Compiler Project

Code Generation for VSOP

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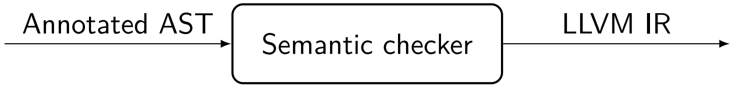
Outline

Outline

Code Generation



For **semantically valid** VSOP programs, generate **LLVM IR**

No error should be found during this phase

`vsopc -i example.vsop` should:

- If the source file is valid, return 0 and dump on `stdout` the LLVM IR
- Otherwise, return a non-zero value and print on `stderr` (at least) one error

Generating an Executable

`vsopc /path/example.vsop` should:

- If the source file is valid, return 0 and create an executable `/path/example` from the generated IR
  - This executable will then be run without argument
- Otherwise, return a non-zero value and print on `stderr` (at least) one error

Assignment

Due May 16, 2023

Automated tests worth 5% of your grade

You can use **LLVM bindings** to generate the IR, an example is provided on eCampus

Support for **custom tests** in `tests` subfolder: to **give inputs** to the generated executable, provide a `/path/example.input` file (same name that the source file but with the `input` extension) which will be used as `stdin`

Five modes: no flag, `-i`, `-c`, `-p` and `-l`

Assignment

Optional: you can implement some **VSOP extensions** of your liking

- But they should **only be enabled** when `vsopc` is called with the `-e`
- The `-e` flag should be able to be used with the other flags

A (short) **report** should be provided with your code discussing:

- the **implementation** of your compiler
- the potential **shift/reduce** or **reduce/reduce conflicts** you had to solve
- the **potential extensions** you have implemented
- . . .

Output Format

When called with the `-i` **flag**, your compiler should dump on `stdout` the **generated IR**

When called with **no flag**, **nothing** should be printed on `stdout`

Error Management

Your compiler should not output any error at code generation:

All errors (that could have been detected at compile-time) **should already have been reported**

Of course, it will still report potential **lexical**, **syntax** or **semantic** errors

Report

Provide a **PDF report** describing:

- How your code is organised, which tools, data structures and algorithms are used
- The potential **shift/reduce or reduce/reduce conflicts** you had to solve
- If something in your implementation is not obvious from your **documented** code
- Your **VSOP extensions**
- The **limitations** of your compiler: what would you do differently or with additional time ?
- How long did it take, what were the main difficulties ? How can we improve the project ?

Try to be **succinct**

Outline

What is LLVM ?

- Originally, acronym for *Low Level Virtual Machine*
  - But since its creation, the LLVM project has well evolved
  - Nowadays, **little relationship** with *virtual machines*
- Collection of **modular and reusable** tools to support both **static and dynamic** compilation of arbitray programming languages
- Many sub-projects, the most prominent one being **clang**, a C/C++ compiler
- Wildly used in the industry (e.g. Adobe, Apple, Cray, Intel, NVIDIA, Siemens, Sun, . . .).
- Somewhat **easy**, **fast**, **modular**, and **supports many targets**.

What is the LLVM Language

- An *Intermediate Representation* (**IR**)
- **Assembly**-like language
- Based on the *Single Static Assignment* (**SSA**) form
- **Typed** !
- Allows **low-level** operations, while permitting to represent **high-level** languages cleanly (e.g., function definitions)

Resources

- LLVM Language **Reference Manual** (Link)
- The Often Misunderstood **GEP** Instruction (Link)
- The LLVM **Tutorial**: Kaleidoscope: Implementing a Language with LLVM (Link)
- Static Single Assignment (SSA) Form (Wikipedia) (Link)
- The (**not so**) theoretical course !
- Mapping **High-Level Constructs** to LLVM IR (Link)

Practical Details

Version: Use LLVM **version 11** available in the reference container

How to **generate LLVM code**:

- **Textually**, then call LLVM assembler (and optimizer)
- Using the **LLVM bindings library**:
  - Easier to optimize
  - Allows interpretation and JIT compilation
  - **Poorly documented**, steep learning curve !
  - Official bindings for C/C++ and various unofficial bindings for other languages (e.g., `llvmlite` for Python)
    - Example for C/C++ on eCampus

LLVM Modules

A compilation unit is called a **module**, it contains:

- **Type aliases**
- **Declarations**, which states that a symbol exists and give its type
- Definitions of **global variables** (type + initializer)
- **Function definitions**
- Special sections such as module initialization code

A module lies in its own file (`module_name.ll`) or is generated in-memory using the library

You are expected to generate a **single module** in this project, but adding the possibility to import external modules is a possible extension

LLVM Types

```
i1                         ; 1-bit integer (may be used for bool)
i8                         ; 8-bit integer (used for char)
i32                        ; 32-bit integer
i64                        ; 64-bit integer
float                      ; 32-bit IEEE 754 floating-point number
double                     ; 64-bit IEEE 754 floating-point number
void                       ; empty type
label                      ; named adresses (see later)
i32 *                      ; pointer to one (or more) i32
[40 x i8]                  ; array of 40 8-bit numbers (static size)
float (i16, i32 *)         ; function (i16, i32 *) -> float
i32 (i8 *, ...)            ; signature of printf()
{ i32, float }             ; structure with i32 and float fields
%MyVeryOwnType             ; named type
```

SSA Values

Also known as *registers* (somewhat improperly)

They are **immutable**, i.e. do not change after initialization

Two kinds of identifiers:

- **Global identifiers** (functions, global variables) begin with the `@` character (e.g. `@puts`, `@my_global_var`)
- **Local identifiers** (register names) a,d types begin with the `%` character (e.g. `%result`, `%MyStruct`)

Infinite supply of registers and globals

Unnamed values are (and **must** be) **numbered sequentially** (e.g. %31, %32, %33, . . .)

Literals

Simple literals:

- **Integers**: e.g. 42, -1028
- **Booleans**: `true` and `false` of `i1` type (resp. 1 and 0)
- **Floating-point**: usual notation (e.g. 3.14159265, 6.673981e-11), but requires **exact decimal value** (e.g. 0.1 is rejected), or direct representation (e.g. 0x141d7038)
- **Null pointer**: `null`, of any pointer type

Complex literals:

- **Structures**: e.g. `{ i32 4, float 17.0, i32* @g }`
- **Arrays**: `[i32 1, i32 2, i32 3]`
- **Zeroes**: `zeroinitializer`
- **Undefined**: `undef`
- Global variables and functions are **always implicit pointers**:
    - i.e. `@x` always has a pointer type

Blocks, Labels and Terminator Instructions

A function body is a set of **SSA blocks**

A block spans from a **label** to a **terminating instruction**:

```
  ret void                                         ; return from procedure
  ret i32 42                                       ; return 42
  ret { i32, double } { i32 42, double 84.0 }      ; return struct literal
  br label %end_of_process                         ; unconditional jump
  br i1 %cond, label %if_true, label %if_false     ; conditional jump
```

Example:

```
  br i1 %cond, label %if_true, label %if_false
  ; A statement here would be illegal
if_true:                                           ; Labels are as in C
  ret i32 42
if_false:
  ret i32 0
```

Arithmetic Instructions

Remarks:

- **Separate instructions** for **integers** and **floating-point** numbers (e.g. `add` and `fadd`)
- Operands type (and size) must be **known**
- No signedness in types, but **signedness in some instructions** (e.g. `udiv` and `sdiv`)

```
%1 = add i32 42, %var     ; integers addition, %var must also be i32
%3 = fadd double 42.0, %x ; different instruction for floats
%4 = sub i32 0, %var      ; yields -%var
%5 = fmul double 3.0, %x  ; multiplication for floats
%6 = udiv i32 %var, 5     ; unsigned integers division
%7 = sdiv i32 %var, 5     ; signed integers division (rounded towards 0)
%8 = fdiv double %x, 5.0  ; floats division
```

There exist other operations (and flags), see full reference

Logical Instructions

Remark: the logical instructions are **always bitwise**

```
%1 = and i1 %a, %b  ; 'and' on two booleans
%2 = and i32 9, 10  ; bitwise, yields 8 (1001 & 1010 = 1000)
%3 = or i32 9, 10   ; yields 11 (1001 | 1010 = 1011)
%4 = xor i32 9, 10  ; yields 3 (1001 ^ 1010 = 0011)
%5 = xor i32 %x, -1 ; yields ~%x
```

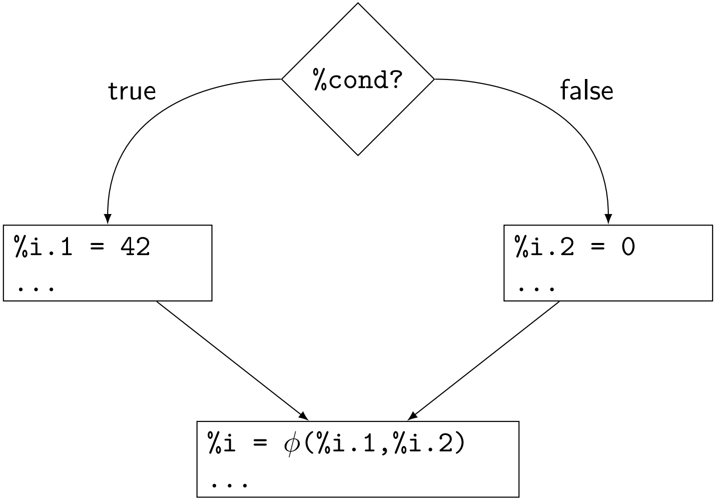
Comparisons

Remarks:

- Comparisons are made with the `icmp` (for integers) and the `fcmp` (for floats) instructions followed by a flag indicating the comparison type
- Comparions always return an `i1`

```
%1 = icmp eq i32 %a, %b       ; %a == %b, returns i1 type
%2 = icmp ne i32 %a, %b       ; %a != %b
%3 = icmp ugt i32 %a, %b      ; unsigned %a > %b
%4 = icmp sle i32 %a, %b      ; signed %a <= %b
%5 = icmp eq i32* @p, @q      ; works also on pointers
%7 = fcmp oeq float %x, %y    ; ordered equal, i.e.
                              ; %x != NaN && %y != NaN && %x == %y
%8 = fcmp ueq float %x, %y    ; unordered equal, i.e.
                              ; %x == NaN || %y == NaN || %x == %y
%9 = fcmp olt float %x, %y    ; %x != NaN && %y != NaN && %x < %y
```

The Magical Phi Instruction



The Magical Phi Instruction in LLVM

phi takes on the value specified by the pair corresponding to the block that executed **just before** the current block

```
  br i1 %cond, label %if_true, label %if_false
if_true:
  %i.1 = i32 42
  br label %end_if
if_false:
  %i.2 = i32 0
  br label %end_if
end_if:
  %i = phi i32 [%i.1, %if_true], [%i.2, %if_false]
```

Constants values are allowed as well

Functions Declarations and Calls

Declarations:

```
; use '...' to have variable number of arguments
declare i32 @printf(i8*, ...)
; use C (default) calling convention
declare ccc i32 @printf(i8*, ...)
; use fast calling convention
declare fastcc void @someFastCCFun(i32, i8*)
```

Calls:

```
%z = call double @pow(double %x, double %y)
call i32(i8*, ...)* @printf(i8* @fmt, i32 %val)
call fastcc void @someFastCCFun(i32 42, i8* @str)
```

- Functions are **always pointers**
- Catching return value is not mandatory, but catching `void` is **illegal**
- Type can be just return type, unless vararg

Memory Accesses

```
%ptr = alloca i32            ; yields i32* to STACK-allocated i32
store i32 42, i32* %ptr      ; stores 42 into allocated cell
%val = load i32, i32* %ptr   ; %val := 42 (read from cell)

%aPtr = alloca i32, i64 100 ; int32_t aPtr[100];
; fill(aPtr, 100)
call fastcc void @fill(i32* %aPtr, i32 100)
; int *a4ptr = &(aPtr[4]);
%a4ptr = getelementptr i32, i32* %aPtr, i64 4
%a4 = load i32, i32* %a4ptr ; int a4 = *a4ptr;

%sPtr = alloca {i32, i8}     ; struct { int32_t a, int8_t b } s;
%bPtr = getelementptr {i32, i8}, {i32, i8}* %sPtr, i32 0, i32 1
store i8 42, i8* %bPtr       ; s.b = 42;
```

- Structures are indexed with `i32`, any integer for arrays
- Use `malloc` for heap-allocated memory

The getelementptr Instruction

This instruction is used to access an element from an array or a field of a structure, but **no memory dereferencing** is performed with this instruction

In C, **address computation** and **dereferencing** are performed within the **same instruction**:

```
int x = array[2]
int f = my_struct.f
```

While in LLVM, they are **separated**:

```
%x_addr = getelementptr i32, i32* %array, i64 2
%x = load i32, i32* %x_addr
%f_addr = getelementptr {i8, i32}, {i8, i32}* %my_struct, i32 0, i32 1
%f = load i32, i32* %f_addr
```

Note: 2 indexes are used when dealing with a structure, the first one tells which structure to access (only one possibility is this case, but what if we have an array of stuctures ?) and the second one which field to access

Function Definitions

```
define fastcc void @fill(i32* %array, i32 %len) {
entry:  ; If not specified, label %0 will be inserted
  br label %loop_cond

loop_cond:
  %i = phi i32 [ 0, %entry], [ %ip1, %loop_body ]
  %cond = icmp ult i32 %i, %len
  br i1 %cond, label %loop_body, label %loop_end

loop_body:
  %ptr = getelementptr i32, i32* %array, i32 %i
  store i32 %i, i32* %ptr
  %ip1 = add i32 %i, 1
  br label %loop_cond

loop_end:
  ret void
}
```

Translation of Lecture IR

Quite similar, but **typed** and **no assignments**

```
; LABEL my_label
my_label:

; GOTO my_label
br label %my_label

; id := 42     (7th assignment to id in that scope)
%id.6 = add i32 0, 42
; id := a + 1  (assumming i32 type)
%id = add i32 %a, 1
; id := g      (where g assigned in a if-then-else above)
%id = phi i32 [%g.1, %if_true], [%g.2, %if_false]
```

Translation of Lecture IR (cnt'd)

```
; id := M[addr]
%id = load i32, i32* %ptr
; M[addr] := id
store i32 %id, i32* %ptr

; a_exp_addr := exp * 4
; a_exp_addr := a_exp_addr + a_base_addr
%a_exp_ptr = getelementptr i32, i32* %a, i32 %exp

; IF n > 0 THEN if_greater ELSE if_lower
%cond = icmp sgt i32 %n, 0
br i1 %cond, label %if_greater, label %if_lower

; ret = CALL my_fun(arg1, arg2)
%val = call i32 (i32, i32)* @my_fun(i32 %arg1, i32 %arg2)
ret i32 %val
```

Obtain the Size of a Structure `%T`

Take the address of the second element of an hypothetical array of `%T` starting at address 0:

```
%size_as_ptr = getelementptr %T, %T* null, i32 1
%size_as_i32 = ptrtoint %T* %size_as_ptr to i32
```

As `getelementptr` returns a pointer, you must do a **conversion** to an integer afterwards

Avoid trying to compute the size of a structure yourself: its size may be **target-dependent** because of **alignment issues**

Strings

In VSOP, all strings are ultimately string literals:

- They are **not mutable**
- They support **no operation** other than printing

LLVM support string literals **natively**, as arrays of i8:

```
@s = constant [14 x i8] c"Hello, world!\00"

declare i32 @puts(i8*)

define i32 @main() {
    %1 = getelementptr [14 x i8], [14 x i8]* @s, i64 0, i64 0
    %2 = call i32 @puts(i8* %1)
    ret i32 0
}
```

You can store them as i8*

What’s Next

We haven’t covered all of LLVM language (not even close)

Have a look at the language reference and the **tutorial**

Use `clang -S -emit-llvm` to get the LLVM IR when compiling with `clang`

Notable omissions:

- tail call optimization
- function and argument attributes
- conversion and casting operations
- LLVM intrinsics (e.g. for `pow`)
- linkage types
- undef and poison values
- vectors and vectored operations
- parallelism-oriented features
- memory management features
- special control flow (e.g. for exceptions)
- low-level stuff (e.g. access to volatile memory)

The LLVM Library

The LLVM Library allows:

- declarations of (external) functions and global variables
- definitions of global variables and functions
- adding blocks to functions
- moving the insertion point (*builder position*) at start/end of any block
- emitting instructions
- checking functions/modules are well-formed
- executing optimization passes in any order

However, it is:

- **poorly documented** (see the tutorial and Doxygen)
- not mandatory

A small **example** is available on eCampus

Compilation/Execution with the Library

Once you built (and optimized) a module, you can:

- **interpret** it using a built-in interpreter
- **execute** it after *just-in-time* (JIT) compilation
- **compile** it into a native executable
- **dumps** its LLVM assembly code

Outline

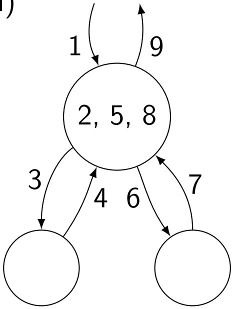
AST Traversal Reminder

You should **refer** to the (not so) theoretical course

Generally a mix between **top-down** and **bottom-up** approaches

At each node:

1. Receive some info from parent node (inherited)
2. Update received info based on current node
3. Process first child, passing needed info
4. Get back info from child processing (synth.)
5. Process that info
6. Process next child, passing needed info
7. Get back info from child processing
8. Process that info
9. Return useful info back to parent node



Do as many passes as needed

Factorize Common Code

VSOP being an **expression-based language**, nearly everything is an expression, and can be used in any context were an expression is expected

Try to be **as general as possible** in your code:

E.g., there is likely no need for a separate `compile_cond()` function, just call your `compile_expr()` function. If you need specific checks or operations (checking the type is `bool` or adding a `br` instruction), it should likely go into `compile_if()` If you want to share condition-checking code between, say *if-then-else* and *while* loops, make a `compile_cond()` function, but have it call `compile_expr()` rather than reimplementing the same logic.

Avoid redundant code !

Static vs Dynamic

- *Static properties* are known at **compile time**
- *Static behaviour* is what your compiler does **when compiling**
- **Safer** and more **efficient**

- *Dynamic properties* are only known at **runtime**
- *Dynamic behaviour* is what your compiled program does **when running**
- More **expressive**

Before implementing a feature, ask yourself whether it is **static**, **dynamic**, or if it needs **both** static and dynamic support

Static vs Dynamic Types

```
class Foo { ... }
class Bar extends Foo {
    ...
    public void barOnlyMethod() { ... }
}

class Main {
    public static void main(String[] args) {
      Foo iAmABar = new Bar();  // Static type is Foo
                                // Dynamic type is Bar
                                // OK since Foo <: Bar
      iAmABar.barOnlyMethod();  // Always valid, but
                                // forbidden in VSOP,
    }                           // Java, C++, ...
}                               // but OK in python
```

Static vs Dynamic values

In general, **values** are only known at run-time, but some values can be determined at compile-time by **constant propagation**, which can lead to **dead-code** elimination

```
if a == b (* Is the condition true? *)
          (* In general, we don't know until run-time *)
then 42
else 1984;

if true (* Statically known to be true *)
then print("I knew it!")
else print("Oh no! A bug :'("); (* Dead code *)
```

Keep It Simple

```
@.str = private unnamed_addr constant [14 x i8] c"Hello, world!\00", align 1
define i32 @main() #0 {
  %1 = alloca i32, align 4
  store i32 0, i32* %1, align 4
  %2 = call i32 @puts(i8* getelementptr inbounds ([14 x i8], [14 x i8]* @.str, i64 0, i64 0))
  ret i32 0
}
declare i32 @puts(i8* nocapture readonly) #1
attributes #0 = { noinline nounwind optnone uwtable
"correctly-rounded-divide-sqrt-fp-math"="false"
"disable-tail-calls"="false" "less-precise-fpmad"="false" "min-legal-vector-width"="0"
"no-frame-pointer-elim"="true" "no-frame-pointer-elim-non-leaf" "no-infs-fp-math"="false"
"no-jump-tables"="false" "no-nans-fp-math"="false" "no-signed-zeros-fp-math"="false"
"no-trapping-math"="false" "stack-protector-buffer-size"="8" "target-cpu"="x86-64"
"target-features"="+cx8,+fxsr,+mmx,+sse,+sse2,+x87" "unsafe-fp-math"="false"
"use-soft-float"="false" }
```

does (roughly) the same as the much simpler

```
@.str = constant [14 x i8] c"Hello, World!\00"
define i32 @main() {
  %1 = getelementptr [14 x i8], [14 x i8]* @.str, i64 0, i64 0
  %2 = call i32 @puts(i8* %1)
  ret i32 0
}
declare i32 @puts(i8*)
```

Generated Code vs Runtime

You can generate code inline for most operations, even in a dynamic language

This is **efficient** but:

- may lead to **code explosion**
- may be hard to do

You can **factorize** out common functionalities into a **library** provided with every VSOP program (called the **runtime**):

- It can be written in a different, usually lower-level language
- Some languages go as far as using a *virtual machine* to run programs, which are more data than code (e.g. Java)
- For VSOP, we will provide a runtime for I/O (the `Object` class)

How to Check/Implement the `Object` Class ?

Semantic analysis:

- The fact that `Object` exists and its method prototypes should be known during typechecking
- Add their *prototypes* manually to your symbol tables, or parse their definitions directly in VSOP (with dummy method bodies)

Code generation:

- **Don't generate** code for `Object` methods within your compiler !
- **Provide** the `Object` method definitions **separately**:
  - by **appending** their LLVM IR directly to generated IR
  - or by **linking** with an object file with their definitions (e.g. generated from C)

Alternatively, implement the *Foreign Function Interface* **FFI** extension and write the `Object` class directly in VSOP

Accessing the Runtime on the Platform

Your generated compiler is **not run** in your `vsopcompiler` folder, so you will not be able to access your `runtime` folder using **relative path** (`./runtime/`)

Solution: Use the `Makefile` to **copy** the runtime file(s) you need in a known location, e.g. `/usr/local/lib/vsop/`

⇒ Your compiler can access it using an **absolute path**

By-value vs By-reference

By-Value: Function arguments are **copied** before call, modifying an argument inside the callee **does not modify** corresponding variable at caller site

By-Reference: function arguments are **passed by pointer**, modifying an argument inside the callee **modifies caller variable**

By-Value is generally safer, modification allowed through explicit pointers

Like Java, VSOP uses by-value semantics for primitive types (like `int32`), but by-reference semantics for objects

Outline

How to Implement Dynamic Dispatch ?

How would you compile the following ?

```
class MyClass {
  j : int32 <- 42;
  someMethod(i : int32) : int32 {
      i + j
  }
}
// ...
  let myObject : MyClass <- new MyClass in
  myObject.someMethod(1942)
```

Simple Static Dispatch

Key idea: pass the **object** instance as **first argument** to methods.

```c
// struct to keep fields data
typedef struct { int32_t j; } MyClass;
// Allocation and initialization
MyClass *MyClass_new(void) {
  MyClass *self = malloc(sizeof (MyClass));
  self->j = 42;
  return self;
}
// Methods
int32_t MyClass_someMethod(MyClass *self, int32_t i) {
  return i + self->j;
}

// ...
  MyClass *myObject = MyClass_new();
  MyClass_someMethod(myObject, 1942);
```

Field Inheritance

How to **reuse** parent field in child method ?

How to **add new** fields to children classes ?

```
class Parent {
  i : int32 <- 42;
  j : int32;
}

class Child extends Parent {
  k : int32;
  sum() : int32 { i + j + k }
}

// ...
  let child : Child <- new Child
  in child.sum()
```

Field Inheritance: Parent Class

Note that we decouple **allocation** and **initialization**

```
// Parent fields
typedef struct {
  int32_t i;
  int32_t j;
} Parent;
// Initialization of already allocated structure
void Parent_init(Parent *self) {
  self->i = 42;
  self->j = 0;
}
// Allocation and initialization
Parent *Parent_new(void) {
  Parent *self = malloc(sizeof (Parent));
  Parent_init(self); // Initialization
  return self;
}
```

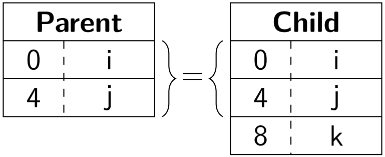
Field Inheritance: Parent Class

```
typedef struct {
  int32_t i; // FIRST: fields of parent, IN SAME ORDER
  int32_t j;
  int32_t k; // THEN: additional field(s) of Child
} Child;
// Initialization of child object
void Child_init(Child *self) {
  Parent_init((Parent *) self); // super()
  self->k = 0; }
// Allocation and initialization of a new child
Child *Child_new(void) {
  Child *self = malloc(sizeof (Child));
  Child_init(self); // Initialization
  return self; }
// Child method
int32_t Child_sum(Child *self) {
  return self->i + self->j + self->k; }

// ...
  Child *child = Child_new();
  Child_sum(child);
```

Field Inheritance: Memory Layout

```
;                   i,   j
%Parent = type { i32, i32 }
;                   i,   j,   k
%Child  = type { i32, i32, i32 }
```



Method Inheritance

```
class Parent {
  i : int32 <- 42;
  inParent() : int32 { i }
}

class Child extends Parent {
  inChild() : int32 { 1942 + i }
}

// ...
  let c : Child <- new Child in {
    c.inParent();
    c.inChild()
  }
```

Method Inheritance: Static Dispatch

Use a `Child` as a `Parent` using a cast

Same data layout for common fields of `Child` and `Parent`

```
typedef struct { int32_t i; } Parent;
void Parent_init(Parent *self) { self->i = 42; }
Parent *Parent_new(void) { /* ... */ }
int32_t Parent_inParent(Parent *self) { return self->i; }

typedef struct { int32_t i; /* Same as parent */ } Child;
void Child_init(Child *self) { /* ... */ }
Child *Child_new(void) { /* ... */ }
int32_t Child_inChild(Child *self) { return 1942 + self->i; }

// ...
  Child *c = Child_new();
  // c.inParent()
  Parent_inParent((Parent *) c); // Cast needed (and OK) here
  // c.inChild()
  Child_inChild(c);
```

Static Dispatch is not enough

```
class Person {
  i : int32;
  name() : string { "Someone" }
}

class John extends Person {
  name() : string { "John" }
}

class MyClass {
  someMethod(p : Person): unit {
    print(p.name()); // What to call here?
    // Person_name(), John_name(), Mary_name(), ...?
    ()
  }
}
```

Method Overridding: Function Pointers as Fields

```
typedef struct Person {
  int32_t i;
  char *(*_name)(struct Person *);
} Person;
char *Person_name(Person *self) { return "Someone"; }
void Person_init(Person *self) {
  self->i = 0;
  self->_name = &Person_name;
}

typedef struct John {
  int32_t i; // Same as Person
  char *(*_name)(struct John *); // John instead of Person, is it safe?
} John;
char *John_name(John *self) { return "John"; }
void John_init(John *self) {
  Person_init((Person *) self);
  self->_name = &John_name; // Overrides name()
}
// ...
  p->_name(p) // p.name()
```

Method Overridding: Function Pointers as Fields

Using fields for methods works, but is very **wasteful**:

- **All objects** of the same class share the **same set** of methods
- But every object carries **one pointer per method**
- So ONE pointer PER method PER object $\Rightarrow$ **Waste of memory** !

Idea: **Share** the method pointers between objects of the same class

We need to **associate** each **object** with a **table of method pointers** (called the *vtable*):

- Either use **fat pointers**, i.e. a pointer to the object + a pointer to the *vtable*
- Or keep a pointer to the *vtable* in the object itself as a **field** (the *vtable* pointer)

Method Dispatch: Types

```
// Type for object instances
typedef struct {
  // Virtual function table (see below)
  MyClassVTable *vtable;
  // Fields (each object instance needs its own)
  int32_t j;
} MyClass;

// Type of the vtable
typedef struct {
  // Types of all the methods of MyClass
  void (*someMethod)(MyClass *, bool);
  int32_t (*someOtherMethod)(MyClass *, int32_t);
} MyClassVTable;
```

Method Dispatch: Constructor and Methods

```
void MyClass_init(MyClass *self) {
  // Initialize fields, including virtual function table
  self->vtable = &MyClass_vtable;
  self->j = 42; // j : int32 <- 42
}

// someMethod(b : bool) : unit { ... }
void MyClass_someMethod(MyClass *self, bool b) { /* ... */ }

// someOtherMethod(i : int32) : int32 { i + j }
int32_t MyClass_someOtherMethod(MyClass *self, int32_t i) {
  return i + self->j;
}

// Actual function table object (only one needed)
struct MyClassVTable MyClass_vtable = {
  .someMethod = &MyClass_someMethod,
  .someOtherMethod = &MyClass_someOtherMethod
};
```

Method Dispatch: Calling a Method

```
// let myObject : MyClass <- new MyClass in
MyClass *myObject = MyClass_new();
// myObject.someOtherMethod(42)
myObject->vtable->someOtherMethod(myObject, 42);
```

Note the **cost** of vtable-based dispatch: each method call now requires **two memory accesses** (*double dispatch*):

- One to get the vtable pointer
- One to get the method pointer

One can **optimize** out virtual calls when the actual type of the object is known (e.g. just after `new`)

In loops, one can also **cache** the method pointer

Method Dispatch: Adding Inheritance to the Mix

```
class Parent { (* ... *) }
class Child extends Parent { (* ... *) }

class X {
  someMethod(Parent p) : unit {
    // Static type of p is Parent, but dynamic type?
    p.overridenMethod()
  }
}


void X_someMethod(X *self, Parent *p) {
  /* Will find the right method, whether p is a Parent,
   * a Child or any other descendant of Parent */
  p->vtable->overriddenMethod(p);
}
```

Method Dispatch: Adding Inheritance to the Mix (Cnt'd)

```
class Parent {
  inheritedField : int32 <- 42;
  inheritedMethod() : unit { (* ... *) }
  overriddenMethod() : unit { (* ... *) }
}

class Child extends Parent {
  newField : bool <- true;
  newMethod() : unit { (* ... *) }
  overriddenMethod() : unit { (* ... *) }
}
```

Method Dispatch: Adding Inheritance to the Mix (Cnt'd)

```
// A Child must be able to masquerade as a Parent
typedef struct {
  struct ChildVTable *vtable; // Virtual function table first
  int32_t inheritedField; // Parent fields, in the same order as parent!
  bool newField; // And, finally, Child's new fields
} Child;

// A ChildVTable must be able to masquerade as a ParentVTable
struct ChildVTable {
  // First, parent methods in the same order
  void (*inheritedMethod)(Child *), // Why not Parent * here?
  void (*overriddenMethod)(Child *),
  // Then child's new methods
  void (*newMethod)(Child *)
}

// Child VTable can mix inherited, overridden and new methods
struct ChildVTable Child_vtable = {
  // Necessary (but legit) cast for inherited method
  .inheritedMethod = (void (*)(Child *)) Parent_inheritedMethod,
  .overriddenMethod = Child_overriddenMethod,
  .newMethod = Child_newMethod
}
```

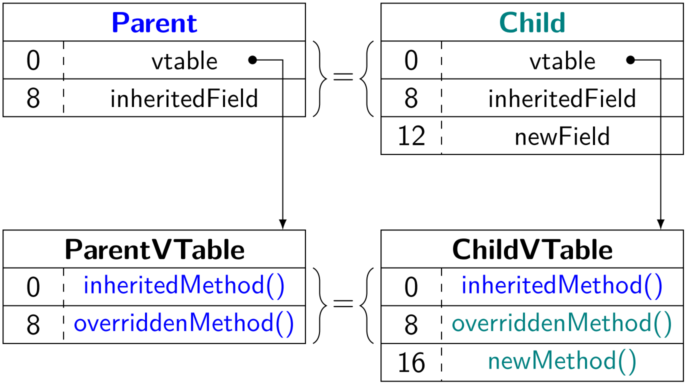
Method Dispatch: Adding Inheritance to the Mix (Cnt'd)

Chain constructors properly !

```
void Child_init(Child *self) {
  Parent_init((Parent *) self); // Parent initializers
  self->vtable = &Child_vtable; // Override vtable
  self->newField = true;
}

Child *Child_new() {
  Child *self = malloc(sizeof (Child));
  Child_init(self);
  return self;
}
```

In Summary


Parent
0
vtable
8
inheritedField
=
Child
0
vtable
8
inheritedField
12
newField
ParentVTable
0
inheritedMethod()
8
overriddenMethod()
=
ChildVTable
0
inheritedMethod()
8
overriddenMethod()
16
newMethod()

Beware

What if my class has a field named `vtable` ?

What if my class has a method called `init` ?

What if I have both:

- a class named `Base` with a method `jump_ship()` and
- a class named `Base_jump` with a method `ship()` ?

Beware of Symbol Conflicts

What if my class has a field named `vtable` ?

What if my class has a method called `init` ?

What if I have both:

- a class named `Base` with a method `jump_ship()` and
- a class named `Base_jump` with a method `ship()` ?

$\Rightarrow$ Symbol conflicts !

Use **name mangling** to avoid all possible conflicts in generated symbol names, e.g.:

- `_vtable` field (fields cannot start with _)
- `ClassName__methodName` (methods cannot begin with _)
- `ClassName___init` and `ClassName___vtable`

Outline

Questions and (possibly) answers

?