.rs.

Memory Manipulation

In this example, we'll present how to manipulate the linear memory with the APIs defined in wasmedge_sdk::Memory.

The code in the following example is verified on

- wasmedge-sdk v0.5.0
- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Wasm module

Before talking about the code, let's first see the wasm module we use in this example. In the wasm module, a linear memory of 1-page (64KiB) size is defined; in addition, three functions are exported from this module: `get_at`, `set_at`, and `mem_size`.

```
(module
  (type $mem_size_t (func (result i32)))
  (type $get_at_t (func (param i32) (result i32)))
  (type $set_at_t (func (param i32) (param i32)))

  # A memory with initial size of 1 page
  (memory $mem 1)

  (func $get_at (type $get_at_t) (param $idx i32) (result i32)
    (i32.load (local.get $idx)))

  (func $set_at (type $set_at_t) (param $idx i32) (param $val i32)
    (i32.store (local.get $idx) (local.get $val)))

  (func $mem_size (type $mem_size_t) (result i32)
    (memory.size))

  # Exported functions
  (export "get_at" (func $get_at))
  (export "set_at" (func $set_at))
  (export "mem_size" (func $mem_size))
  (export "memory" (memory $mem)))
```

Next, we'll demonstrate how to manipulate the linear memory by calling the exported functions.

Load and Register Module

Let's start off by getting all imports right away so you can follow along

```
// please add this feature if you're using rust of version < 1.63
// #![feature(explicit_generic_args_with_impl_trait)]

use wasmedge_sdk::{params, wat2wasm, Executor, Module, Store, WasmVal};
```

To load a `Module`, `wasmedge-sdk` defines two methods:

- from_file loads a wasm module from a file, and meanwhile, validates the loaded wasm module.
- from_bytes loads a wasm module from an array of in-memory bytes, and meanwhile, validates the loaded wasm module.

Here we use `Module::from_bytes` method to load our wasm module from an array of in-memory bytes.

```
let wasm_bytes = wat2wasm(
        r#"
(module
  (type $mem_size_t (func (result i32)))
  (type $get_at_t (func (param i32) (result i32)))
  (type $set_at_t (func (param i32) (param i32)))

  (memory $mem 1)

  (func $get_at (type $get_at_t) (param $idx i32) (result i32)
    (i32.load (local.get $idx)))

  (func $set_at (type $set_at_t) (param $idx i32) (param $val i32)
    (i32.store (local.get $idx) (local.get $val)))

  (func $mem_size (type $mem_size_t) (result i32)
    (memory.size))

  (export "get_at" (func $get_at))
  (export "set_at" (func $set_at))
  (export "mem_size" (func $mem_size))
  (export "memory" (memory $mem)))
"#
    .as_bytes(),
)?;

// loads a wasm module from the given in-memory bytes
let module = Module::from_bytes(None, &wasm_bytes)?;
```

The module returned by `Module::from_bytes` is a compiled module, also called AST Module in WasmEdge terminology. To use it in WasmEdge runtime environment, we need to instantiate the AST module. We use Store::register_named_module API to achieve the goal.

```
// create an executor
let mut executor = Executor::new(None, None)?;

// create a store
let mut store = Store::new()?;

// register the module into the store
let extern_instance = store.register_named_module(&mut executor, "extern",
&module)?;
```

In the code above, we register the AST module into a `Store`, in which the module is instantiated, and as a result, a module instance named `extern` is returned.

Memory

In the previous section, we get an instance by registering a compiled module into the runtime environment. Now we retrieve the memory instance from the module instance, and make use of the APIs defined in Memory to manipulate the linear memory.

```
// get the exported memory instance
let mut memory = extern_instance
    .memory("memory")
    .ok_or_else(|| anyhow::anyhow!("failed to get memory instance named
'memory'"))?;

// check memory size
assert_eq!(memory.size(), 1);
assert_eq!(memory.data_size(), 65536);

// grow memory size
memory.grow(2)?;
assert_eq!(memory.size(), 3);
assert_eq!(memory.data_size(), 3 * 65536);

// get the exported functions: "set_at" and "get_at"
let set_at = extern_instance
    .func("set_at")
    .ok_or_else(|| anyhow::Error::msg("Not found exported function named
'set_at'."))?;
let get_at = extern_instance
    .func("get_at")
    .ok_or_else(|| anyhow::Error::msg("Not found exported function named
'get_at`."))?;

// call the exported function named "set_at"
let mem_addr = 0x2220;
let val = 0xFEFEFFE;
set_at.call(&mut executor, params!(mem_addr, val))?;

// call the exported function named "get_at"
let returns = get_at.call(&mut executor, params!(mem_addr))?;
assert_eq!(returns[0].to_i32(), val);

// call the exported function named "set_at"
let page_size = 0x1_0000;
let mem_addr = (page_size * 2) - std::mem::size_of_val(&val) as i32;
let val = 0xFEA09;
set_at.call(&mut executor, params!(mem_addr, val))?;

// call the exported function named "get_at"
let returns = get_at.call(&mut executor, params!(mem_addr))?;
assert_eq!(returns[0].to_i32(), val);
```

The comments in the code explain the meaning of the code sample above, so we don't describe more.

The complete code of this example can be found in memory.rs.

Table and FuncRef

In this example, we'll present how to use Table and FuncRef stored in a slot of a `Table` instance to implement indirect function invocation.

The code in the following example is verified on

- wasmedge-sdk v0.5.0
- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Let's start off by getting all imports right away so you can follow along

```
// If the version of rust used is less than v1.63, please uncomment the follow
attribute.
// #![feature(explicit_generic_args_with_impl_trait)]

#![feature(never_type)]

use wasmedge_sdk::{
    config::{CommonConfigOptions, ConfigBuilder},
    error::HostFuncError,
    host_function, params,
    types::Val,
    Caller, Executor, Func, ImportObjectBuilder, RefType, Store, Table,
TableType, ValType,
    WasmVal, WasmValue,
};
```

Define host function

In this example we defines a native function `real_add` that takes two numbers and returns their sum. This function will be registered as a host function into WasmEdge runtime environment

```rust
#[host_function]
fn real_add(_caller: &Caller, input: Vec<WasmValue>) -> Result<Vec<WasmValue>,
HostFuncError> {
    println!("Rust: Entering Rust function real_add");

    if input.len() != 2 {
        return Err(HostFuncError::User(1));
    }

    let a = if input[0].ty() == ValType::I32 {
        input[0].to_i32()
    } else {
        return Err(HostFuncError::User(2));
    };

    let b = if input[1].ty() == ValType::I32 {
        input[1].to_i32()
    } else {
        return Err(HostFuncError::User(3));
    };

    let c = a + b;
    println!("Rust: calcuating in real_add c: {:?}", c);

    println!("Rust: Leaving Rust function real_add");
    Ok(vec![WasmValue::from_i32(c)])
}
```

Register Table instance

The first thing we need to do is to create a `Table` instance. After that, we register the table instance along with an import module into the WasmEdge runtime environment. Now let's see the code.

```
// create an executor
let config = ConfigBuilder::new(CommonConfigOptions::default()).build()?;
let mut executor = Executor::new(Some(&config), None)?;

// create a store
let mut store = Store::new()?;

// create a table instance
let result = Table::new(TableType::new(RefType::FuncRef, 10, Some(20)));
assert!(result.is_ok());
let table = result.unwrap();

// create an import object
let import = ImportObjectBuilder::new()
    .with_table("my-table", table)?
    .build("extern")?;

// register the import object into the store
store.register_import_module(&mut executor, &import)?;
```

In the code snippet above, we create a `Table` instance with the initial size of `10` and the maximum size of 20. The element type of the `Table` instance is `reference to function`.

Store a function reference into Table

In the previous steps, we defined a native function `real_add` and registered a `Table` instance named `my-table` into the runtime environment. Now we'll save a reference to `read_add` function to a slot of `my-table`.

```
// get the imported module instance
let instance = store
    .module_instance("extern")
    .expect("Not found module instance named 'extern'");

// get the exported table instance
let mut table = instance
    .table("my-table")
    .expect("Not found table instance named 'my-table'");

// create a host function
let host_func = Func::wrap::<(i32, i32), i32, !>(Box::new(real_add), None)?;

// store the reference to host_func at the given index of the table instance
table.set(3, Val::FuncRef(Some(host_func.as_ref())))?;
```

We save the reference to `host_func` into the third slot of `my-table`. Next, we can retrieve

the function reference from the table instance by index and call the function via its reference.

Call native function via `FuncRef`

```
// retrieve the function reference at the given index of the table instance
let value = table.get(3)?;
if let Val::FuncRef(Some(func_ref)) = value {
    // get the function type by func_ref
    let func_ty = func_ref.ty()?;

    // arguments
    assert_eq!(func_ty.args_len(), 2);
    let param_tys = func_ty.args().unwrap();
    assert_eq!(param_tys, [ValType::I32, ValType::I32]);

    // returns
    assert_eq!(func_ty.returns_len(), 1);
    let return_tys = func_ty.returns().unwrap();
    assert_eq!(return_tys, [ValType::I32]);

    // call the function by func_ref
    let returns = func_ref.call(&mut executor, params!(1, 2))?;
    assert_eq!(returns.len(), 1);
    assert_eq!(returns[0].to_i32(), 3);
}
```

The complete code of this example can be found in table_and_funcref.rs.

Run a WebAssembly function with WasmEdge low-level Rust APIs

Overview

This section demonstrates how to use the Rust APIs of the `wasmedge-sys` crate to run a host function.

As you may know, several mainstream programming languages, such as C/C++, Rust, Go, and Python, support compiling their programs into WebAssembly binary. In this demo, we'll introduce how to use the APIs defined in `Vm` of `wasmedge-sys` crate to call a WebAssembly function which could be coded in any programming language mentioned above.

The code in the example is verified on

- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Example

We use `fibonacci.wasm` in this demo, and the contents of the WebAssembly file are presented below. The statement, `(export "fib" (func $fib))`, declares an exported function named `fib`. This function computes a Fibonacci number with a given `i32` number as input. We'll use the function name later to achieve the goal of computing a Fibonacci number.

```
(module
  (export "fib" (func $fib))
  (func $fib (param $n i32) (result i32)
    (if
      (i32.lt_s
        (get_local $n)
        (i32.const 2)
      )
      (return
        (i32.const 1)
      )
    )
    (return
      (i32.add
        (call $fib
          (i32.sub
            (get_local $n)
            (i32.const 2)
          )
        )
        (call $fib
          (i32.sub
            (get_local $n)
            (i32.const 1)
          )
        )
      )
    )
  )
)
```

Step 1: Create a WasmEdge AST Module

In this step, we'll create a WasmEdge `AST Module` instance from a WebAssembly file.

- First, create a `Loader` context;
- Then, load a specified WebAssebly file ("fibonacci.wasm") via the `from_file` method of the `Loader` context. If the process is successful, then a WasmEdge `AST Module` instance is returned.

```
use wasmedge_sys::Loader;
use std::path::PathBuf;

// create a Loader context
let loader = Loader::create(None).expect("fail to create a Loader context");

// load a wasm module from a specified wasm file, and return a WasmEdge AST
Module instance
let path = PathBuf::from("fibonacci.wasm");
let module = loader.from_file(path).expect("fail to load the WebAssembly
file");
```

Step 2: Create a WasmEdge `Vm` context

In WasmEdge, a `Vm` defines a running environment, in which all varieties of instances and contexts are stored and maintained. In the demo code below, we explicitly create a WasmEdge `Store` context, and then use it as one of the inputs in the creation of a `Vm` context. If not specify a `Store` context explicitly, then `Vm` will create a store by itself.

```
use wasmedge_sys::{Config, Store, Vm};

// create a Config context
let config = Config::create().expect("fail to create a Config context");

// create a Store context
let mut store = Store::create().expect("fail to create a Store context");

// create a Vm context with the given Config and Store
let mut vm = Vm::create(Some(config), Some(&mut store)).expect("fail to create
a Vm context");
```

Step 3: Invoke the `fib` function

In Step 1, we got a module that hosts the target `fib` function defined in the WebAssembly. Now, we can call the function via the `run_wasm_from_module` method of the `Vm` context by passing the exported function name, `fib` .

```
use wasmedge_sys::WasmValue;

// run a function
let returns = vm.run_wasm_from_module(module, "fib",
[WasmValue::from_i32(5)]).expect("fail to run the target function in the
module");

println!("The result of fib(5) is {}", returns[0].to_i32());
```

This is the final result printing on the screen:

```
The result of fib(5) is 8
```

Compute Fibonacci numbers concurrently

Overview

In this example, we will demonstrate how to use the objects and the APIs defined in `wasmedge-sys` to compute Fibonacci numbers concurrently. we creates two child threads, `thread_a` and `thread_b`, which are responsible for compute `Fib(4)` and `Fib(5)` by calling the host function `fib`, respectively. After that, the main thread computes `Fib(6)` by adding the numbers returned by `thread_a` and `thread_b`.

The code in the example is verified on

- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Step 1: create a Vm context and register the WebAssembly module

```
// create a Config context
let mut config = Config::create()?;
config.bulk_memory_operations(true);

// create a Store context
let mut store = Store::create()?;

// create a Vm context with the given Config and Store
let mut vm = Vm::create(Some(config), Some(&mut store))?;

// register a wasm module from a wasm file
let file = std::path::PathBuf::from(env!("WASMEDGE_DIR"))
    .join("bindings/rust/wasmedge-sys/tests/data/fibonacci.wasm");
vm.register_wasm_from_file("extern", file)?;
```

Step 2: create two child threads to compute `Fib(4)` and `Fib(5)` respectively

```
let vm = Arc::new(Mutex::new(vm));

// compute fib(4) by a child thread
let vm_cloned = Arc::clone(&vm);
let handle_a = thread::spawn(move || {
    let vm_child_thread = vm_cloned.lock().expect("fail to lock vm");
    let returns = vm_child_thread
        .run_registered_function("extern", "fib", [WasmValue::from_i32(4)])
        .expect("fail to compute fib(4)");

    let fib4 = returns[0].to_i32();
    println!("fib(4) by child thread: {}", fib4);

    fib4
});

// compute fib(5) by a child thread
let vm_cloned = Arc::clone(&vm);
let handle_b = thread::spawn(move || {
    let vm_child_thread = vm_cloned.lock().expect("fail to lock vm");
    let returns = vm_child_thread
        .run_registered_function("extern", "fib", [WasmValue::from_i32(5)])
        .expect("fail to compute fib(5)");

    let fib5 = returns[0].to_i32();
    println!("fib(5) by child thread: {}", fib5);

    fib5
});
```

Step3: Get the returns from the two child threads, and compute `Fib(6)`

```
let fib4 = handle_a.join().unwrap();
let fib5 = handle_b.join().unwrap();

// compute fib(6)
println!("fib(6) = fib(5) + fib(1) = {}", fib5 + fib4);
```

The final result of the code above should be printed on the screen like below:

```
fib(4) by child thread: 5
fib(5) by child thread: 8
fib(6) = fib(5) + fib(1) = 13
```

The complete code in this demo can be found in threads.rs.

Introduction to WasmEdge module instance

The code in the following examples are verified on

- wasmedge-sys v0.10.0
- wasmedge-types v0.3.0

Example 1

In this example, we'll demonstrate how to use the APIs of `Vm` to

- Create Wasi and WasmEdgeProcess module instances implicitly by using a `Config` while creating a `Vm`.

```
// create a Config context
let mut config = Config::create()?;
config.bulk_memory_operations(true);
assert!(config.bulk_memory_operations_enabled());
config.wasi(true);
assert!(config.wasi_enabled());
config.wasmedge_process(true);
assert!(config.wasmedge_process_enabled());

// create a Vm context with the given Config and Store
let mut vm = Vm::create(Some(config), None)?;
```

- Retrieve the Wasi and WasmEdgeProcess module instances from the `Vm`.

```
// get the default Wasi module
let wasi_instance = vm.wasi_module_mut()?;
assert_eq!(wasi_instance.name(), "wasi_snapshot_preview1");
// get the default WasmEdgeProcess module instance
let wasmedge_process_instance = vm.wasmedge_process_module_mut()?;
assert_eq!(wasmedge_process_instance.name(), "wasmedge_process");
```

- Register an import module as a named module into the `Vm`.

```
// create ImportModule instance
let module_name = "extern_module";
let mut import = ImportModule::create(module_name)?;

// a function to import
#[sys_host_function]
fn real_add(_frame: &CallingFrame, inputs: Vec<WasmValue>) ->
Result<Vec<WasmValue>, u8> {
    if inputs.len() != 2 {
        return Err(1);
    }

    let a = if inputs[0].ty() == ValType::I32 {
        inputs[0].to_i32()
    } else {
        return Err(2);
    };

    let b = if inputs[1].ty() == ValType::I32 {
        inputs[1].to_i32()
    } else {
        return Err(3);
    };

    let c = a + b;

    Ok(vec![WasmValue::from_i32(c)])
}

// add host function
let func_ty = FuncType::create(vec![ValType::I32; 2], vec![ValType::I32])?;
let host_func = Function::create(&func_ty, Box::new(real_add), 0)?;
import.add_func("add", host_func);

// add table
let table_ty = TableType::create(RefType::FuncRef, 0..=u32::MAX)?;
let table = Table::create(&table_ty)?;
import.add_table("table", table);

// add memory
```

```
let mem_ty = MemType::create(0..=u32::MAX)?;
let memory = Memory::create(&mem_ty)?;
import.add_memory("mem", memory);

// add global
let ty = GlobalType::create(ValType::F32, Mutability::Const)?;
let global = Global::create(&ty, WasmValue::from_f32(3.5))?;
import.add_global("global", global);

// register the import module as a named module
vm.register_wasm_from_import(ImportObject::Import(import))?;
```

- Retrieve the internal `Store` instance from the `Vm`, and retrieve the named module instance from the `Store` instance.

```
let mut store = vm.store_mut()?;
let named_instance = store.module(module_name)?;
assert!(named_instance.get_func("add").is_ok());
assert!(named_instance.get_table("table").is_ok());
assert!(named_instance.get_memory("mem").is_ok());
assert!(named_instance.get_global("global").is_ok());
```

- Register an active module into the `Vm`.

```
// read the wasm bytes
let wasm_bytes = wat2wasm(
    br#"
    (module
      (export "fib" (func $fib))
      (func $fib (param $n i32) (result i32)
        (if
          (i32.lt_s
            (get_local $n)
            (i32.const 2)
          )
          (return
            (i32.const 1)
          )
        )
        (return
          (i32.add
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 2)
              )
            )
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 1)
              )
            )
          )
        )
      )
    )
"#,
)?;

// load a wasm module from a in-memory bytes, and the loaded wasm module
works as an anonymous
// module (aka. active module in WasmEdge terminology)
vm.load_wasm_from_bytes(&wasm_bytes)?;
```

```
// validate the loaded active module
vm.validate()?;

// instantiate the loaded active module
vm.instantiate()?;

// get the active module instance
let active_instance = vm.active_module()?;
assert!(active_instance.get_func("fib").is_ok());
```

- Retrieve the active module from the `Vm`.

```
// get the active module instance
let active_instance = vm.active_module()?;
assert!(active_instance.get_func("fib").is_ok());
```

The complete code in this demo can be found on WasmEdge Github.

Example 2

In this example, we'll demonstrate how to use the APIs of `Executor` to

- Create an `Executor` and a `Store`.

```
// create an Executor context
let mut executor = Executor::create(None, None)?;

// create a Store context
let mut store = Store::create()?;
```

- Register an import module into the `Executor`.

```
// read the wasm bytes
let wasm_bytes = wat2wasm(
    br#"
    (module
      (export "fib" (func $fib))
      (func $fib (param $n i32) (result i32)
        (if
          (i32.lt_s
            (get_local $n)
            (i32.const 2)
          )
          (return
            (i32.const 1)
          )
        )
        (return
          (i32.add
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 2)
              )
            )
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 1)
              )
            )
          )
        )
      )
    )
"#,
)?;

// load module from a wasm file
let config = Config::create()?;
let loader = Loader::create(Some(config))?;
let module = loader.from_bytes(&wasm_bytes)?;
```

```
// validate module
let config = Config::create()?;
let validator = Validator::create(Some(config))?;
validator.validate(&module)?;

// register a wasm module into the store context
let module_name = "extern";
let named_instance = executor.register_named_module(&mut store, &module,
module_name)?;
assert!(named_instance.get_func("fib").is_ok());
```

- Register an active module into the `Executor`.

```
// read the wasm bytes
let wasm_bytes = wat2wasm(
    br#"
    (module
      (export "fib" (func $fib))
      (func $fib (param $n i32) (result i32)
        (if
          (i32.lt_s
            (get_local $n)
            (i32.const 2)
          )
          (return
            (i32.const 1)
          )
        )
        (return
          (i32.add
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 2)
              )
            )
            (call $fib
              (i32.sub
                (get_local $n)
                (i32.const 1)
              )
            )
          )
        )
      )
    )
"#,
)?;

// load module from a wasm file
let config = Config::create()?;
let loader = Loader::create(Some(config))?;
let module = loader.from_bytes(&wasm_bytes)?;
```

```
// validate module
let config = Config::create()?;
let validator = Validator::create(Some(config))?;
validator.validate(&module)?;

// register a wasm module as an active module
let active_instance = executor.register_active_module(&mut store,
&module)?;
assert!(active_instance.get_func("fib").is_ok());
```

The complete code in this demo can be found in mdbook_example_module_instance.rs.

WasmEdge Python SDK

Coming soon, or you can help out.

WasmEdge Command Line Tools

After the WasmEdge installation, the `wasmedge` and `wasmedgec` tools are installed.

Users can use these WasmEdge CLI tools to execute the WebAssembly files quickly.

- The `wasmedge` CLI tool is the WebAssembly runtime to execute the WASM files.
- The `wasmedgec` CLI tool is the ahead-of-time compiler to compile the WebAssembly file into native code.

`wasmedge` CLI

After installation, users can execute the `wasmedge` tool with commands.

```
$ wasmedge -v
wasmedge version 0.11.2
```

The usage of the `wasmedge` tool will be:

```
$ wasmedge -h
USAGE
   wasmedge [OPTIONS] [--] WASM_OR_SO [ARG ...]

...
```

If users install the WasmEdge from the install script with the option `-e tf,image`, the WasmEdge CLI tools with TensorFlow and TensorFlow-Lite extensions will be installed.

- `wasmedge-tensorflow` CLI tool
  - The `wasmedge` tool with TensorFlow, TensorFlow-Lite, and `wasmedge-image` extensions.
  - Only on `x86_64` and `aarch64` Linux platforms and `x86_64` MacOS.
- `wasmedge-tensorflow-lite` CLI tool
  - The `wasmedge` tool with TensorFlow-Lite, and `wasmedge-image` extensions.
  - Only on `x86_64` and `aarch64` Linux platforms, Android, and `x86_64` MacOS.

The `wasmedge` CLI tool will execute the WebAssembly in ahead-of-time(AOT) mode if available in the input WASM file. For the pure WASM, the `wasmedge` CLI tool will execute it in interpreter mode, which is much slower than AOT mode. If you want to improve the performance, please refer here to compile your WASM file.

Options

The options of the `wasmedge` CLI tool are as follows.

1. `-v|--version` : Show the version information. Will ignore other arguments below.
2. `-h|--help` : Show the help messages. Will ignore other arguments below.
3. (Optional) `--reactor` : Enable the reactor mode.
   - In the reactor mode, `wasmedge` runs a specified function exported by the

WebAssembly program.
    - WasmEdge will execute the function which name should be given in `ARG[0]`.
    - If there's exported function which names `_initialize`, the function will be executed with the empty parameter at first.
4. (Optional) `--dir`: Bind directories into WASI virtual filesystem.
    - Use `--dir guest_path:host_path` to bind the host path into the guest path in WASI virtual system.
5. (Optional) `--env`: Assign the environment variables in WASI.
    - Use `--env ENV_NAME=VALUE` to assign the environment variable.
6. (Optional) Statistics information:
    - Use `--enable-time-measuring` to show the execution time.
    - Use `--enable-gas-measuring` to show the amount of used gas.
    - Use `--enable-instruction-count` to display the number of executed instructions.
    - Or use `--enable-all-statistics` to enable all of the statistics options.
7. (Optional) Resource limitations:
    - Use `--time-limit MILLISECOND_TIME` to limit the execution time. Default value is `0` as no limitation.
    - Use `--gas-limit GAS_LIMIT` to limit the execution cost.
    - Use `--memory-page-limit PAGE_COUNT` to set the limitation of pages(as size of 64 KiB) in every memory instance.
8. (Optional) WebAssembly proposals:
    - Use `--disable-import-export-mut-globals` to disable the Import/Export of Mutable Globals proposal (Default `ON`).
    - Use `--disable-non-trap-float-to-int` to disable the Non-Trapping Float-to-Int Conversions proposal (Default `ON`).
    - Use `--disable-sign-extension-operators` to disable the Sign-Extension Operators proposal (Default `ON`).
    - Use `--disable-multi-value` to disable the Multi-value proposal (Default `ON`).
    - Use `--disable-bulk-memory` to disable the Bulk Memory Operations proposal (Default `ON`).
    - Use `--disable-reference-types` to disable the Reference Types proposal (Default `ON`).
    - Use `--disable-simd` to disable the Fixed-width SIMD proposal (Default `ON`).
    - Use `--enable-multi-memory` to enable the Multiple Memories proposal (Default `OFF`).
    - Use `--enable-tail-call` to enable the Tail call proposal (Default `OFF`).
    - Use `--enable-extended-const` to enable the Extended Constant Expressions proposal (Default `OFF`).

    - Use `--enable-threads` to enable the Threads proposal (Default `OFF`).
    - Use `--enable-all` to enable ALL proposals above.
9. WASM file (`/path/to/wasm/file`).
10. (Optional) `ARG` command line arguments array.
    - In reactor mode, the first argument will be the function name, and the arguments after `ARG[0]` will be parameters of wasm function `ARG[0]`.
    - In command mode, the arguments will be the command line arguments of the WASI `_start` function. They are also known as command line arguments(`argv`) for a standalone C/C++ program.

Examples

Call A WebAssembly Function Written in WAT

We created the hand-written fibonacci.wat and used the wat2wasm tool to convert it into the fibonacci.wasm WebAssembly program. It exported a `fib()` function which takes a single `i32` integer as the input parameter. We can execute `wasmedge` in reactor mode to invoke the exported function.

You can run:

```
wasmedge --reactor fibonacci.wasm fib 10
```

The output will be:

```
89
```

Call A WebAssembly Function Compiled From Rust

The add.wasm WebAssembly program contains an exported `add()` function, which is compiled from Rust. Checkout its Rust source code project here. We can execute `wasmedge` in reactor mode to invoke the `add()` function with two `i32` integer input parameters.

You can run:

```
wasmedge --reactor add.wasm add 2 2
```

The output will be:

```
4
```

Execute A Standalone WebAssembly Program: Hello world

The hello.wasm WebAssembly program contains a `main()` function. Checkout its Rust source code project here. It prints out `hello` followed by the command line arguments.

You can run:

```
wasmedge hello.wasm second state
```

The output will be:

```
hello
second
state
```

Execute With `statistics` Enabled

The CLI supports `--enable-all-statistics` flags for the statistics and gas metering.

You can run:

```
wasmedge --enable-all-statistics hello.wasm second state
```

The output will be:

```
hello
second
state
[2021-12-09 16:03:33.261] [info] ====================  Statistics
====================
[2021-12-09 16:03:33.261] [info]  Total execution time: 268266 ns
[2021-12-09 16:03:33.261] [info]  Wasm instructions execution time: 251610 ns
[2021-12-09 16:03:33.261] [info]  Host functions execution time: 16656 ns
[2021-12-09 16:03:33.261] [info]  Executed wasm instructions count: 20425
[2021-12-09 16:03:33.261] [info]  Gas costs: 20425
[2021-12-09 16:03:33.261] [info]  Instructions per second: 81177218
[2021-12-09 16:03:33.261] [info] ======================   End
======================
```

Execute With `gas-limit` Enabled

The CLI supports `--gas-limit` flags for controlling the execution costs.

For giving sufficient gas as the example, you can run:

```
wasmedge --enable-all-statistics --gas-limit 20425 hello.wasm second state
```

The output will be:

```
hello
second
state
[2021-12-09 16:03:33.261] [info] ====================  Statistics
====================
[2021-12-09 16:03:33.261] [info]  Total execution time: 268266 ns
[2021-12-09 16:03:33.261] [info]  Wasm instructions execution time: 251610 ns
[2021-12-09 16:03:33.261] [info]  Host functions execution time: 16656 ns
[2021-12-09 16:03:33.261] [info]  Executed wasm instructions count: 20425
[2021-12-09 16:03:33.261] [info]  Gas costs: 20425
[2021-12-09 16:03:33.261] [info]  Instructions per second: 81177218
[2021-12-09 16:03:33.261] [info] ======================   End
======================
```

For giving insufficient gas as the example, you can run:

```
wasmedge --enable-all-statistics --gas-limit 20 hello.wasm second state
```

The output will be:

```
[2021-12-23 15:19:06.690] [error] Cost exceeded limit. Force terminate the
execution.
[2021-12-23 15:19:06.690] [error]     In instruction: ref.func (0xd2) ,
Bytecode offset: 0x00000000
[2021-12-23 15:19:06.690] [error]     At AST node: expression
[2021-12-23 15:19:06.690] [error]     At AST node: element segment
[2021-12-23 15:19:06.690] [error]     At AST node: element section
[2021-12-23 15:19:06.690] [error]     At AST node: module
[2021-12-23 15:19:06.690] [info] ====================  Statistics
====================
[2021-12-23 15:19:06.690] [info]  Total execution time: 0 ns
[2021-12-23 15:19:06.690] [info]  Wasm instructions execution time: 0 ns
[2021-12-23 15:19:06.690] [info]  Host functions execution time: 0 ns
[2021-12-23 15:19:06.690] [info]  Executed wasm instructions count: 21
[2021-12-23 15:19:06.690] [info]  Gas costs: 20
```

JavaScript Examples

It is possible to use WasmEdge as a high-performance, secure, extensible, easy to deploy, and Kubernetes-compliant JavaScript runtime.

The qjs.wasm program is a JavaScript interpreter compiled into WebAssembly. The hello.js file is a very simple JavaScript program.

You can run:

```
wasmedge --dir .:. qjs.wasm hello.js 1 2 3
```

The output will be:

```
Hello 1 2 3
```

The qjs_tf.wasm is a JavaScript interpreter with WasmEdge Tensorflow extension compiled into WebAssembly. To run qjs_tf.wasm, you must use the `wasmedge-tensorflow-lite` CLI tool, which is a build of WasmEdge with Tensorflow-Lite extension built-in. You can download a full Tensorflow-based JavaScript example to classify images.

```
# Download the Tensorflow example
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/aiy_food_V1_labelmap.txt
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/food.jpg
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/lite-
model_aiy_vision_classifier_food_V1_1.tflite
$ wget https://raw.githubusercontent.com/second-state/wasmedge-quickjs
/main/example_js/tensorflow_lite_demo/main.js

$ wasmedge-tensorflow-lite --dir .:. qjs_tf.wasm main.js
label: Hot dog
confidence: 0.8941176470588236
```

`wasmedgec` CLI

After installation, users can execute the `wasmedgec` tool with commands.

```
$ wasmedgec -v
wasmedge version 0.11.2
```

The usage of the `wasmedge` tool will be:

```
$ wasmedge -h
USAGE
   wasmedgec [OPTIONS] [--] WASM WASM_SO

...
```

The `wasmedgec` can compile WebAssembly into native machine code (i.e., the AOT compiler). For the pure WebAssembly, the `wasmedge` tool will execute the WASM in interpreter mode. After compiling with the `wasmedgec` AOT compiler, the `wasmedge` tool can execute the WASM in AOT mode which is much faster.

Options

The options of the `wasmedgec` CLI tool are as follows.

1. `-v|--version` : Show the version information. Will ignore other arguments below.
2. `-h|--help` : Show the help messages. Will ignore other arguments below.
3. (Optional) `--dump` : Dump the LLVM IR to `wasm.ll` and `wasm-opt.ll` .
4. (Optional) `--interruptible` : Generate the binary which supports interruptible execution.
    - By default, the AOT-compiled WASM not supports interruptions in asynchronous executions.
5. (Optional) Statistics information:
    - By default, the AOT-compiled WASM not supports all statistics even if the options are turned on when running the `wasmedge` tool.
    - Use `--enable-time-measuring` to generate code for enabling the statistics of time measuring in execution.
    - Use `--enable-gas-measuring` to generate code for enabling the statistics of gas measuring in execution.
    - Use `--enable-instruction-count` to generate code for enabling the statistics of

counting WebAssembly instructions.
    - Or use `--enable-all-statistics` to generate code for enabling all of the statistics.
6. (Optional) `--generic-binary` : Generate the generic binary of the current host CPU architecture.
7. (Optional) WebAssembly proposals:
    - Use `--disable-import-export-mut-globals` to disable the Import/Export of Mutable Globals proposal (Default `ON`).
    - Use `--disable-non-trap-float-to-int` to disable the Non-Trapping Float-to-Int Conversions proposal (Default `ON`).
    - Use `--disable-sign-extension-operators` to disable the Sign-Extension Operators proposal (Default `ON`).
    - Use `--disable-multi-value` to disable the Multi-value proposal (Default `ON`).
    - Use `--disable-bulk-memory` to disable the Bulk Memory Operations proposal (Default `ON`).
    - Use `--disable-reference-types` to disable the Reference Types proposal (Default `ON`).
    - Use `--disable-simd` to disable the Fixed-width SIMD proposal (Default `ON`).
    - Use `--enable-multi-memory` to enable the Multiple Memories proposal (Default `OFF`).
    - Use `--enable-tail-call` to enable the Tail call proposal (Default `OFF`).
    - Use `--enable-extended-const` to enable the Extended Constant Expressions proposal (Default `OFF`).
    - Use `--enable-threads` to enable the Threads proposal (Default `OFF`).
    - Use `--enable-all` to enable ALL proposals above.
8. (Optional) `--optimize` : Select the LLVM optimization level.
    - Use `--optimize LEVEL` to set the optimization level. The `LEVEL` should be one of `0` , `1` , `2` , `3` , `s` , or `z` .
    - The default value will be `2` , which means `O2` .
9. Input WASM file (`/path/to/wasm/file`).
10. Output path (`/path/to/output/file`).
    - By default, the `wasmedgec` tool will output the universal WASM format.
    - If the specific file extension (`.so` on Linux, `.dylib` on MacOS, and `.dll` on Windows) is assigned in the output path, the `wasmedgec` tool will output the shared library format.

Example

Take the fibonacci.wasm for example. It exported a `fib()` function which takes a single `i32` integer as the input parameter.

You can run:

```
wasmedgec fibonacci.wasm fibonacci_aot.wasm
```

or:

```
wasmedgec fibonacci.wasm fibonacci_aot.so # On Linux.
```

The output will be:

```
[2022-09-09 14:22:10.540] [info] compile start
[2022-09-09 14:22:10.541] [info] verify start
[2022-09-09 14:22:10.542] [info] optimize start
[2022-09-09 14:22:10.547] [info] codegen start
[2022-09-09 14:22:10.552] [info] output start
[2022-09-09 14:22:10.600] [info] compile done
```

Then you can execute the output file with `wasmedge` and measure the execution time:

```
time wasmedge --reactor fibonacci_aot.wasm fib 30
```

The output will be:

```
1346269

real    0m0.029s
user    0m0.012s
sys     0m0.014s
```

Then you can compare it with the interpreter mode:

```
time wasmedge --reactor fibonacci.wasm fib 30
```

The output shows that the AOT-compiled WASM is much faster than the interpreter mode:

```
1346269

real    0m0.442s
user    0m0.427s
sys     0m0.012s
```

Develop WasmEdge Plug-in

This chapter is WORK IN PROGRESS.

WasmEdge provides a C++ based API for registering extension modules and host functions. While the WasmEdge language SDKs allow registering host functions from a host (wrapping) application, the plugin API allows such extensions to be incorporated into WasmEdge's own building and releasing process.

The C API for the plug-in mechanism is under development. In the future, we will release the C API of plug-in mechanism and recommend developers to implement the plug-ins with C API.

Loadable Plug-in

Loadable plugin is a standalone `.so` / `.dylib` / `.dll` file that WasmEdge can load during runtime environment, and provide modules to be imported.

Please refer to the plugin example code.

WasmEdge Currently Released Plug-ins

There are several plug-in releases with the WasmEdge official releases. Please check the following table to check the release status and how to build from source with the plug-ins.

The `WasmEdge-Process` plug-in is attached in the WasmEdge release tarballs.

Plug-in	Rust Crate	Released Platforms	Build Steps

Plug-in	Rust Crate	Released Platforms	Build Steps
WasmEdge-Process	wasmedge_process_interface	`manylinux2014 x86_64`, `manylinux2014 aarch64`, and `ubuntu 20.04 x86_64` (since `0.10.0`)	Default
WASI-Crypto	wasi-crypto	`manylinux2014 x86_64`, `manylinux2014 aarch64`, and `ubuntu 20.04 x86_64` (since `0.10.1`)	Build With WASI-Crypto
WASI-NN with OpenVINO backend	wasi-nn	`ubuntu 20.04 x86_64` (since `0.10.1`)	Build With WASI-NN
WASI-NN with PyTorch backend	wasi-nn	`ubuntu 20.04 x86_64` (since `0.11.1`)	Build With WASI-NN
WASI-NN with TensorFlow-Lite backend	wasi-nn	`manylinux2014 x86_64`, `manylinux2014 aarch64`, and `ubuntu 20.04 x86_64` (since `0.11.2`)	Build With WASI-NN
WasmEdge-HttpsReq	wasmedge_http_req	`manylinux2014 x86_64`, and `manylinux2014 aarch64` (since `0.11.1`)	Build With WasmEdge-HttpsReq

Due to the `OpenVINO` and `PyTorch` dependencies, we only release the WASI-NN plug-in on `Ubuntu 20.04 x86_64` now. We'll work with `manylinux2014` versions in the

future.

Contribute to WasmEdge

WasmEdge is developed in the open, and is constantly being improved by our **users, contributors, and maintainers**. It is because of you that we can bring great software to the community.

This guide provides information on filing issues and guidelines for open source contributors. **Please leave comments / suggestions if you find something is missing or incorrect.**

WasmEdge follows the release process to release the new versions.

For contributing to WasmEdge, you can follow the contribution guide and build from source first.

To understanding the architecture, you can refer to the WasmEdge internal.

If you are looking for ideas for contribution, here is a wish list of items we'd like to get some help with!

WasmEdge Release Process

Create the releasing process issue of the new version

- ☐ Keep adding the new features, issues, documents, and builds check list into the issue.
- ☐ Add the GitHub project of the new version.

Write Changelog

- ☐ Make sure every change is written in the changelog.
- ☐ Make sure the `Changelog.md` has the correct version number and the release date.
- ☐ Copy the changelog of this version to `.CurrentChangelog.md`. (Our release CI will take this file as the release notes.)
- ☐ Record the contributor lists.
- ☐ Create a pull request, make sure the CI are all passed, and merge it.

Create the Alpha Pre-Release

- ☐ In this step, the main features are completed. No more major feature will be merged after the first Alpha pre-release.
- ☐ Make sure that the features in the releasing process issue are completed.
- ☐ Use git tag to create a new release tag `major.minor.patch-alpha.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and turn into Beta or RC phase in about 3 days if there's no critical issues.

Create the Beta Pre-Release

- ☐ This step is for the issue fixing if needed. No more feature will be accepted.
- ☐ Make sure that all the features in the releasing process issue are completed.
- ☐ Use git tag to create a new release tag `major.minor.patch-beta.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and turn into RC phase in about 3 days if there's no critical issues.

Create the RC Pre-Release

- ☐ In this step, the issue fixing is finished. The `RC` pre-releases are for the installation, bindings, and packages testing.
- ☐ Make sure that all the issues in the releasing process issue are completed.
- ☐ Update `WASMEDGE_CAPI_VERSION` in `CMakeLists.txt`.
- ☐ Update `wasmedge_version` in `docs/book/en/book.toml`.
- ☐ Use git tag to create a new release tag `major.minor.patch-rc.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and announce the official release in about 3 days if there's no critical issues.

Create the Official Release

- ☐ Make sure the `Changelog.md` and `.CurrentChangelog.md` have the correct version number and the release date.
- ☐ Use git tag to create a new release tag `major.minor.patch`. And push this tag to GitHub.
- ☐ Wait for the CI builds and push the release binaries and release notes to the GitHub release page.
- ☐ Publish the release.
- ☐ Close the releasing process issue and the GitHub project.

Update the Extensions

The following projects will be updated with the `Alpha`, `Beta`, and `RC` pre-releases and the official release:

- [ ] WasmEdge-Image
- [ ] WasmEdge-TensorFlow-Deps
- [ ] WasmEdge-TensorFlow
- [ ] WasmEdge-TensorFlow-Tools
- [ ] WasmEdge-Go SDK
- [ ] WasmEdge-core NAPI package
- [ ] WasmEdge-extensions NAPI package

Contribution Steps

Setup Development Environment

The WasmEdge is developed on Ubuntu 20.04 to take advantage of advanced LLVM features for the AOT compiler. The WasmEdge team also builds and releases statically linked WasmEdge binaries for older Linux distributions.

Our development environment requires `libLLVM-12` and `>=GLIBCXX_3.4.26`.

If you are using an operating system older than Ubuntu 20.04, please use our special docker image to build WasmEdge. If you are looking for the pre-built binaries for the older operating system, we also provide several pre-built binaries based on `manylinux2014` distribution.

Build WasmEdge please refer to: Build WasmEdge from source.

Contribution Workflow

Pull requests are always welcome, even if they only contain small fixes like typos or a few lines of code. If there will be a significant effort, please document it as an issue and get a discussion going before starting to work on it.

Please submit a pull request broken down into small changes bit by bit. A pull request consisting of a lot features and code changes may be hard to review. It is recommended to submit pull requests in an incremental fashion.

> If you split your pull request into small changes, please make sure any of the changes that goes to master will not break anything. Otherwise, it can not be merged until this feature is complete.

Fork and Clone the Repository

Fork the WasmEdge repository and clone the code to your local workspace

---

> The WasmEdge team builds lots of extensions of Server-side WebAssembly, see TensorFlow, Storage, Command interface, Ethereum, Substrate. If you want to contribute to the extensions, please go to those repositories.

Branches and Commits

Changes should be made on your own fork in a new branch. Pull requests should be rebased on the top of master.

The WasmEdge project adopts DCO to manage all contributions. Please make sure you add your `sign-off-statement` through the `-s` or `--signoff` flag or the GitHub Web UI before committing the pull request message.

Develop, Build and Test

Write code on the new branch in your fork, and build from source code with the option `-DWASMEDGE_BUILD_TESTS=ON`.

Then you can use these tests to verify the correctness of WasmEdge binaries.

```
cd <path/to/wasmedge/build_folder>
LD_LIBRARY_PATH=$(pwd)/lib/api ctest
```

Push and Create A Pull Request

When ready for review, push your branch to your fork repository on github.

Then visit your fork at https://github.com/$user/WasmEdge and click the `Compare & Pull Request` button next to your branch to create a new pull request. Description of a pull request should refer to all the issues that it addresses. Remember to put a reference to issues (such as Closes #XXX and Fixes #XXX) in the comment so that the issues can be closed when the PR is merged. After creating a pull request, please check that the CI passes with your code changes.

Once your pull request has been opened it will be assigned to one or more reviewers. Those reviewers will do a thorough code review, looking for correctness, bugs, opportunities for improvement, documentation and comments, and coding style.

Commit changes made in response to review comments to the same branch on your fork.

Reporting issues

It is a great way to contribute to WasmEdge by reporting an issue. Well-written and complete bug reports are always welcome! Please open an issue on Github.

Before opening any issue, please look up the existing issues to avoid submitting a duplication. If you find a match, you can "subscribe" to it to get notified on updates. If you have additional helpful information about the issue, please leave a comment.

When reporting issues, always include:

- Version of your system
- Configuration files of WasmEdge

Because the issues are open to the public, when submitting the log and configuration files, be sure to remove any sensitive information, e.g. user name, password, IP address, and company name. You can replace those parts with "REDACTED" or other strings like "****". Be sure to include the steps to reproduce the problem if applicable. It can help us understand and fix your issue faster.

Documenting

Update the documentation if you are creating or changing features. Good documentation is as important as the code itself. Documents are written with Markdown. See Writing on GitHub for more details.

Design new features

You can propose new designs for existing WasmEdge features. You can also design entirely new features, please submit a proposal via the GitHub issues.

WasmEdge maintainers will review this proposal as soon as possible. This is necessary to ensure the overall architecture is consistent and to avoid duplicated work in the roadmap.

Build WasmEdge from source

Please follow this guide to build and test WasmEdge from the source code.

- Linux
- MacOS
- Windows
- Android
- seL4
- Raspberry Pi
- OpenWrt
- OpenHarmony

If you just want the latest builds from the `HEAD` of the `master` branch, and do not want to build it yourself, you can download the release package directly from our Github Action's CI artifact. Here is an example.

What Will Be Built

WasmEdge provides various tools for enabling different runtime environments for optimal performance. You can find that there are several wasmedge related tools:

1. `wasmedge` is the general wasm runtime.
   - `wasmedge` executes a `WASM` file in the interpreter mode or a compiled `WASM` file in the ahead-of-time compilation mode.
   - To disable building all tools, you can set the CMake option `WASMEDGE_BUILD_TOOLS` to `OFF`.
2. `wasmedgec` is the ahead-of-time `WASM` compiler.
   - `wasmedgec` compiles a general `WASM` file into a compiled `WASM` file.
   - To disable building the ahead-of-time compiler only, you can set the CMake option `WASMEDGE_BUILD_AOT_RUNTIME` to `OFF`.
3. `libwasmedge.so` is the WasmEdge C API shared library. (`libwasmedge.dylib` on MacOS and `wasmedge.dll` on Windows)
   - `libwasmedge.so`, `libwasmedge.dylib`, or `wasmedge.dll` provides the C API for the ahead-of-time compiler and the WASM runtime.
   - The APIs related to the ahead-of-time compiler will always fail if the CMake option `WASMEDGE_BUILD_AOT_RUNTIME` is set as `OFF`.

    - To disable building just the shared library, you can set the CMake option `WASMEDGE_BUILD_SHARED_LIB` to `OFF`.
4. `ssvm-qitc` is for AI applications and supports the ONNC runtime for AI models in the ONNX format.
    - If you want to try `ssvm-qitc`, please refer to ONNC-Wasm project to set up the working environment and tryout several examples.
    - And here is our tutorial for ONNC-Wasm project(YouTube Video).

CMake Building Options

Developers can set the CMake options to customize the WasmEdge building.

1. `WASMEDGE_BUILD_TESTS`: build the WasmEdge tests. Default is `OFF`.
2. `WASMEDGE_BUILD_AOT_RUNTIME`: build with the Ahead-of-Time compiler supporting. Default is `ON`.
3. `WASMEDGE_BUILD_SHARED_LIB`: build the WasmEdge shared library (`libwasmedge.so`, `libwasmedge.dylib`, or `wasmedge.dll`). Default is `ON`.
    - By default, the WasmEdge shared library will link to the LLVM shared library.
4. `WASMEDGE_BUILD_STATIC_LIB`: build the WasmEdge static library (`libwasmedge.a`, Linux and MacOS platforms, experimental). Default is `OFF`.
    - If this option is set as `ON`, the option `WASMEDGE_FORCE_DISABLE_LTO` will forcefully be set as `ON`.
    - If this option is set as `ON`, the `libz` and `libtinfo` on Linux platforms will be statically linked.
    - For linking with `libwasmedge.a`, developers should also add the `-ldl`, `-pthread`, `-lm`, and `-lstdc++` linker options on both Linux and MacOS platforms, and `-lrt` on Linux platforms.
5. `WASMEDGE_BUILD_TOOLS`: build the `wasmedge` and `wasmedgec` tools. Default is `ON`.
    - The `wasmedge` and `wasmedgec` tools will link to the WasmEdge shared library by default.
    - If this option is set as `ON` and `WASMEDGE_BUILD_AOT_RUNTIME` is set as `OFF`, the `wasmedgec` tool for the AOT compiler will not be built.
    - If this option is set as `ON` but the option `WASMEDGE_LINK_TOOLS_STATIC` is set as `OFF`, the option `WASMEDGE_BUILD_SHARED_LIB` will forcefully be set as `ON`.
    - If this option and the option `WASMEDGE_LINK_TOOLS_STATIC` are both set as `ON`, the `WASMEDGE_LINK_LLVM_STATIC` and `WASMEDGE_BUILD_STATIC_LIB` will both be set as `ON`, and the `wasmedge` and `wasmedgec` tools will link to the WasmEdge static library instead. In this case, the plugins will not work in tools.

6. `WASMEDGE_BUILD_PLUGINS` : build the WasmEdge plugins. Default is `ON` .
7. `WASMEDGE_BUILD_EXAMPLE` : build the WasmEdge examples. Default is `OFF` .
8. `WASMEDGE_PLUGIN_WASI_NN_BACKEND` : build the WasmEdge WASI-NN plugin (Linux platforms only). Default is empty.
    - This option is useless if the option `WASMEDGE_BUILD_PLUGINS` is set as `OFF` .
    - To build the WASI-NN plugin with backend, please use `-DWASMEDGE_PLUGIN_WASI_NN_BACKEND=<backend_name>` .
    - To build the WASI-NN plugin with multiple backends, please use `-DWASMEDGE_PLUGIN_WASI_NN_BACKEND=<backend_name1>,<backend_name2>` .
9. `WASMEDGE_PLUGIN_WASI_CRYPTO` : build the WasmEdge WASI-Crypto plugin (Linux platforms only). Default is `OFF` .
    - This option is useless if the option `WASMEDGE_BUILD_PLUGINS` is set as `OFF` .
10. `WASMEDGE_FORCE_DISABLE_LTO` : forcefully turn off the link time optimization. Default is `OFF` .
11. `WASMEDGE_LINK_LLVM_STATIC` : link the LLVM and lld libraries statically (Linux and MacOS platforms only, experimental). Default is `OFF` .
12. `WASMEDGE_LINK_TOOLS_STATIC` : make the `wasmedge` and `wasmedgec` tools to link the WasmEdge library and LLVM libraries statically (Linux and MacOS platforms only, experimental). Default is `OFF` .
    - If the option `WASMEDGE_BUILD_TOOLS` and this option are both set as `ON` , the `WASMEDGE_LINK_LLVM_STATIC` will be set as `ON` .

Build WasmEdge with Plug-ins

Developers can follow the steps to build WasmEdge with plug-ins from source.

- WASI-NN (OpenVINO and PyTorch backends)
- WASI-Crypto
- WasmEdge-HttpsReq

Run Tests

The tests are only available when the build option `WASMEDGE_BUILD_TESTS` is set to `ON` .

Users can use these tests to verify the correctness of WasmEdge binaries built.

```
cd <path/to/wasmedge/build_folder>
LD_LIBRARY_PATH=$(pwd)/lib/api ctest
```

Build WasmEdge on Linux

Get the Source Code

```
git clone https://github.com/WasmEdge/WasmEdge.git
cd WasmEdge
```

Prepare the Environment

Docker Images

The easiest way to setup the environment is using the WasmEdge docker images.

You can use the following commands to get our latest docker image from dockerhub:

```
docker pull wasmedge/wasmedge # Pulls the latest - wasmedge/wasmedge:latest
```

Or you can pull with the available tags.

Install Dependencies on Ubuntu 20.04 Manually

For the developers who don't want to use docker, they can setup the environment on Ubuntu Manually.

Please check that these dependencies are satisfied.

- LLVM 12.0.0 (>= 10.0.0)
- GCC 11.1.0 (>= 9.4.0)

```
# Tools and libraries
sudo apt install -y \
   software-properties-common \
   cmake \
   libboost-all-dev

# And you will need to install llvm for the AOT runtime
sudo apt install -y \
   llvm-12-dev \
   liblld-12-dev

# WasmEdge supports both clang++ and g++ compilers.
# You can choose one of them to build this project.
# If you prefer GCC, then:
sudo apt install -y gcc g++
# Or if you prefer clang, then:
sudo apt install -y clang-12
```

Support for Legacy Operating Systems

Our development environment requires `libLLVM-12` and `>=GLIBCXX_3.4.33`.

If users are using operating systems older than Ubuntu 20.04, please use our special docker image to build WasmEdge. If you are looking for the pre-built binaries for the older operating system, we also provide several pre-built binaries based on `manylinux*` distributions.

Docker Image	Base Image	Provided Requirements
`wasmedge/wasmedge:manylinux2014_x86_64`	CentOS 7.9	GLIBC <= 2.17 CXXABI <= 1.3.7 GLIBCXX <= 3.4.19 GCC <= 4.8.0
`wasmedge/wasmedge:manylinux2014_aarch64`	CentOS 7.9	GLIBC <= 2.17 CXXABI <= 1.3.7 GLIBCXX <= 3.4.19 GCC <= 4.8.0

Build WasmEdge

Please refer to here for the descriptions of all CMake options.

```
# After pulling our wasmedge docker image
docker run -it --rm \
    -v <path/to/your/wasmedge/source/folder>:/root/wasmedge \
    wasmedge/wasmedge:latest
# In docker
cd /root/wasmedge
# If you don't use docker then you need to run only the following commands in
the cloned repository root
mkdir -p build && cd build
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_BUILD_TESTS=ON .. && make -j
```

Run Tests

The following tests are available only when the build option `WASMEDGE_BUILD_TESTS` is set to `ON`.

Users can use these tests to verify the correctness of WasmEdge binaries.

```
# In docker
cd <path/to/wasmedge/build_folder>
LD_LIBRARY_PATH=$(pwd)/lib/api ctest
```

Build WasmEdge on MacOS

Currently, WasmEdge project on MacOS supports both Intel and M1 models. However, we only test and develop on `Catalina`, `Big Sur`, and `Monterey`.

- Model:
  - Intel
  - M1
- Operating System
  - Monterey
  - Big Sur
  - Catalina

If you would like to develop WasmEdge on MacOS, please follow this guide to build and test from source code.

Get Source Code

```
git clone https://github.com/WasmEdge/WasmEdge.git
cd WasmEdge
```

Requirements and Dependencies

WasmEdge will try to use the latest LLVM release to create our nightly build. If you want to build from source, you may need to install these dependencies by yourself.

- LLVM 14.0.1 (>= 10.0.0)

```
# Tools and libraries
brew install boost cmake ninja llvm
export LLVM_DIR="/usr/local/opt/llvm/lib/cmake"
export CC=clang
export CXX=clang++
```

Build WasmEdge

Please refer to here for the descriptions of all CMake options.

```
cmake -Bbuild -GNinja -DWASMEDGE_BUILD_TESTS=ON .
cmake --build build
```

If you don't want to dynamically link LLVM on MacOS, you can set the option `WASMEDGE_LINK_LLVM_STATIC` to `ON`.

Run Tests

The following tests are available only when the build option `WASMEDGE_BUILD_TESTS` is set to `ON`.

Users can use these tests to verify the correctness of WasmEdge binaries.

```
cd build
DYLD_LIBRARY_PATH=$(pwd)/lib/api ctest
```

Known issues

The following tests can not pass on macos, we are investigating these issues:

- wasmedgeWasiSocketTests

Build WasmEdge on Windows 10

You can also find the details here.

Get Source Code

```
git clone https://github.com/WasmEdge/WasmEdge.git
cd WasmEdge
```

Requirements and Dependencies

WasmEdge requires LLVM 13 and you may need to install these following dependencies by yourself.

- Chocolatey, we use it to install `cmake`, `ninja`, and `vswhere`.
- Windows SDK 19041
- LLVM 13.0.1, you can find the pre-built files here or you can just follow the `instructions/commands` to download automatically.

```
# Install the required tools
choco install cmake ninja vswhere

$vsPath = (vswhere -latest -property installationPath)
Import-Module (Join-Path $vsPath "Common7\Tools
\Microsoft.VisualStudio.DevShell.dll")
Enter-VsDevShell -VsInstallPath $vsPath -SkipAutomaticLocation -DevCmdArguments
"-arch=x64 -host_arch=x64 -winsdk=10.0.19041.0"

# Download our pre-built LLVM 13 binary
$llvm = "LLVM-13.0.1-win64.zip"
curl -sLO https://github.com/WasmEdge/llvm-windows/releases/download/llvmorg-
13.0.1/LLVM-13.0.1-win64.zip -o $llvm
Expand-Archive -Path $llvm

# Set LLVM environment
$llvm_dir = "$pwd\\LLVM-13.0.1-win64\\LLVM-13.0.1-win64\\lib\\cmake\\llvm"
$Env:CC = "clang-cl"
$Env:CXX = "clang-cl"
```

Build WasmEdge

```
$vsPath = (vswhere -latest -property installationPath)
Import-Module (Join-Path $vsPath "Common7\Tools
\Microsoft.VisualStudio.DevShell.dll")
Enter-VsDevShell -VsInstallPath $vsPath -SkipAutomaticLocation -DevCmdArguments
"-arch=x64 -host_arch=x64 -winsdk=10.0.19041.0"

cmake -Bbuild -GNinja -DCMAKE_SYSTEM_VERSION=10.0.19041.0
-DCMAKE_MSVC_RUNTIME_LIBRARY=MultiThreadedDLL "-DLLVM_DIR=$llvm_dir"
-DWASMEDGE_BUILD_TESTS=ON -DWASMEDGE_BUILD_PACKAGE="ZIP" .
cmake --build build
```

Run Tests

The following tests are available only when the build option `WASMEDGE_BUILD_TESTS` was set to `ON`.

Users can use these tests to verify the correctness of WasmEdge binaries.

```
$vsPath = (vswhere -latest -property installationPath)
Import-Module (Join-Path $vsPath "Common7\Tools
\Microsoft.VisualStudio.DevShell.dll")
Enter-VsDevShell -VsInstallPath $vsPath -SkipAutomaticLocation -DevCmdArguments
"-arch=x64 -host_arch=x64 -winsdk=10.0.19041.0"

$Env:PATH += ";$pwd\\build\\lib\\api"
cd build
ctest --output-on-failure
cd -
```

Build WasmEdge for Android

The WasmEdge Runtime releases come with pre-built binaries for the Android OS. Why WasmEdge on Android?

- Native speed & sandbox safety for Android apps
- Support multiple dev languages — eg C, Rust, Swift, Go & JS
- Embed 3rd party functions in your android app
- Kubernetes managed android apps

However, the WasmEdge installer does not support Android. The user must download the release files to a computer, and then use the `adb` tool to transfer the files to an Android device or simulator. We will show you how to do that.

- WasmEdge CLI tools for Android
- Call WasmEdge functions from an NDK native app
- Call WasmEdge functions from an Android APK app

Build from source for Android platforms

Please follow this guide to build and test WasmEdge from source code with Android NDK.

In current state, we only support the runtime for the interpreter mode.

Prepare the Environment

We recommend developers to use our Docker images and follow the steps to prepare the building environment.

- Download and extract the Android NDK 23b.
- Check the cmake for CMake 3.21 or greater version.
- Download and install the ADB platform tools.
    - If you use the debian or ubuntu Linux distributions, you can install the ADB platform tools via `apt`.
- An Android device which is enabled developer options and USB debugging and with at least Android 6.0 or higher system version.

Build WasmEdge for Android platforms

Get the WasmEdge source code.

```
git clone https://github.com/WasmEdge/WasmEdge.git
cd WasmEdge
```

Add the Android NDK path into the environment variable.

```
export ANDROID_NDK_HOME=path/to/you/ndk/dir
```

Run the build script in WasmEdge source code. This script will automatically build the WasmEdge for Android, and the results are in the `build` folder.

```
./utils/android/standalone/build_for_android.sh
```

Test the WasmEdge CLI on Android platforms

Push the WasmEdge CLI and related test data onto Android platforms

1. Connect the device by using a USB cable or Wi-Fi. Then you can check the attached devices via the `adb devices` command.

   ```
   $ adb devices
   List of devices attached
   0a388e93      device
   ```

2. Use the `adb push` command to push the entire `build/tools/wasmedge` folder into the `/data/local/tmp` folder on your Android device.

   ```
   cp -r examples build/tools/wasmedge/examples
   cd build
   adb push ./tools/wasmedge /data/local/tmp
   ```

Run WasmEdge CLI on Android platforms

1. Please use the `adb shell` command to access into the Android device.
2. Follow the steps to test the WasmEdge CLI on the Android device.

```
$ cd /data/local/tmp/wasmedge/examples
$ ../wasmedge hello.wasm 1 2 3
hello
1
2
3

$ ../wasmedge --reactor add.wasm add 2 2
4

$ ../wasmedge --reactor fibonacci.wasm fib 8
34

$ ../wasmedge --reactor factorial.wasm fac 12
479001600

$ cd js
$ ./../wasmedge --dir .:. qjs.wasm hello.js 1 2 3
Hello 1 2 3
```

Notice

- For the Android 10 or greater versions, SELinux will disallow the untrusted applications' `exec()` system call to execute the binaries in `home` or `/data/local/tmp` folder.
- The Android SELinux policy will disallow the untrusted applications to access the `/data/local/tmp` folder.

WasmEdge CLI tools for Android

In this section, we will show you how to use WasmEdge CLI tools on Android devices. We will showcase a full WasmEdge demo to perform image classification (Tensorflow-based AI inference) on an Android device.

Install Android version of WasmEdge-TensorFlow-Tools

First, install WasmEdge-TensorFlow-Tools pre-release on your Android device. It works with the Android version of TensorFlow-Lite dynamic shared library.

Preparation

Android developer options

Currently, WasmEdge only supports the arm64-v8a architecture on Android devices. You need an arm64-v8a Android simulator or a physical device with developer options turned on. WasmEdge requires Android 6.0 and above.

Android development CLI

In Ubuntu Linux, you can use the `apt-get` command to install Android debugging and testing tool `adb`. Using the `adb shell` command on the Ubuntu dev machine, you can open a CLI shell to execute commands on the connected Android device.

```
$ sudo apt-get install adb
$ adb devices
* daemon not running; starting now at tcp:5037
* daemon started successfully
List of devices attached
c657c643 device
$ adb shell
sirius:/ $
```

Install WasmEdge-TensorFlow-Tools packages

Use the following commands on your Ubuntu dev machine to download the WasmEdge-

TensorFlow-Tools pre-release packages.

```
$ wget https://github.com/second-state/WasmEdge-tensorflow-tools/releases
/download/0.11.2/WasmEdge-tensorflow-tools-0.11.2-android_aarch64.tar.gz
$ mkdir WasmEdge-tensorflow-tools && tar zxvf WasmEdge-tensorflow-tools-0.11.2-
android_aarch64.tar.gz -C WasmEdge-tensorflow-tools
show-tflite-tensor
wasmedge-tensorflow-lite
```

Install Android version of the TensorFlow-Lite shared library

We provide an Android compatible version of TensorFlow-Lite dynamic shared library in the WasmEdge-Tensorflow-deps package. Download the package to your Ubuntu dev machine as follows.

```
$ wget https://github.com/second-state/WasmEdge-tensorflow-deps/releases
/download/0.11.2/WasmEdge-tensorflow-deps-TFLite-0.11.2-android_aarch64.tar.gz
$ tar zxvf WasmEdge-tensorflow-deps-TFLite-0.11.2-android_aarch64.tar.gz -C
WasmEdge-tensorflow-tools
libtensorflowlite_c.so
```

Next use the `adb` tool to push the downloaded WasmEdge-TensorFlow packages onto a connected Android device.

```
adb push WasmEdge-tensorflow-tools /data/local/tmp
```

Try it out

Sample application

In this example, we will demonstrate a standard WasmEdge Tensorflow-Lite sample application. It can recognize and classify the bird type from a JPG or PNG picture of a bird. The explanation of the source code can be found here.

```
git clone https://github.com/second-state/wasm-learning.git
cd wasm-learning/rust/birds_v1
```

Use the `cargo` command to build a Wasm bytecode file from the Rust source code. The

Wasm file is located at `target/wasm32-wasi/release/birds_v1.wasm`.

```
rustup target add wasm32-wasi
cargo build --release --target=wasm32-wasi
```

Push the Wasm bytecode file, tensorflow lite model file, and the test bird picture file onto the Android device using `adb`.

```
adb push target/wasm32-wasi/release/birds_v1.wasm /data/local/tmp/WasmEdge-
tensorflow-tools
adb push lite-model_aiy_vision_classifier_birds_V1_3.tflite /data/local
/tmp/WasmEdge-tensorflow-tools
adb push bird.jpg /data/local/tmp/WasmEdge-tensorflow-tools
```

Run the WasmEdge-TensorFlow-Tools

Type `adb shell` from the Ubuntu CLI to open a command shell for the connected Android device. Confirm that the tools, programs, and test image are all available on the Android device under the `/data/local/tmp/WasmEdge-tensorflow-tools` folder.

```
$ adb shell
sirius:/ $ cd /data/local/tmp/WasmEdge-tensorflow-tools
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ ls
bird.jpg                lite-model_aiy_vision_classifier_birds_V1_3.tflite
birds_v1.wasm           show-tflite-tensor
libtensorflowlite_c.so wasmedge-tensorflow-lite
```

Load the TensorFlow-Lite dynamic shared library, and use the `show-tflite-tensor` CLI tool to examine the Tensorflow Lite model file.

```
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ export
LD_LIBRARY_PATH=.:$LD_LIBRARY_PATH
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ chmod 777 show-tflite-tensor
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ ./show-tflite-tensor lite-
model_aiy_vision_classifier_birds_V1_3.tflite
INFO: Initialized TensorFlow Lite runtime.
Input tensor nums: 1
    Input tensor name: module/hub_input/images_uint8
        dimensions: [1 , 224 , 224 , 3]
        data type: UInt8
        tensor byte size: 150528
Output tensor nums: 1
    Output tensor name: module/prediction
        dimensions: [1 , 965]
        data type: UInt8
        tensor byte size: 965
```

Use the extended WasmEdge Runtime in `wasmedge-tensorflow-lite` to execute the compiled Wasm program on the Android device. It loads the Tensorflow Lite model and bird image, and outputs the bird classification and its confidence.

```
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ chmod 777 wasmedge-
tensorflow-lite
sirius:/data/local/tmp/WasmEdge-tensorflow-tools $ ./wasmedge-tensorflow-lite
--dir .:. birds_v1.wasm lite-model_aiy_vision_classifier_birds_V1_3.tflite
bird.jpg
INFO: Initialized TensorFlow Lite runtime.
166 : 0.84705883
```

The result shows that the bird type is in line 166 of the label file (Sicalis flaveola) and the confidence level is 84.7%.

Call WasmEdge functions from an NDK native app

In this section, we will demonstrate how to build an Android native application using C and the Android SDK. The native application uses the WasmEdge C SDK to embed the WasmEdge Runtime, and call WASM functions through WasmEdge.

Prerequisite

Android

Currently, WasmEdge only supports the arm64-v8a architecture on Android devices. You need an arm64-v8a Android simulator or a physical device with developer options turned on. WasmEdge requires Android 6.0 and above.

Android development CLI

In Ubuntu Linux, you can use the `apt-get` command to install Android debugging and testing tool `adb`. Using the `adb shell` command on the Ubuntu dev machine, you can open a CLI shell to execute commands on the connected Android device.

```
sudo apt-get install adb
```

Android NDK

To compile programs with the wasmedge-tensorflow c api, you need to install the Android NDK. In this example, we use the latest LTS version (r23b).

Review of source code

The `test.c` uses the wasmedge-tensorflow c api to run a WebAssembly function. The WebAssembly file `birds_v1.wasm` is compiled from Rust source code and explained here.

```
#include <wasmedge/wasmedge.h>
#include <wasmedge/wasmedge-image.h>
#include <wasmedge/wasmedge-tensorflowlite.h>

#include <stdio.h>

int main(int argc, char *argv[]) {
  /*
   * argv[0]: ./a.out
   * argv[1]: WASM file
   * argv[2]: tflite model file
   * argv[3]: image file
   * Usage: ./a.out birds_v1.wasm lite-
model_aiy_vision_classifier_birds_V1_3.tflite bird.jpg
   */

  /* Create the VM context. */
  WasmEdge_ConfigureContext *ConfCxt = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(ConfCxt,
WasmEdge_HostRegistration_Wasi);
  WasmEdge_VMContext *VMCxt = WasmEdge_VMCreate(ConfCxt, NULL);
  WasmEdge_ConfigureDelete(ConfCxt);

  /* Create the image and TFLite import objects. */
  WasmEdge_ModuleInstanceContext *ImageImpObj =
WasmEdge_Image_ModuleInstanceCreate();
  WasmEdge_ModuleInstanceContext *TFLiteImpObj =
WasmEdge_TensorflowLite_ModuleInstanceCreate();
  WasmEdge_ModuleInstanceContext *TFDummyImpObj =
WasmEdge_Tensorflow_ModuleInstanceCreateDummy();

  /* Register into VM. */
  WasmEdge_VMRegisterModuleFromImport(VMCxt, ImageImpObj);
  WasmEdge_VMRegisterModuleFromImport(VMCxt, TFLiteImpObj);
  WasmEdge_VMRegisterModuleFromImport(VMCxt, TFDummyImpObj);

  /* Init WASI. */
  const char *Preopens[] = {".:."};
  const char *Args[] = {argv[1], argv[2], argv[3]};
  WasmEdge_ModuleInstanceContext *WASIImpObj =
WasmEdge_VMGetImportModuleContext(VMCxt, WasmEdge_HostRegistration_Wasi);
  WasmEdge_ModuleInstanceInitWASI(WASIImpObj, Args, 3, NULL, 0, Preopens, 1);

  /* Run WASM file. */
  WasmEdge_String FuncName = WasmEdge_StringCreateByCString("_start");
  WasmEdge_Result Res = WasmEdge_VMRunWasmFromFile(VMCxt, argv[1], FuncName,
NULL, 0, NULL, 0);
  WasmEdge_StringDelete(FuncName);

  /* Check the result. */
  if (!WasmEdge_ResultOK(Res)) {
    printf("Run WASM failed: %s\n", WasmEdge_ResultGetMessage(Res));
```

```
    return -1;
  }

  WasmEdge_ModuleInstanceDelete(ImageImpObj);
  WasmEdge_ModuleInstanceDelete(TFLiteImpObj);
  WasmEdge_ModuleInstanceDelete(TFDummyImpObj);
  WasmEdge_VMDelete(VMCxt);
  return 0;
}
```

Build

Install dependencies

Use the following commands to download WasmEdge for Android on your Ubuntu dev machine.

```
wget https://github.com/WasmEdge/WasmEdge/releases/download/0.11.2/WasmEdge-0.11.2-android_aarch64.tar.gz
wget https://github.com/second-state/WasmEdge-image/releases/download/0.11.2/WasmEdge-image-0.11.2-android_aarch64.tar.gz
wget https://github.com/second-state/WasmEdge-tensorflow/releases/download/0.11.2/WasmEdge-tensorflowlite-0.11.2-android_aarch64.tar.gz
wget https://github.com/second-state/WasmEdge-tensorflow-deps/releases/download/0.11.2/WasmEdge-tensorflow-deps-TFLite-0.11.2-android_aarch64.tar.gz
tar -zxf WasmEdge-0.11.2-android_aarch64.tar.gz
tar -zxf WasmEdge-image-0.11.2-android_aarch64.tar.gz -C WasmEdge-0.11.2-Android/
tar -zxf WasmEdge-tensorflowlite-0.11.2-android_aarch64.tar.gz -C WasmEdge-0.11.2-Android/
tar -zxf WasmEdge-tensorflow-deps-TFLite-0.11.2-android_aarch64.tar.gz -C WasmEdge-0.11.2-Android/lib/
```

Compile

The following command compiles the C program to `a.out` on your Ubunu dev machine.

```
(/path/to/ndk)/toolchains/llvm/prebuilt/(HostPlatform)/bin/aarch64-linux-(AndroidApiVersion)-clang test.c -I./WasmEdge-0.11.2-Android/include -L./WasmEdge-0.11.2-Android/lib -lwasmedge-image_c -lwasmedge-tensorflowlite_c -ltensorflowlite_c -lwasmedge
```

Run

Push files onto Android

Install the compiled program, Tensorflow Lite model file, test image file, as well as WasmEdge shared library files for Android, onto the Android device using `adb` from your Ubuntu dev machine.

```
adb push a.out /data/local/tmp
adb push birds_v1.wasm /data/local/tmp
adb push lite-model_aiy_vision_classifier_birds_V1_3.tflite /data/local/tmp
adb push bird.jpg /data/local/tmp
adb push ./WasmEdge-0.11.2-Android/lib /data/local/tmp
```

Run the example

Now you can run the compiled C program on the Android device via a remote shell command. Run `adb shell` from your Ubuntu dev machine.

```
$ adb shell
sirius:/ $ cd /data/local/tmp
sirius:/data/local/tmp $ export LD_LIBRARY_PATH=/data/local
/tmp/lib:$LD_LIBRARY_PATH
sirius:/data/local/tmp $ ./a.out birds_v1.wasm lite-
model_aiy_vision_classifier_birds_V1_3.tflite bird.jpg
INFO: Initialized TensorFlow Lite runtime.
166 : 0.84705883
```

Call WasmEdge functions from an Android APK app

In this section, we will show you how to build a "regular" Android app (i.e., an APK file that can be installed on an Android device). The APK app embeds a WasmEdge Runtime. It can call WebAssembly functions through the embedded WasmEdge. The benefit is that developers can safely embed high-performance functions written in several different languages (e.g., Rust, JS, Grain, TinyGo etc) into a Kotlin application.

Quickstart

The demo project is available here. You can build the project using the Gradle tool or using the Android Studio IDE.

Building Project with Gradle

1. Setup environment variable `ANDROID_HOME=path/to/your/android/sdk`
2. Run Command `./gradlew assembleRelease`
3. Sign your APK file with `apksigner`. The apk file is at `./app/build/outputs/apk/release`. The `apksigner` utility is at `$ANDROID_HOME/build-tools/$VERSION/apksigner`.

Building Project with Android Studio

Open this folder with Android Studio 2020.3.1 or later.

For Release APK, click `Menu -> Build -> Generate Signed Bundle/APK`, select APK, setup keystore configuration and wait for build finished.

Review of the source code

The Android UI app is written in Kotlin, and it uses JNI (Java Native Interface) to load a C shared library, which in turn embeds WasmEdge.

Android UI

The Android UI application is located here. It is written in Kotlin using the Android SDK.

```
class MainActivity : AppCompatActivity() {
  lateinit var lib: NativeLib

  override fun onCreate(savedInstanceState: Bundle?) {
    super.onCreate(savedInstanceState)
    setContentView(R.layout.activity_main)

    val tv = findViewById<TextView>(R.id.tv_text)

    lib = NativeLib(this)

    Thread {
      val lines = Vector<String>()
      val idxArr = arrayOf(20, 25, 28, 30, 32)
      for (idx: Int in idxArr) {
        lines.add("running fib(${idx}) ...")
        runOnUiThread {
          tv.text = lines.joinToString("\n")
        }
        val begin = System.currentTimeMillis()
        val retVal = lib.wasmFibonacci(idx)
        val end = System.currentTimeMillis()
        lines.removeLast()
        lines.add("fib(${idx}) -> ${retVal}, ${end - begin}ms")
        runOnUiThread {
          tv.text = lines.joinToString("\n")
        }
      }
    }.start()
  }
}
```

The native library

The Android UI app calls a `NativeLib` Kotlin object to access WasmEdge functions. The `NativeLib` source code is available here. It uses JNI (Java Native Interface) to load a C shared library called `wasmedge_lib`. It then calls the `nativeWasmFibonacci` function in `wasmedge_lib` to execute the `fibonacci.wasm` WebAssembly bytecode.

```
class NativeLib(ctx : Context) {
  private external fun nativeWasmFibonacci(imageBytes : ByteArray, idx : Int )
: Int

  companion object {
    init {
      System.loadLibrary("wasmedge_lib")
    }
  }

  private var fibonacciWasmImageBytes : ByteArray =
ctx.assets.open("fibonacci.wasm").readBytes()

  fun wasmFibonacci(idx : Int) : Int{
    return nativeWasmFibonacci(fibonacciWasmImageBytes, idx)
  }
}
```

The C shared library

The C shared library source code `wasmedge_lib.cpp` is available here. It uses the WasmEdge C SDK to embed a WasmEdge VM and execute the WebAssembly function.

```
extern "C" JNIEXPORT jint JNICALL
Java_org_wasmedge_native_1lib_NativeLib_nativeWasmFibonacci(
    JNIEnv *env, jobject, jbyteArray image_bytes, jint idx) {
  jsize buffer_size = env->GetArrayLength(image_bytes);
  jbyte *buffer = env->GetByteArrayElements(image_bytes, nullptr);

  WasmEdge_ConfigureContext *conf = WasmEdge_ConfigureCreate();
  WasmEdge_ConfigureAddHostRegistration(conf, WasmEdge_HostRegistration_Wasi);

  WasmEdge_VMContext *vm_ctx = WasmEdge_VMCreate(conf, nullptr);

  const WasmEdge_String &func_name = WasmEdge_StringCreateByCString("fib");
  std::array<WasmEdge_Value, 1> params{WasmEdge_ValueGenI32(idx)};
  std::array<WasmEdge_Value, 1> ret_val{};

  const WasmEdge_Result &res = WasmEdge_VMRunWasmFromBuffer(
      vm_ctx, (uint8_t *)buffer, buffer_size, func_name, params.data(),
      params.size(), ret_val.data(), ret_val.size());

  WasmEdge_VMDelete(vm_ctx);
  WasmEdge_ConfigureDelete(conf);
  WasmEdge_StringDelete(func_name);

  env->ReleaseByteArrayElements(image_bytes, buffer, 0);
  if (!WasmEdge_ResultOK(res)) {
    return -1;
  }
  return WasmEdge_ValueGetI32(ret_val[0]);
}
```

The WebAssembly function

The `factorial.wat` is a handwritten WebAssembly script to compute factorial numbers. It is compiled into WebAssembly using the WABT tool.

Build dependencies

Android Studio and Gradle use CMake to build the C shared library. The CMakeLists.txt file builds the WasmEdge source into Android shared library files and embeds them into the final APK application. In this case, there is no separate step to install WasmEdge share libraries onto the Android device.

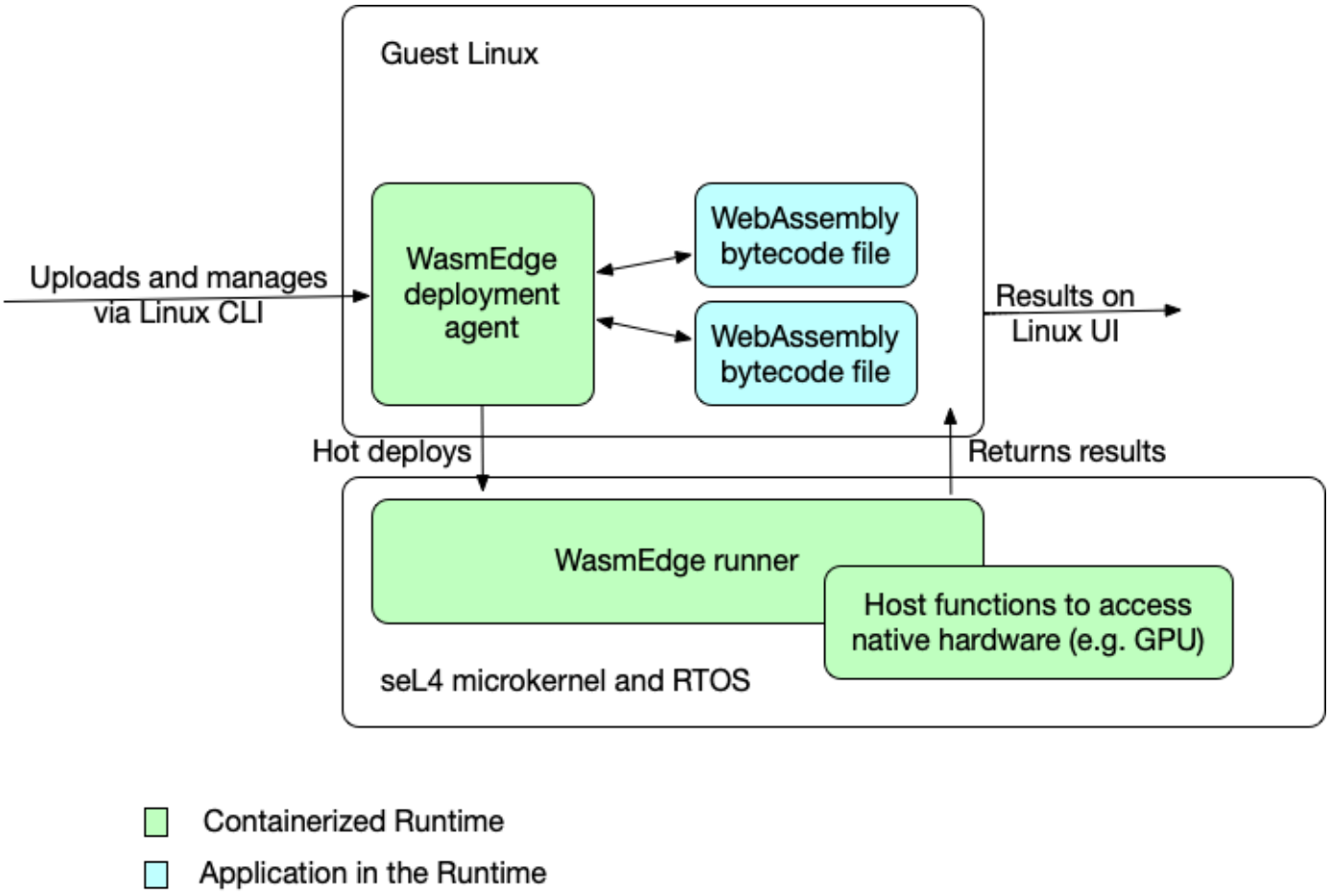
Build WasmEdge for seL4

Video demo | Build logs | Build artifact

In this article, we demonstrate how to run WasmEdge on the seL4 RTOS, there are two parts:

1. Guest Linux OS on seL4: This is the controller of WasmEdge runtime, which will send wasm program to WasmEdge runner that is a agent on seL4 to execute.
2. WasmEdge runner on seL4: This is the wasm program runtime, which will execute the given wasm program from Guest Linux OS.

The figure below illustrates the architecture of the system.



This demo is based on the seL4 simulator on Linux.

Getting Started

System requirements

Hardware:

- at least 4GB of RAM
- at least 20GB of disk storage (the wasmedge_sel4 directory will contain over 11 GB of data after the following installation completes)

Software: Ubuntu 20.04 with dev tools packages (ep. Python) installed. We recommend the GitHub Actions Ubuntu 20.04 VM (See a list of installed apt packages). Or, you could use our Docker image (see the Dockerfile).

```
$ docker pull wasmedge/sel4_build
$ docker run --rm -v $(pwd):/app -it wasmedge/sel4_build
(docker) root#
```

> If you do not want to build the seL4 system simulator yourself, you can download the build artifact from our GitHub Actions, and skip directly to Boot wasmedge-seL4

Automatic installation: all-in-one script

Use our all-in-one build script:

```
wget -qO- https://raw.githubusercontent.com/second-state/wasmedge-seL4/main
/build.sh | bash
```

And this will clone and build our wasmedge on seL4 to an image.

After finishing the build script, you will have a folder `sel4_wasmedge` .

If this automatic installation completed successfully, skip over the manual installation information and proceed to boot wasmedge-sel4

Manual installation: managing memory usage

The above all-in-one script will work in most cases. However, if your system resources were stressed and you encountered an error such as `ninja: build stopped: subcommand failed` please note that you can decrease the parallelization of the install by explicitly passing in a `-j` parameter to the `ninja` command (on the last line of the `build.sh` file).

You see, Ninja runs the most amount of parallel processes by default and so the following procedure is a way to explicitly set/reduce parallelization.

Manually fetch the `wasmedge-sel4 repository.

```
cd ~
git clone https://github.com/second-state/wasmedge-seL4.git
cd wasmedge-seL4
```

Manually edit the `build.sh` file.

```
vi build.sh
```

Add the following `-j` parameter to the last line of the file i.e.

```
ninja -j 2
```

Make the `build.sh` file executable.

```
sudo chmod a+x build.sh
```

Run the edited `build.sh file.

```
./build.sh
```

Once this manual installation is complete, follow along with the following steps; boot wasmedge-sel4

Boot wasmedge-seL4

```
cd sel4_wasmedge/build
./simulate
```

Expected output:

```
$ ./simulate: qemu-system-aarch64 -machine
virt,virtualization=on,highmem=off,secure=off -cpu cortex-a53 -nographic  -m
size=2048  -kernel images/capdl-loader-image-arm-qemu-arm-virt
ELF-loader started on CPU: ARM Ltd. Cortex-A53 r0p4
  paddr=[6abd8000..750cf0af]
No DTB passed in from boot loader.
Looking for DTB in CPIO archive...found at 6ad18f58.
Loaded DTB from 6ad18f58.
   paddr=[60243000..60244fff]
ELF-loading image 'kernel' to 60000000
  paddr=[60000000..60242fff]
  vaddr=[ff8060000000..ff8060242fff]
  virt_entry=ff8060000000
ELF-loading image 'capdl-loader' to 60245000
  paddr=[60245000..6a7ddfff]
  vaddr=[400000..a998fff]
  virt_entry=408f38
Enabling hypervisor MMU and paging
Jumping to kernel-image entry point...

Bootstrapping kernel
Warning: Could not infer GIC interrupt target ID, assuming 0.
Booting all finished, dropped to user space
<<seL4(CPU 0) [decodeUntypedInvocation/205 T0xff80bf85d400 "rootserver"
@4006f8]: Untyped Retype: Insufficient memory (1 * 2097152 bytes needed, 0
bytes available).>>
Loading Linux: 'linux' dtb: 'linux-dtb'

...(omitted)...

Starting syslogd: OK
Starting klogd: OK
Running sysctl: OK
Initializing random number generator... [    3.512482] random: dd:
uninitialized urandom read (512 bytes read)
done.
Starting network: OK
[    4.086059] connection: loading out-of-tree module taints kernel.
[    4.114686] Event Bar (dev-0) initialised
[    4.123771] 2 Dataports (dev-0) initialised
[    4.130626] Event Bar (dev-1) initialised
[    4.136096] 2 Dataports (dev-1) initialised

Welcome to Buildroot
buildroot login:
```

Login on guest linux

Enter `root` to login

```
buildroot login: root
```

Expected output:

```
buildroot login: root
#
```

Execute wasm examples

Example A: nbody-c.wasm

Run nbody simulation.

```
wasmedge_emit /usr/bin/nbody-c.wasm 10
```

Expected output:

```
[1900-01-00 00:00:00.000] [info] executing wasm file
-0.169075164
-0.169073022
[1900-01-00 00:00:00.000] [info] execution success, exit code:0
```

Example B: hello.wasm

Run an easy application to print `hello, sel4` and a simple calculation.

```
wasmedge_emit /usr/bin/hello.wasm
```

Expected output:

```
[1900-01-00 00:00:00.000] [info] executing wasm file
hello, sel4
1+2-3*4 = -9
[1900-01-00 00:00:00.000] [info] execution success, exit code:0
```

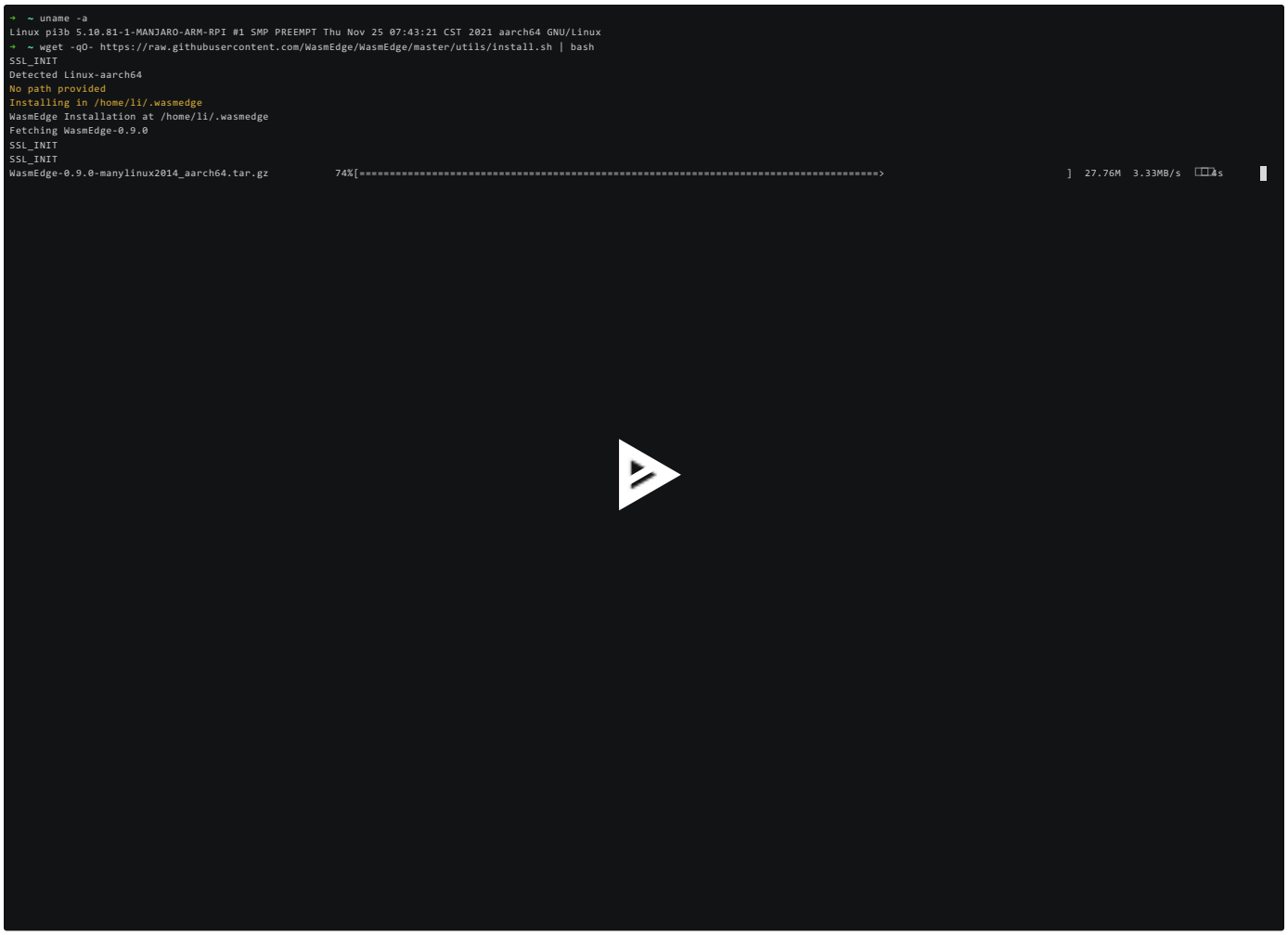
Build WasmEdge for Open Harmony

WIP. For Chinese speakers, please check out this instruction.

Build WasmEdge for Raspberry Pi 3/4

Raspberry Pi uses 64-bit processors starting from the 3 Model B. So WasmEdge can be executed on Raspberry Pi as well. You can choose any 64-bit Linux distribution, such as Raspbian, Ubuntu or Manjaro for ARM. This document has been tested on the Manjaro for ARM distribution and the hardware is the Raspberry Pi 3 Model B.

The installation steps are no different from the installation document, and the execution is the same. Here's a video about installing WasmEdge and running a simple WebAssembly module to add two numbers up.



Build and test WasmEdge for OpenWrt

Please follow this tutorial to build and test WasmEdge in OpenWrt(x86_64) from source code.

Currently, we only support the runtime for the interpreter mode.

Prepare the Environment

OpenWrt

First, we need to obtain the source code of OpenWrt and install the relevant tools to compile OpenWrt. The following commands take Debian / Ubuntu system as an example. For commands to install OpenWrt compilation tools in other host systems, see Building OpenWrt System Settings.

```
$ git clone https://github.com/openwrt/openwrt
$ sudo apt update
$ sudo apt install build-essential ccache ecj fastjar file g++ gawk \
gettext git java-propose-classpath libelf-dev libncurses5-dev \
libncursesw5-dev libssl-dev python python2.7-dev python3 unzip wget \
python-distutils-extra python3-setuptools python3-dev rsync subversion \
swig time xsltproc zlib1g-dev
```

Then, obtain all the latest package definitions of OpenWrt and install the symlinks for all obtained packages.

```
cd openwrt
./scripts/feeds update -a
./scripts/feeds install -a
```

Build WasmEdge

Get WasmEdge source code

```
git clone https://github.com/WasmEdge/WasmEdge.git
cd WasmEdge
```

Run the build script

Run the build script `build_for_openwrt.sh` in WasmEdge source code, and input the path of the OpenWrt source code as parameter. This script will automatically add the WasmEdge into the packages list which will be built of OpenWrt, and build the OpenWrt firmware. The generated OpenWrt images are in the `openwrt/bin/targets/x86/64` folder.

```
./utils/openwrt/build_for_openwrt.sh ~/openwrt
```

When running the build script, the OpenWrt configuration interface will appear. In this interface, we need to set `Target System` to x86, `Target Profile` to Generic x86/64, and find `WasmEdge` in the `Runtime` column and check it . Once set up, the script automatically builds WasmEdge and compiles the OpenWrt system.

Test

Deploy OpenWrt in VMware

In order to verify the availability of WasmEdge, we use a VMware virtual machine to install the compiled OpenWrt image. Before creating a virtual machine, we need to use the `QEMU` command to convert the OpenWrt image to vmdk format.

```
cd ~/openwrt/bin/targets/x86/64
sudo apt install qemu
gunzip openwrt-x86-64-generic-squashfs-combined.img.gz
qemu-img convert -f raw -O vmdk openwrt-x86-64-generic-squashfs-combined.img
Openwrt.vmdk
```

After that, create a virtual machine in VMware and install the OpenWrt system.

upload the test files

After setting the IP address of OpenWrt according to the gateway of the host, use `scp` to

transfer the wasm file on the host to the OpenWrt system.

For example, we set the ip address of OpenWrt as 192.168.0.111, then we use the following commands to upload hello.wasm and add.wasm these two test files to OpenWrt.

```
scp hello.wasm root@192.168.0.111:/
scp add.wasm root@192.168.0.111:/
```

Test the wasmedge program

```
$ wasmedge hello.wasm second state
hello
second
state
$ wasmedge --reactor add.wasm add 2 2
4
```

Build WasmEdge With WASI-NN Plug-in

Prerequisites

Currently, WasmEdge used OpenVINO™ or PyTorch as the WASI-NN backend implementation. For using WASI-NN on WasmEdge, you need to install OpenVINO™(2021) or PyTorch 1.8.2 LTS for the backend.

By default, we don't enable any WASI-NN backend in WasmEdge. Therefore developers should build the WasmEdge from source with the cmake option `WASMEDGE_PLUGIN_WASI_NN_BACKEND` to enable the backends.

Build WasmEdge with WASI-NN OpenVINO Backend

For choosing and installing OpenVINO™ on `Ubuntu 20.04` for the backend, we recommend the following commands:

```
export OPENVINO_VERSION="2021.4.582"
export OPENVINO_YEAR="2021"
curl -sSL https://apt.repos.intel.com/openvino/$OPENVINO_YEAR/GPG-PUB-KEY-
INTEL-OPENVINO-$OPENVINO_YEAR | sudo gpg --dearmor > /usr/share/keyrings/GPG-
PUB-KEY-INTEL-OPENVINO-$OPENVINO_YEAR.gpg
echo "deb [signed-by=/usr/share/keyrings/GPG-PUB-KEY-INTEL-
OPENVINO-$OPENVINO_YEAR.gpg] https://apt.repos.intel.com/openvino
/$OPENVINO_YEAR all main" | sudo tee /etc/apt/sources.list.d/intel-
openvino-$OPENVINO_YEAR.list
sudo apt update
sudo apt install -y intel-openvino-runtime-ubuntu20-$OPENVINO_VERSION
source /opt/intel/openvino_2021/bin/setupvars.sh
ldconfig
```

Then build and install WasmEdge from source:

```
cd <path/to/your/wasmedge/source/folder>
mkdir -p build && cd build
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_PLUGIN_WASI_NN_BACKEND="OpenVINO"
.. && make -j
# For the WASI-NN plugin, you should install this project.
cmake --install .
```

If the built `wasmedge` CLI tool cannot find the WASI-NN plug-in, you can set the `WASMEDGE_PLUGIN_PATH` environment variable to the plug-in installation path (`/usr/local/lib/wasmedge/` , or the built plug-in path `build/plugins/wasi_nn/`) to try to fix this issue.

Then you will have an executable `wasmedge` runtime under `/usr/local/bin` and the WASI-NN with OpenVINO backend plug-in under `/usr/local/lib/wasmedge /libwasmedgePluginWasiNN.so` after installation.

Build WasmEdge with WASI-NN PyTorch Backend

For choosing and installing PyTorch on `Ubuntu 20.04` for the backend, we recommend the following commands:

```
export PYTORCH_VERSION="1.8.2"
curl -s -L -O --remote-name-all https://download.pytorch.org/libtorch/lts/1.8
/cpu/libtorch-cxx11-abi-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip
unzip -q "libtorch-cxx11-abi-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
rm -f "libtorch-cxx11-abi-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
export LD_LIBRARY_PATH=$(pwd)/libtorch/lib:${LD_LIBRARY_PATH}
export Torch_DIR=$(pwd)/libtorch
```

For the legacy operating system such as `CentOS 7.6` , please use the `pre-cxx11-abi` version of `libtorch` instead:

```
export PYTORCH_VERSION="1.8.2"
curl -s -L -O --remote-name-all https://download.pytorch.org/libtorch/lts/1.8
/cpu/libtorch-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip
unzip -q "libtorch-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
rm -f "libtorch-shared-with-deps-${PYTORCH_VERSION}%2Bcpu.zip"
export LD_LIBRARY_PATH=$(pwd)/libtorch/lib:${LD_LIBRARY_PATH}
export Torch_DIR=$(pwd)/libtorch
```

The PyTorch library will be extracted in the current directory `./libtorch` .

Then build and install WasmEdge from source:

```
cd <path/to/your/wasmedge/source/folder>
mkdir -p build && cd build
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_PLUGIN_WASI_NN_BACKEND="PyTorch" ..
&& make -j
# For the WASI-NN plugin, you should install this project.
cmake --install .
```

If the built `wasmedge` CLI tool cannot find the WASI-NN plug-in, you can set the `WASMEDGE_PLUGIN_PATH` environment variable to the plug-in installation path (`/usr/local/lib/wasmedge/` , or the built plug-in path `build/plugins/wasi_nn/`) to try to fix this issue.

Then you will have an executable `wasmedge` runtime under `/usr/local/bin` and the WASI-NN with OpenVINO backend plug-in under `/usr/local/lib/wasmedge /libwasmedgePluginWasiNN.so` after installation.

Build WasmEdge with WASI-NN TensorFlow-Lite Backend

You can build and install WasmEdge from source directly:

```
cd <path/to/your/wasmedge/source/folder>
mkdir -p build && cd build
cmake -DCMAKE_BUILD_TYPE=Release
-DWASMEDGE_PLUGIN_WASI_NN_BACKEND="TensorflowLite" .. && make -j
# For the WASI-NN plugin, you should install this project.
cmake --install .
```

If the built `wasmedge` CLI tool cannot find the WASI-NN plug-in, you can set the `WASMEDGE_PLUGIN_PATH` environment variable to the plug-in installation path (`/usr/local/lib/wasmedge/` , or the built plug-in path `build/plugins/wasi_nn/`) to try to fix this issue.

Then you will have an executable `wasmedge` runtime under `/usr/local/bin` and the WASI-NN with OpenVINO backend plug-in under `/usr/local/lib/wasmedge /libwasmedgePluginWasiNN.so` after installation.

Installing the necessary `libtensorflowlite_c.so` on both `Ubuntu 20.04` and `manylinux2014` for the backend, we recommend the following commands:

```
curl -s -L -O --remote-name-all https://github.com/second-state/WasmEdge-tensorflow-deps/releases/download/0.11.2/WasmEdge-tensorflow-deps-TFLite-0.11.2-manylinux2014_x86_64.tar.gz
tar -zxf WasmEdge-tensorflow-deps-TFLite-0.11.2-manylinux2014_x86_64.tar.gz
rm -f WasmEdge-tensorflow-deps-TFLite-0.11.2-manylinux2014_x86_64.tar.gz
```

The shared library will be extracted in the current directory `./libtensorflowlite_c.so`.

Then you can move the library to the installation path:

```
mv libtensorflowlite_c.so /usr/local/lib
```

Or set the environment variable `export LD_LIBRARY_PATH=$(pwd):${LD_LIBRARY_PATH}`.

> We also provided the `MacOS` and `manylinux_aarch64` version of the TensorFlow-Lite pre-built shared library.

Build WasmEdge With WASI-Crypto Plug-in

Prerequisites

Currently, WasmEdge used `OpenSSL 1.1` or `3.0` for the WASI-Crypto implementation.

For installing `OpenSSL 1.1` development package on `Ubuntu 20.04`, we recommend the following commands:

```
sudo apt update
sudo apt install -y libssl-dev
```

For legacy systems such as `CensOS 7.6`, or if you want to build `OpenSSL 1.1` from source, you can refer to the following commands:

```
# Download and extract the OpenSSL source to the current directory.
curl -s -L -O --remote-name-all https://www.openssl.org/source/openssl-
1.1.1n.tar.gz
echo "40dceb51a4f6a5275bde0e6bf20ef4b91bfc32ed57c0552e2e8e15463372b17a openssl-
1.1.1n.tar.gz" | sha256sum -c
tar -xf openssl-1.1.1n.tar.gz
cd ./openssl-1.1.1n
# OpenSSL configure need newer perl.
curl -s -L -O --remote-name-all https://www.cpan.org/src/5.0/perl-5.34.0.tar.gz
tar -xf perl-5.34.0.tar.gz
cd perl-5.34.0
mkdir localperl
./Configure -des -Dprefix=$(pwd)/localperl/
make -j
make install
export PATH="$(pwd)/localperl/bin/:$PATH"
cd ..
# Configure by previous perl.
mkdir openssl
./perl-5.34.0/localperl/bin/perl ./config --prefix=$(pwd)/openssl
--openssldir=$(pwd)/openssl
make -j
make test
make install
cd ..
# The OpenSSL installation directory is at `$(pwd)/openssl-1.1.1n/openssl`.
# Then you can use the `-DOPENSSL_ROOT_DIR=` option of cmake to assign the
directory.
```

> We'll soon update this chapter to use `OpenSSL 3.0`.

Build WasmEdge with WASI-Crypto Plug-in

To enable the WasmEdge WASI-Crypto, developers need to building the WasmEdge from source with the cmake option `-DWASMEDGE_PLUGIN_WASI_CRYPTO=ON`.

```
cd <path/to/your/wasmedge/source/folder>
mkdir -p build && cd build
# For using self-get OpenSSL, you can assign the cmake option
`-DOPENSSL_ROOT_DIR=<path/to/openssl>`.
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_PLUGIN_WASI_CRYPTO=On .. && make -j
# For the WASI-Crypto plugin, you should install this project.
cmake --install .
```

> If the built `wasmedge` CLI tool cannot find the WASI-Crypto plug-in, you can set the `WASMEDGE_PLUGIN_PATH` environment variable to the plug-in installation path (`/usr/local/lib/wasmedge/`, or the built plug-in path `build/plugins/wasi_crypto/`) to try to fix this issue.

Then you will have an executable `wasmedge` runtime under `/usr/local/bin` and the WASI-Crypto plug-in under `/usr/local/lib/wasmedge/libwasmedgePluginWasiCrypto.so` after installation.

Build WasmEdge With WasmEdge-HttpsReq Plug-in

Prerequisites

Currently, WasmEdge used `OpenSSL 1.1` or `3.0` for the the dependency of WasmEdge-HttpsReq.

For installing `OpenSSL 1.1` development package on `Ubuntu 20.04`, we recommend the following commands:

```
sudo apt update
sudo apt install -y libssl-dev
```

For legacy systems such as `CensOS 7.6`, or if you want to build `OpenSSL 1.1` from source, you can refer to the following commands:

```
# Download and extract the OpenSSL source to the current directory.
curl -s -L -O --remote-name-all https://www.openssl.org/source/openssl-
1.1.1n.tar.gz
echo "40dceb51a4f6a5275bde0e6bf20ef4b91bfc32ed57c0552e2e8e15463372b17a openssl-
1.1.1n.tar.gz" | sha256sum -c
tar -xf openssl-1.1.1n.tar.gz
cd ./openssl-1.1.1n
# OpenSSL configure need newer perl.
curl -s -L -O --remote-name-all https://www.cpan.org/src/5.0/perl-5.34.0.tar.gz
tar -xf perl-5.34.0.tar.gz
cd perl-5.34.0
mkdir localperl
./Configure -des -Dprefix=$(pwd)/localperl/
make -j
make install
export PATH="$(pwd)/localperl/bin/:$PATH"
cd ..
# Configure by previous perl.
mkdir openssl
./perl-5.34.0/localperl/bin/perl ./config --prefix=$(pwd)/openssl
--openssldir=$(pwd)/openssl
make -j
make test
make install
cd ..
# The OpenSSL installation directory is at `$(pwd)/openssl-1.1.1n/openssl`.
# Then you can use the `-DOPENSSL_ROOT_DIR=` option of cmake to assign the
directory.
```

We'll soon update this chapter to use `OpenSSL 3.0`.

Build WasmEdge with WasmEdge-HttpsReq Plug-in

To enable the WasmEdge WasmEdge-HttpsReq, developers need to building the WasmEdge from source with the cmake option `-DWASMEDGE_PLUGIN_HTTPSREQ=On`.

```
cd <path/to/your/wasmedge/source/folder>
mkdir -p build && cd build
# For using self-get OpenSSL, you can assign the cmake option
`-DOPENSSL_ROOT_DIR=<path/to/openssl>`.
cmake -DCMAKE_BUILD_TYPE=Release -DWASMEDGE_PLUGIN_HTTPSREQ=On .. && make -j
# For the WasmEdge-HttpsReq plugin, you should install this project.
cmake --install .
```

> If the built `wasmedge` CLI tool cannot find the WasmEdge-HttpsReq plug-in, you can set the `WASMEDGE_PLUGIN_PATH` environment variable to the plug-in installation path (`/usr/local/lib/wasmedge/` , or the built plug-in path `build/plugins/wasmedge_httpsreq/`) to try to fix this issue.

Then you will have an executable `wasmedge` runtime under `/usr/local/bin` and the WasmEdge-HttpsReq plug-in under `/usr/local/lib/wasmedge/libwasmedgePluginHttpsReq.so` after installation.

Installer Guide

Overview

WasmEdge installer is designed for installing the Core Tools (`wasmedge` , `wasmedgec`), the Libraries (`libwasmedge`), the Extensions(`wasmedge-tensorflow`), and the Plugins(`wasi-nn` , `wasi-crytpo`).

Dependencies

In the first version of the installer, WasmEdge provides a pure shell script implementation. However, it's not easy to maintain and is not suitable when we want to include the extensions and plugins matrix.

To reduce the cost of maintenance and improve the development performance, we decided to move forward to a brand new installer that is written in Python and is compatible with both Python 2 and 3.

To be compatible with the old one, we use the same entry point, `install.sh` .

Usage

```
curl -sSf https://raw.githubusercontent.com/WasmEdge/WasmEdge/master/utils
/install.sh | bash -s -- ${OPTIONS}
```

Roles

`install.sh`

The installer entry point.

Process

1. Check if the `git` is installed; otherwise, exit with an error `Please install git`.
2. If `PYTHON_EXECUTABLE` is given, then try to use `$PYTHON_EXECUTABLE` to execute the `install.py`. Otherwise, go to step 3.
3. If `PYTHON_EXECUTABLE` is not set, `which` command is needed to determine the python-X executable. If it is not found installer exits else it moves on to the next step.
4. Check if the `python3` is installed. If so, go to step 6. Otherwise, go to step 5.
5. Check if the `python2` is installed. If so, go to step 6. Otherwise, go to step 6.
6. Check if the `python` is installed. If so, go to step 7. Otherwise, exit with an error `Please install python or provide python path via $PYTHON_EXECUTABLE`.
7. Print the detected python version `Using Python: $PYTHON_EXECUTABLE`.
8. Download `install.py` with `curl` or `wget`. If the URL of `install.py` is unreachable due to a network issue, exit with an error `$INSTALL_PY_URL not reachable`. If the `curl` and `wget` are not available, exit with an error `curl or wget could not be found`.
9. Execute the `install.py` with all received arguments.

`install.py`

The real installer handles all stuff. It supports python2.7 (not tested on earlier versions) as well as the latest python versions python3.x.

Options

Help Msg

- Short Option: `-h`
- Full Option: `--help`
- Description: Show this help message and exit.

Verbose

- Short Option: `-D`
- Full Option: `--debug`

- Description: Enable verbosity debug

Specify the version of WasmEdge to install

- Short Option: `-v VERSION`
- Full Option: `--version VERSION`
- Description: Install the given VERSION of WasmEdge
- Available Value: VERSION `0.11.2` or other valid release versions.
- Note - In the case of supplied an invalid or nonexistent version, the installer exists with an error.

Installation path

- Short Option: `-p PATH`
- Full Option: `--path PATH`
- Description: Install WasmEdge into the given PATH. The default Path is `$HOME/.wasmedge`.
- Note - In any path other than the ones starting with `/usr` are treated as non system paths in the internals of the installer. The consequences are different directory structures for both.
- Note - If the path not exists, the folder will be created.

Uninstallation

Run uninstaller before installing

- Short Option: `-r {yes,no}`
- Full Option: `--remove-old {yes, no}`
- Description: Run the uninstaller script before installing. Default `yes`.

Use a specific version of the uninstaller

- Short Option: `-u UNINSTALL_SCRIPT_TAG`
- Full Option: `--uninstall-script-tag UNINSTALL_SCRIPT_TAG`
- Description: Use the given GitHub tag to uninstall the script

Install Extensions

- Short Option: `-e [EXTENSIONS [EXTENSIONS ...]]`
- Full Option: `--extension [EXTENSIONS [EXTENSIONS ...]]`
- Description: Install wasmedge-extension tools.
- Available Value (case sensitive): Supported Extensions `'tensorflow', 'image', 'all'`.

Tensorflow Extensions Library Version

- Full Option: `--tf-version TF_VERSION`
- Description: Install the given VERSION of the library of the Tensorflow and Tensorflow lite extension. Only available when the `Extensions` is set to `all` or `tensorflow`.
- Note - It's the same as the WasmEdge version if not specified.

Tensorflow Extensions Dependencies Version

- Full Option: `--tf-deps-version TF_DEPS_VERSION`
- Description: Install the given VERSION of the dependencies of the Tensorflow and Tensorflow lite extension. Only available when the `Extensions` is set to `all` or `tensorflow`.
- Note - It's the same as the WasmEdge version if not specified.

Tensorflow Extensions Tools Version

- Full Option: `--tf-tools-version TF_TOOLS_VERSION`
- Description: Install the given VERSION of the tools of the Tensorflow and Tensorflow lite extension. Only available when the `Extensions` is set to `all` or `tensorflow`.
- Note - It's the same as the WasmEdge version if not specified.

Image Extensions Version

- Full Option: `--image-version IMAGE_VERSION`
- Description: Install the given VERSION of the Image extension. Only available when the `Extensions` is set to `all` or `image`.
- Note - It's the same as the WasmEdge version if not specified.

Plugins

- Note - Currently `--plugins` is an experimental option.
- Full Option: `--plugins wasi_crypto:0.11.0`
- Note - The format for this argument is `<plugin_name>:<version_number>`. `<version_number>` is not compulsory. For example `--plugins wasi_crypto` is a valid option.
- Note - `<plugin_name>` is cases sensitive. Allowed values are stated here in the `Rust Crate` column. The logic is that the release name should be the same.
- Note - It's the same as the WasmEdge version if not specified.

DIST

- Full Option: `--dist ubuntu20.04` or `--dist manylinux2014`
- Note - the `ubuntu20.04` and `manylinux2014` values are case insensitive and only these two are currently supported.
- Note - Specifying `--dist` value for `Darwin` has no effect.
- Note - For `Linux` platform if the distribution matches exactly as `Ubuntu 20.04` which is checked using `lsb_release` and python's `platform.dist()` functionality then it is set to `ubuntu20.04` if not specified, else it is used without questioning. However different release packages for WasmEdge are available only after `0.11.1` release below which there is no effect of specifying this option.

Platform and OS

- Full Option: `--platform PLATFORM` or `--os OS`
- Description: Install the given `PLATFORM` or `OS` version of WasmEdge. This value should be case insensitive to make the maximum compatibility.
- Available Value (case insensitive): "Linux", "Darwin", "Windows".

Machine and Arch

- Full Option: `--machine MACHINE` or `--arch ARCH`
- Description: Install the given `MACHINE` or `ARCH` version of WasmEdge.
- Available Value: "x86_64", "aarch64".

Behaviour

- If there exists an installation at `$HOME/.wasmedge` which is to be noted as the default installation path, it is removed with or without uninstaller's invocation.
- WasmEdge installation appends all the files it installs to a file which is located in the installer directory named `env` with it's path as `$INSTALLATION_PATH/env`

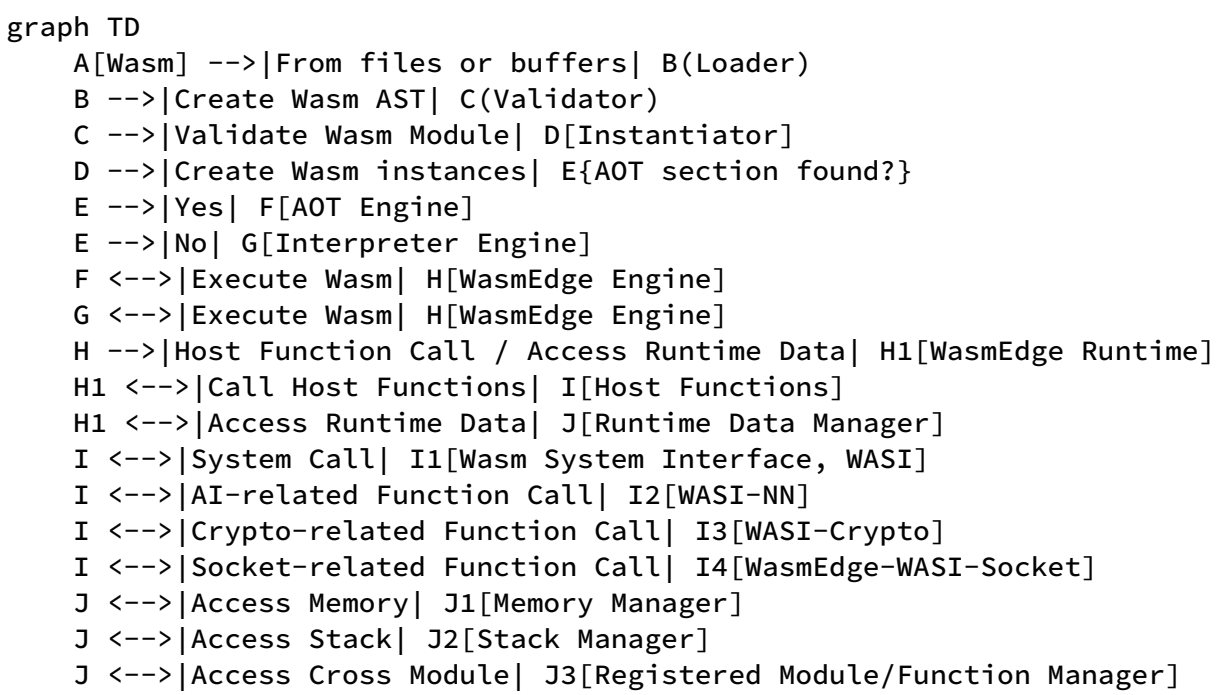
Shell and it's configuration

- Source string in shell configuration is given as `. $INSTALLATION_PATH/env` so that it exports the necessary environment variables for WasmEdge.
- Shell configuration file is appended with source string if it cannot find the source string in that file.
- Currently it detects only `Bash` and `zsh` shells.
- If the above shells are found, then their respective configuration files `$HOME/.bashrc` and `$HOME/.zshrc` are updated along with `$HOME/.zprofile` and `$HOME/.bash_profile` in case of Linux.
- In case of `Darwin`, only `$HOME/.zprofile` is updated with the source string.

WasmEdge Internal

Work in progress.

Overview of WasmEdge Execution Flow



Wish list

👉 Check out our "help wanted" issues!

We are also looking for developer help in the following general areas. Please create an issue and let us know!

- Improvements to technical documentation, examples, and tutorials.
- Non-English language translations of documentation and tutorials.

WasmEdge Release Process

Create the releasing process issue of the new version

- ☐ Keep adding the new features, issues, documents, and builds check list into the issue.
- ☐ Add the GitHub project of the new version.

Write Changelog

- ☐ Make sure every change is written in the changelog.
- ☐ Make sure the `Changelog.md` has the correct version number and the release date.
- ☐ Copy the changelog of this version to `.CurrentChangelog.md`. (Our release CI will take this file as the release notes.)
- ☐ Record the contributor lists.
- ☐ Create a pull request, make sure the CI are all passed, and merge it.

Create the Alpha Pre-Release

- ☐ In this step, the main features are completed. No more major feature will be merged after the first Alpha pre-release.
- ☐ Make sure that the features in the releasing process issue are completed.
- ☐ Use git tag to create a new release tag `major.minor.patch-alpha.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and turn into Beta or RC phase in about 3 days if there's no critical issues.

Create the Beta Pre-Release

- ☐ This step is for the issue fixing if needed. No more feature will be accepted.
- ☐ Make sure that all the features in the releasing process issue are completed.
- ☐ Use git tag to create a new release tag `major.minor.patch-beta.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and turn into RC phase in about 3 days if there's no critical issues.

Create the RC Pre-Release

- ☐ In this step, the issue fixing is finished. The `RC` pre-releases are for the installation, bindings, and packages testing.
- ☐ Make sure that all the issues in the releasing process issue are completed.
- ☐ Update `WASMEDGE_CAPI_VERSION` in `CMakeLists.txt`.
- ☐ Update `wasmedge_version` in `docs/book/en/book.toml`.
- ☐ Use git tag to create a new release tag `major.minor.patch-rc.version`. And push this tag to GitHub.
- ☐ Wait for the CI builds and pushes the release binaries and release notes to the GitHub release page.
- ☐ Check the `Pre-release` checkbox and publish the pre-release.
- ☐ This step will automatically close and announce the official release in about 3 days if there's no critical issues.

Create the Official Release

- ☐ Make sure the `Changelog.md` and `.CurrentChangelog.md` have the correct version number and the release date.
- ☐ Use git tag to create a new release tag `major.minor.patch`. And push this tag to GitHub.
- ☐ Wait for the CI builds and push the release binaries and release notes to the GitHub release page.
- ☐ Publish the release.
- ☐ Close the releasing process issue and the GitHub project.

Update the Extensions

The following projects will be updated with the `Alpha`, `Beta`, and `RC` pre-releases and the official release:

- [ ] WasmEdge-Image
- [ ] WasmEdge-TensorFlow-Deps
- [ ] WasmEdge-TensorFlow
- [ ] WasmEdge-TensorFlow-Tools
- [ ] WasmEdge-Go SDK
- [ ] WasmEdge-core NAPI package
- [ ] WasmEdge-extensions NAPI package