MAMBO - Dynamic Binary Instrumentation on ARM and RISC-V

HiPEAC 2024, Munich, 17 January 2024.

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Tutorial Format

- Getting Started / Logistics
- Introduction to Dynamic Binary Modification and MAMBO (~25 min)
- Introduction to MAMBO’s plugin API (~30 min)
- Coffee break (30 min)
- MAMBO use case and example plugin (~30 min)
- Hands on MAMBO session (~60 min)

SET UP MAMBO NOW!

IT TAKES 30 - 60 MIN WITH QEMU!

https://tinyurl.com/mambo-docker-setup

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Introduction to Dynamic Binary Modification and MAMBO

What is DBM/DBI/DBT?

- **D**ynamic - Working at runtime.
- **B**inary - Natively compiled user-space code.
- **M**odification - Alteration of applications at runtime, at the level of native code.
- **I**nstrumentation – The measurement, analysis or modification of aspects of a computer program's operating behaviour or performance by means of inserting additional code such as timers, counters, or loggers.
- **T**ranslation- In this context, can be either the use of a DBM tool for translation from one binary format to another, or the method by which some DBM tools work; first lifting to an IR and resynthesizing / recompiling.

Uses of DBM/DBI/DBT tools

- Microarchitectural simulation
  - Sniper, ZSim, SimAcc (MAMBO)
- Cache simulation
  - Valgrind Cachegrind, DynamoRIO drcachesim, MAMBO cachesim
- Program analysis
  - Valgrind Callgrind
- Memory error detection / debugging
  - Valgrind Memcheck, Dr. Memory, MAMBO memcheck
- Dynamic binary translation
  - QEMU, Apple Rosetta, TANGO

Why MAMBO?

- Optimized for ARM 32-bit, ARM 64-bit & RISC-V 64-bit
  - Low overhead
  - Only available DBM optimized for RISC-V
- Low complexity
  - Relatively small codebase ~20k LoC
- Simple plugin API for extension/tools
  - Architecture agnostic helper functions for portable plugins

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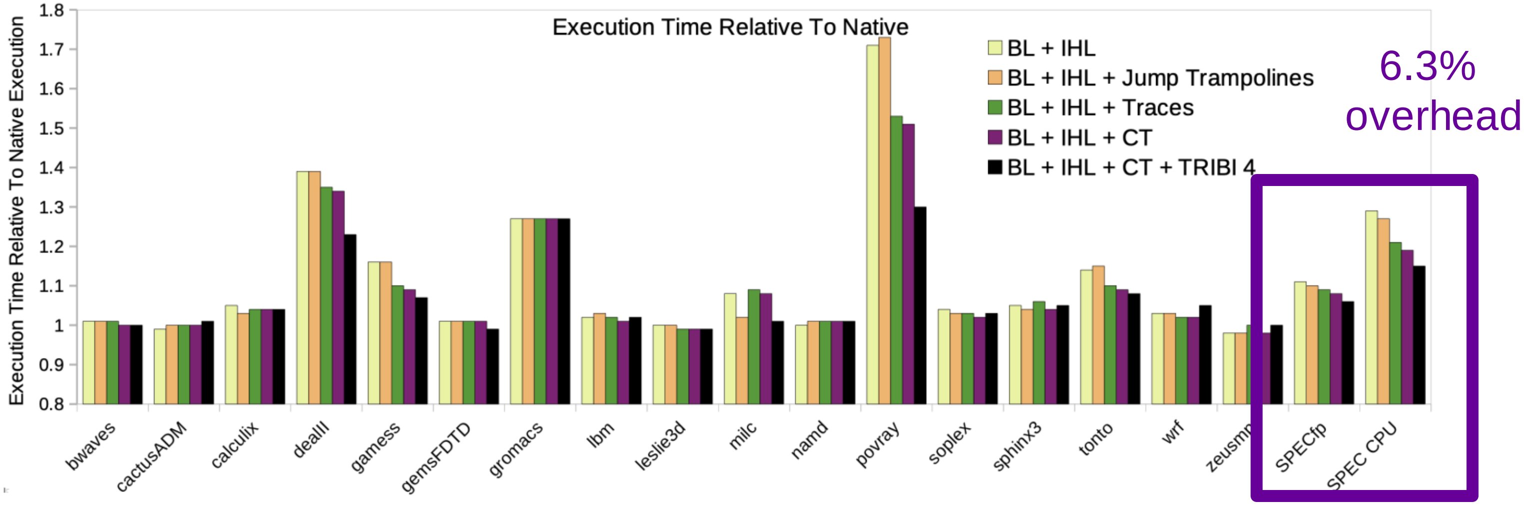
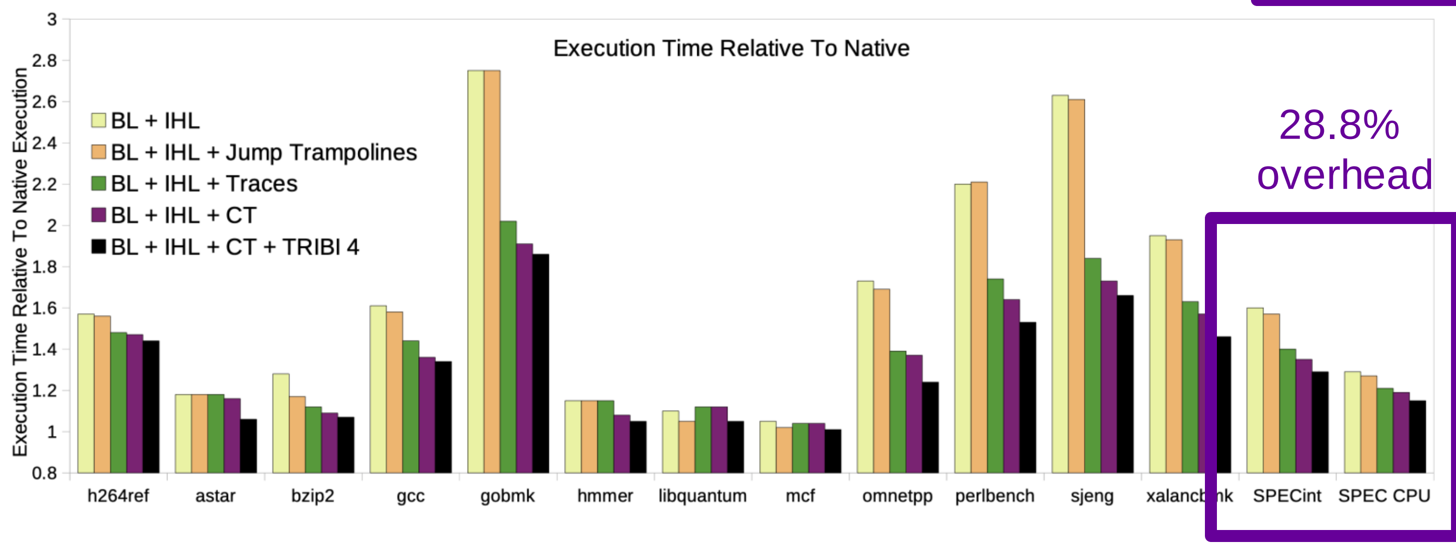
Why MAMBO on RISC-V?

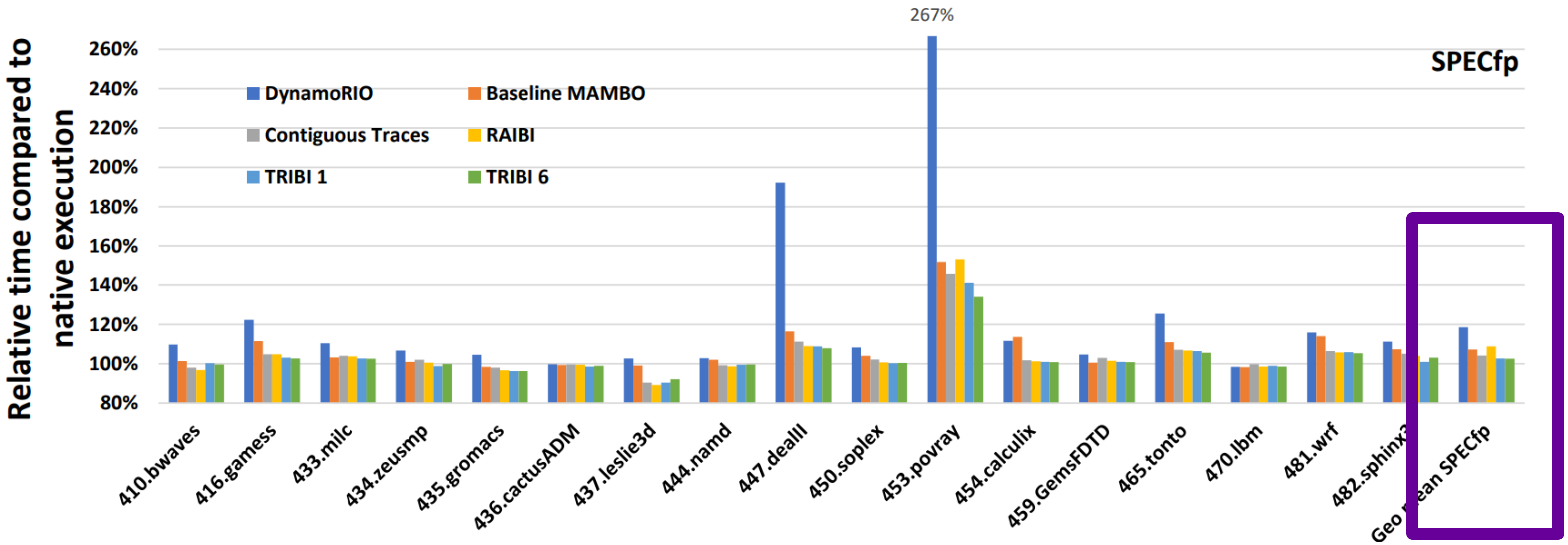


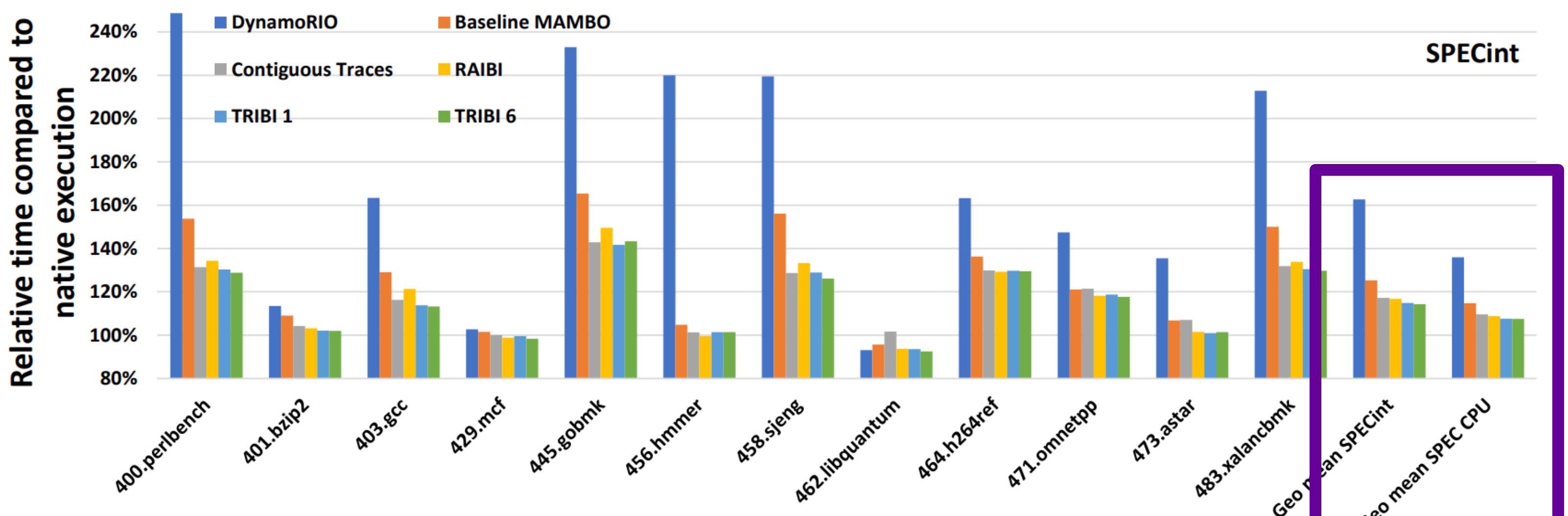


Slowdown relative to native execution for SPEC CPU2006 – RISC-V 64GC.

Kressel et al. Evaluating the Impact of Optimizations for Dynamic Binary Modification on 64-bit RISC-V.

Why MAMBO on ARM?

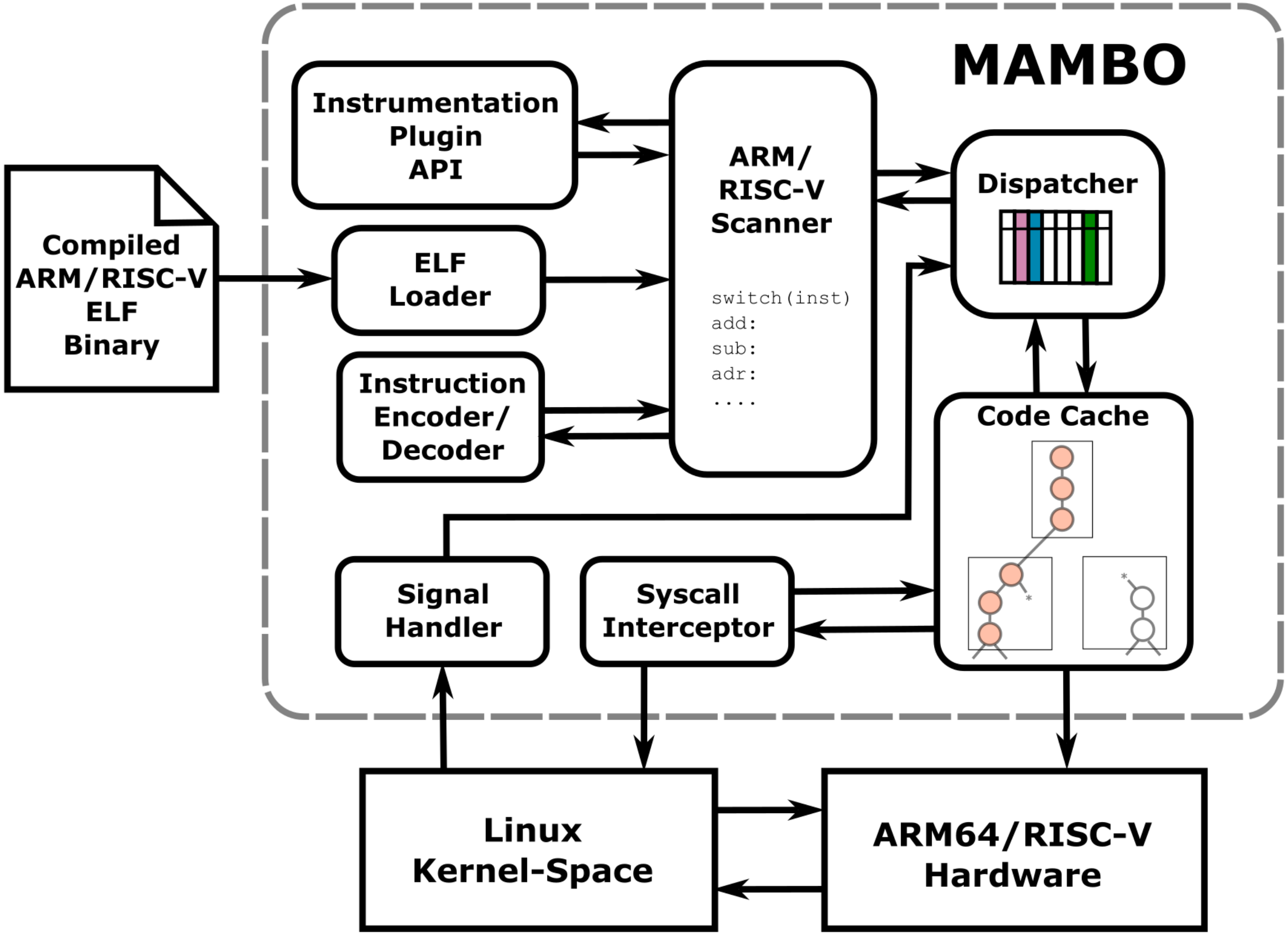




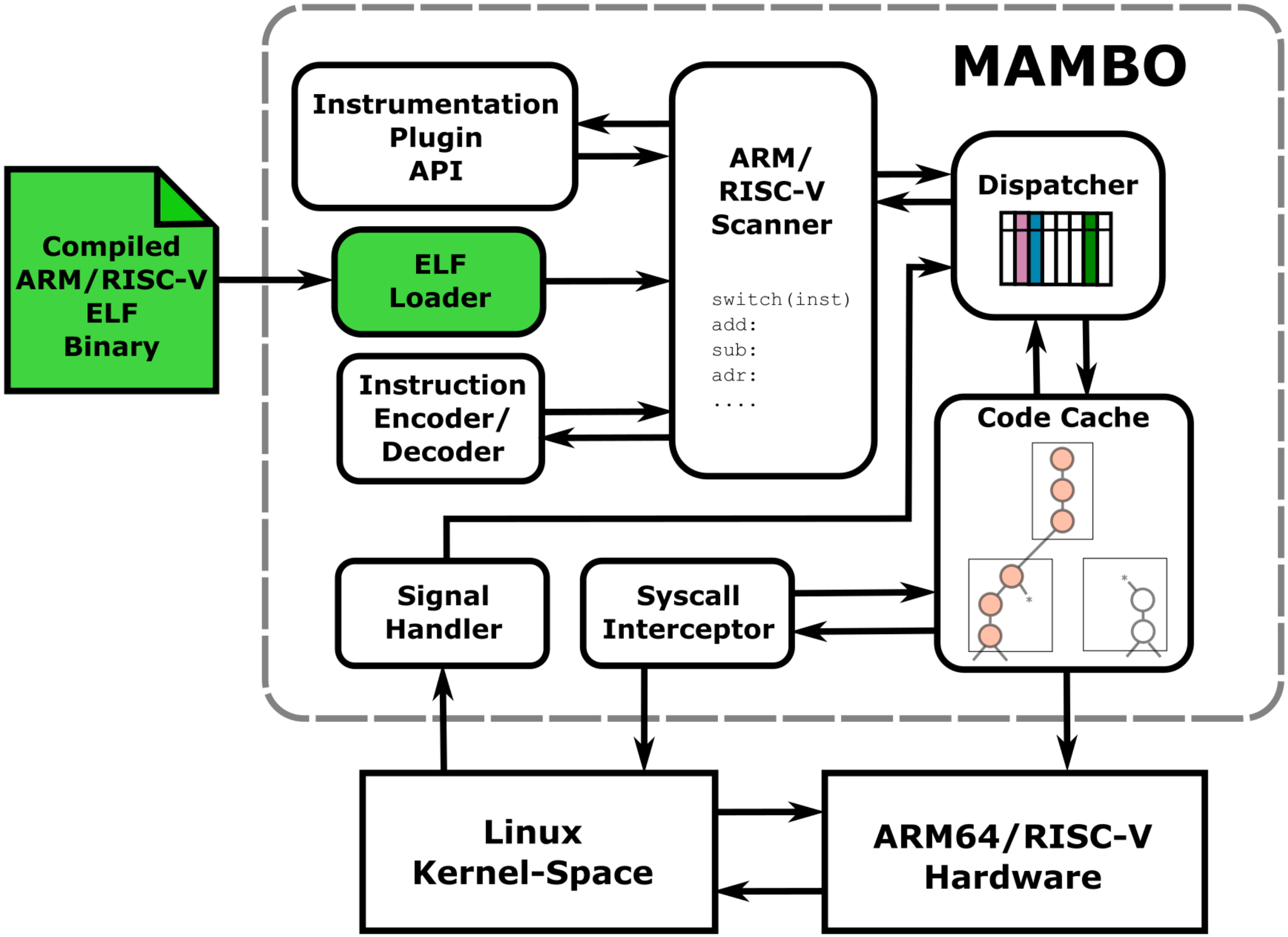
Slowdown relative to native execution for SPEC CPU2006 – ARM64 64.

Callaghan et al. Optimising dynamic binary modification across 64-bit Arm microarchitectures.

MAMBO Architecture

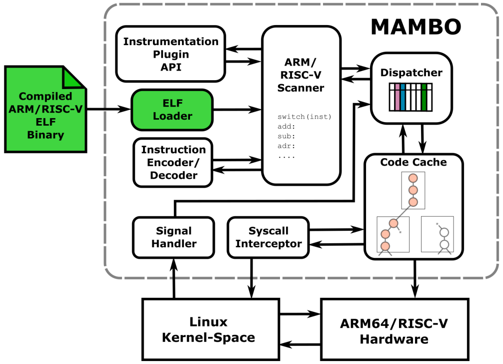


ELF Loading

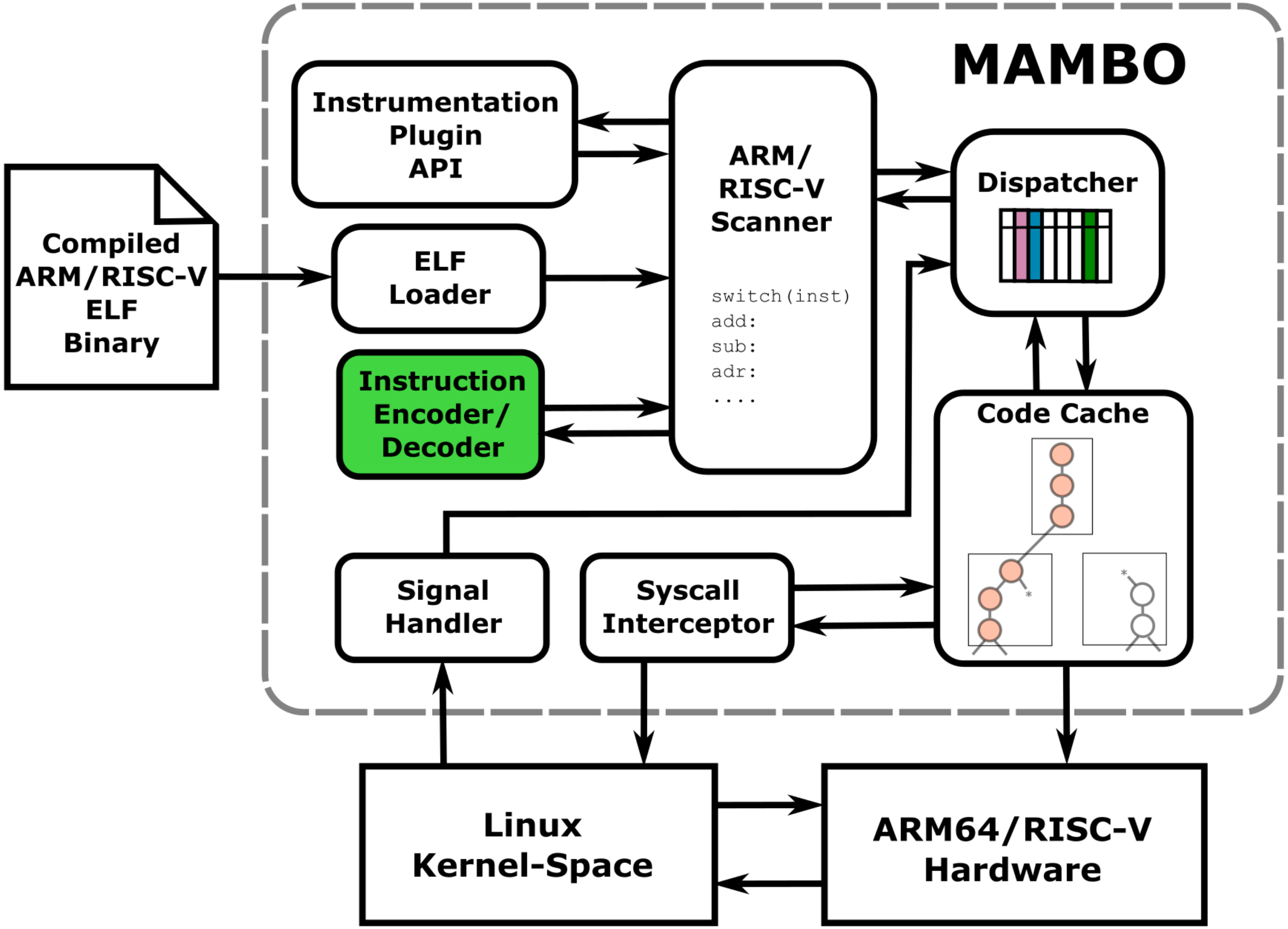

MAMBO
Instrumentation
Plugin
API
Compiled
ARM/RISC-V
ELF
Binary
ELF
Loader
Instruction
Encoder/
Decoder
ARM/
RISC-V
Scanner
switch(inst)
add:
sub:
adr:
....
Dispatcher
Code Cache
Signal
Handler
Syscall
Interceptor
Linux
Kernel-Space
ARM64/RISC-V
Hardware

ELF Loading

- Executable & Linking Format (ELF).
- Binary format for Linux and Unix-like operating systems.
  - Provides static information for linker to build executable.
  - Provides runtime information needed for the loader.
- MAMBO is loaded as a normal program by the Linux loader (ld).
- MAMBO then must act as the loader for the hosted application.
  - Uses libelf to parse ELF header of hosted program.
  - Sets up virtual address space for program to execute.
  - Parses program arguments.
  - Sets up initial stack frame.
  - Sets up global data.
- The readelf utility is useful for many tasks when developing MAMBO plugins.

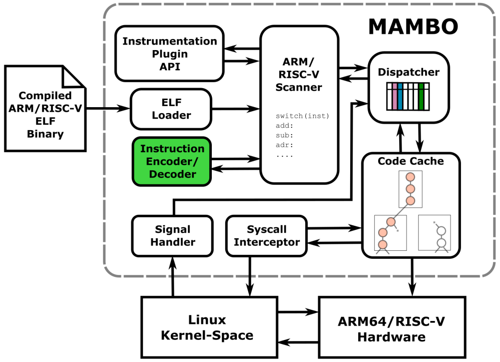


Instruction Encoder/Decoder

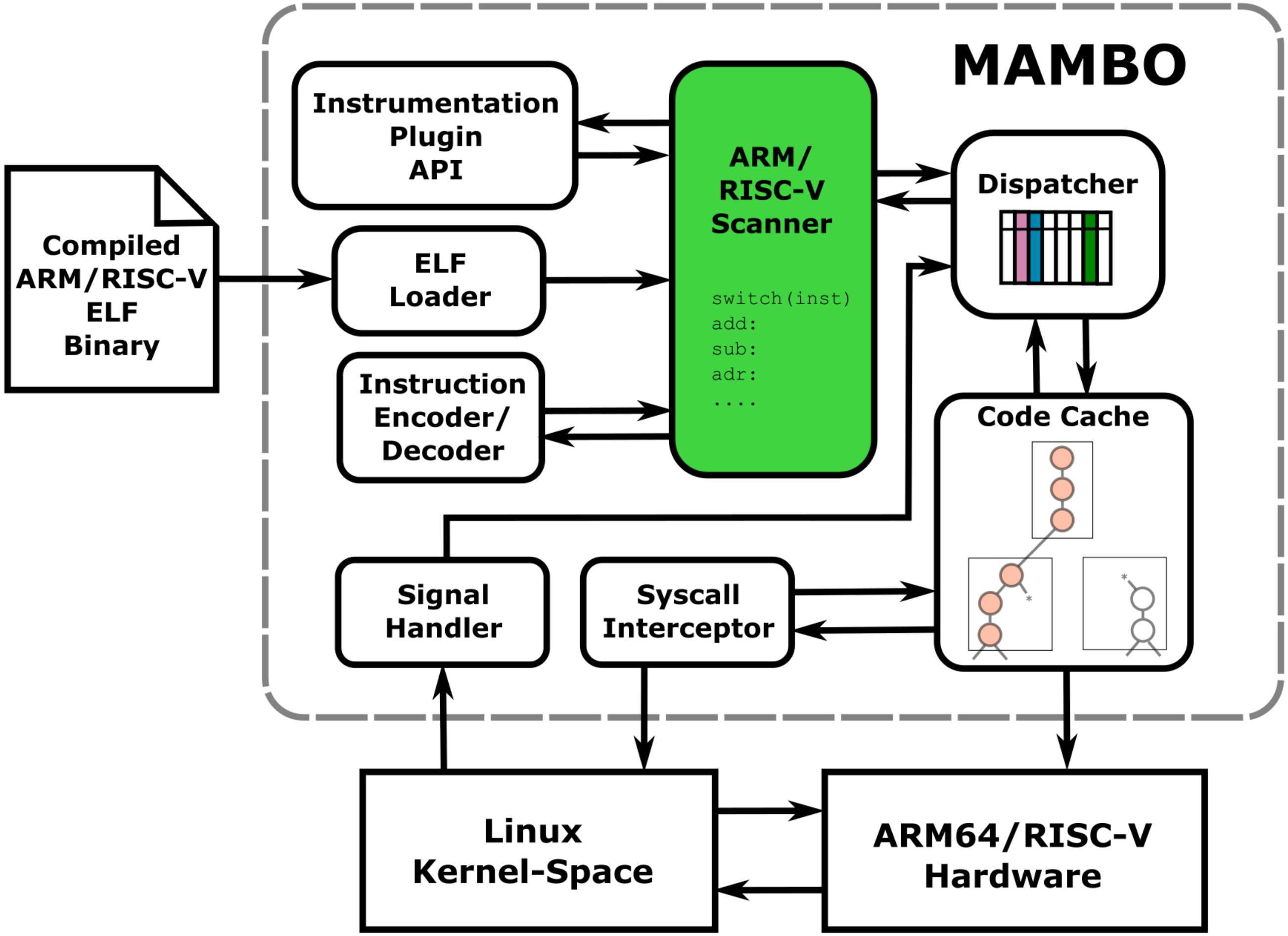


Instruction Encoder/Decoder

– Automatic generation of encoder/decoder from a text file with instructions specification within.
– Raw binary instructions decoded and fields separated for use by the scanner.
– The instructions are grouped into instruction types.
  - Scanner can then decode further, or...
  - User can decode fields with API for certain user plugin tasks.
– If adding a new instruction, this is where you would do it.



Basic Block Scanning



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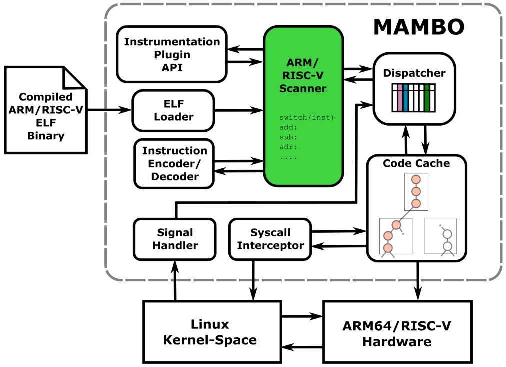
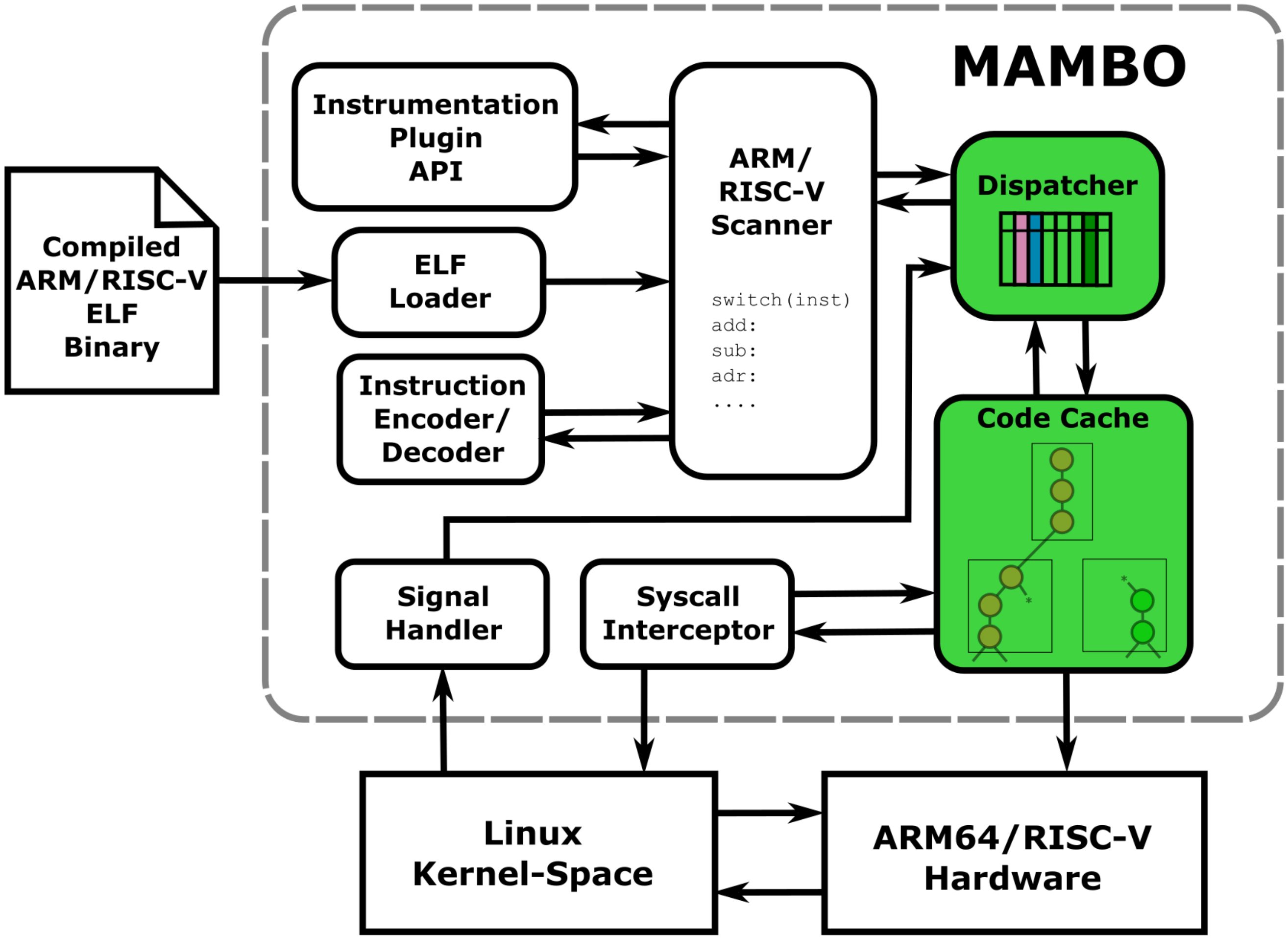
Basic Block Scanning

- The scanner reads basic blocks of the program, which are then placed in the code cache for execution.
- Reads instructions in from the hosted program one by one.
- Modifies the instruction for execution under MAMBO if required.
  - Branching instructions.
  - Instructions which use PC relative addressing.
  - Special instructions such as system register access, or syscalls.
- If no modifications required, straight to the code-cache.
  - Copy & annotate.
  - As opposed to disassemble & resynthesise.
- After the full basic block is scanned, hand off execution to the dispatcher.



Dispatch and Code-Cache



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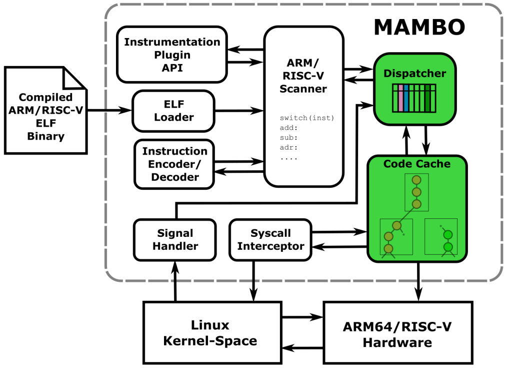
Dispatch and Code-Cache

- The code cache is used to help amortize cost of scanning (pareto principle).
- Basic blocks are scanned into the code cache single entry single exit
  - i.e. only branch taken is scanned in.
- Hash table maps scanned application addresses to code cache addresses.
- Translated blocks branch to hash lookup in dispatcher
  - Fast lookup, 15 instructions for indirect branch (assuming no collisions).
  - If hit, jump to translated address.
  - If not, go to dispatcher to prepare scanning new basic block.
- Thread private code cache. Share nothing.
  - Simple multi-threaded support.
  - Limits thread scalability.



Dispatch and Code-Cache

Original application code

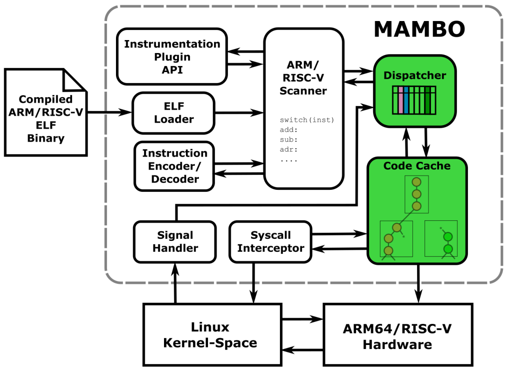
```
BB_X:
0x100    str x1, [x3, x0, lsl #3]
0x104    ldr x0, [x1, #0x10]!
0x108    cbnz x0, 0x80
```

Translated Basic Block in CC

```
T_BB_X:
0xff300    pop x0, x1
0xff304    str x1, [x3, x0, lsl #3]
0xff308    ldr x0, [x1, #0x10]!
0xff30C    cbnz x0, tpc_of(#Next
   BB)
0xff310    b tpc_of(#Next BB)
```

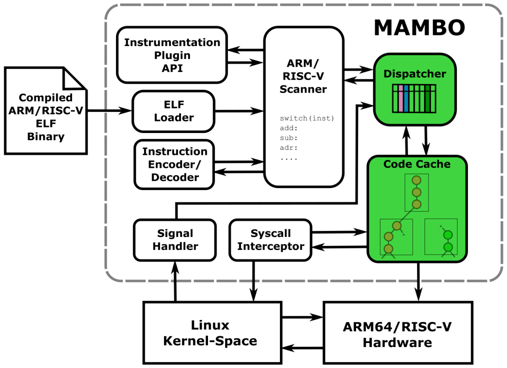
MAMBO dispatcher trampoline

```
tpc_of:
0xe0000    push x0, x1
…
Jumping to scanner or to the next T_BB
```

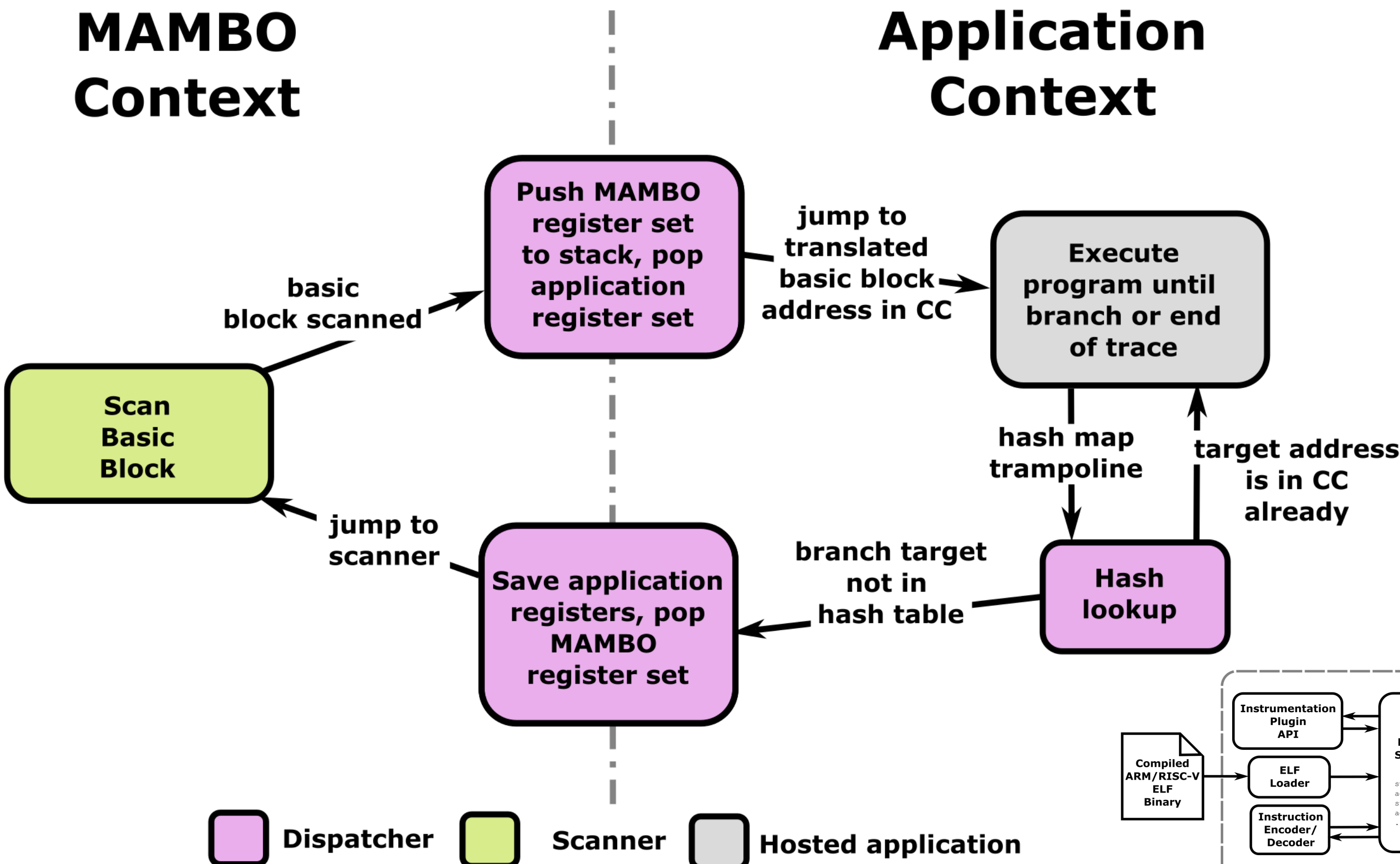


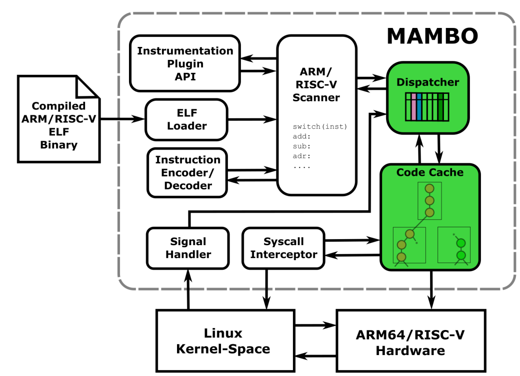
Dispatch and Code-Cache

- Direct branches.
  - Branch exits go to trampoline.
- Indirect branches.
  - Main source of overhead for DBM systems.
  - Optimization uses an inline hash lookup to determine if entry in CC.
- Dispatcher moves between MAMBO and application context.
  - Saves register state for current context.
  - Restores register state for next context.
  - Trampoline jumps to target address.
- *Traces* reduces this overhead by modifying branch targets for *hot* regions.

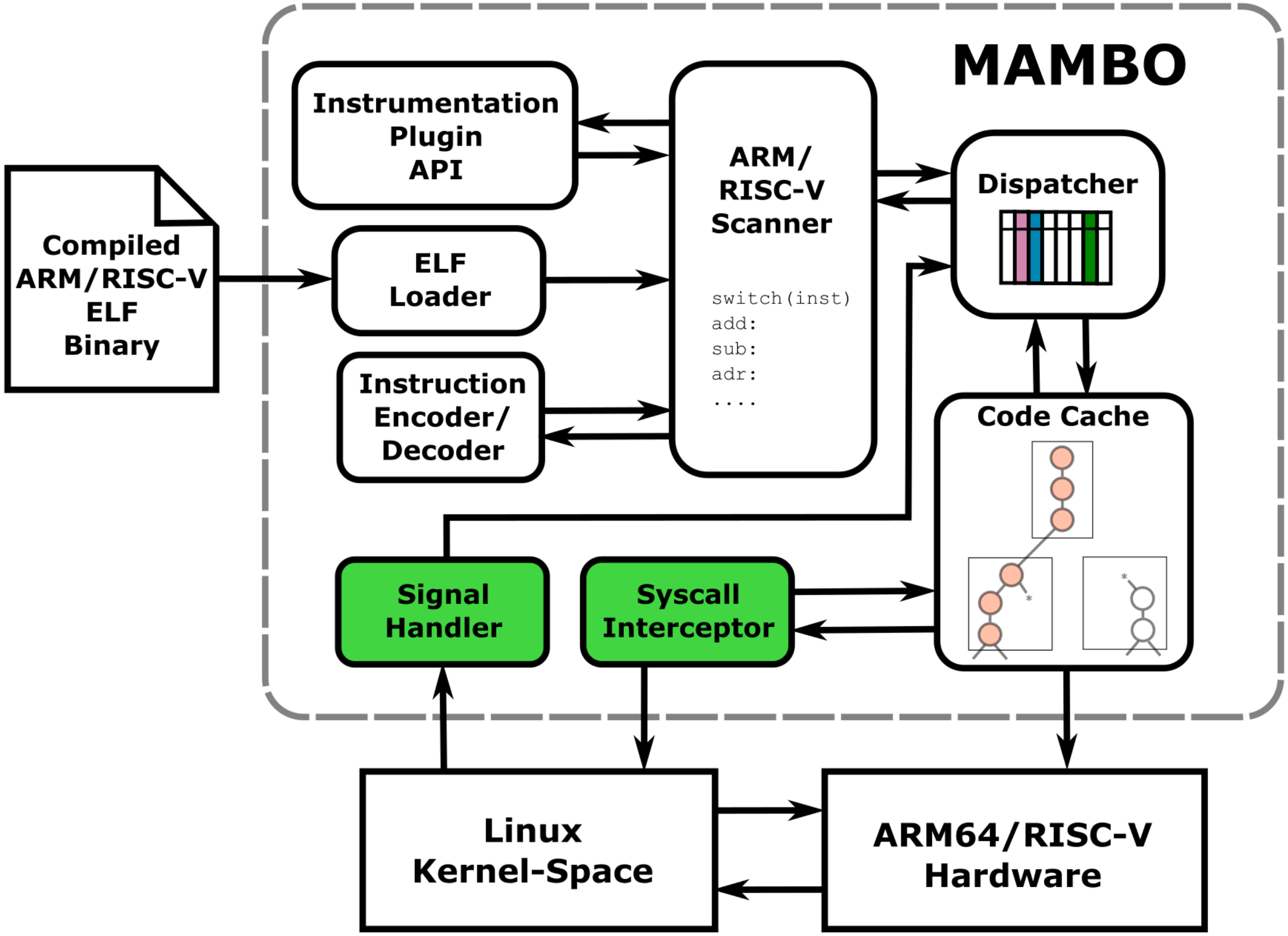


Dispatch and Code-Cache



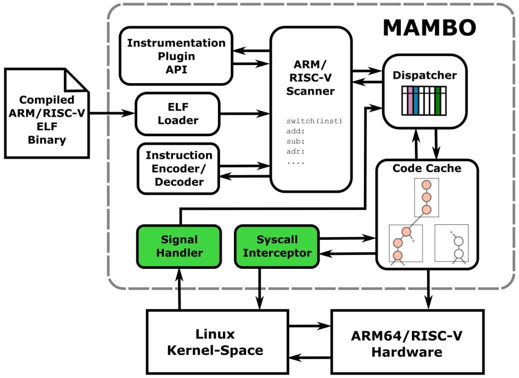


Kernel Interaction



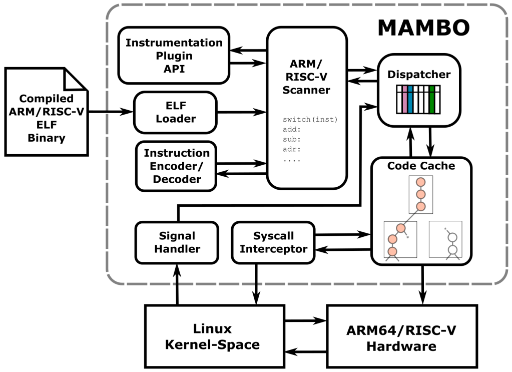
Kernel Interaction

- MAMBO sits in userspace between hosted application and the OS.
  - MAMBO cannot instrument the kernel.
- Some kernel interaction has consequences for MAMBO. So all kernel interaction from application must be wrapped and handled by MAMBO.
- Signals from kernel are passed to MAMBO. MAMBO handles passing signal to application.
  - MAMBO may need to modify stack to remove MAMBO data, allowing stack unwinding for example.
- Syscalls in application code become jumps back to MAMBO space.
  - Syscall not known until runtime.
  - Certain syscalls must be handled differently.
    - E.g. thread creation/destruction.



Main Points for MAMBO

- MAMBO and the hosted application share the same process
  - Thus share the same address space.
  - System registers and execution time are shared between MAMBO and the app.
  - MAMBO is not designed to secure itself against malicious activity from the application it is translating.
- Execution in the process swaps between MAMBO space (scanning & plugin callbacks) and actual application execution.
- MAMBO and the app are in userspace. No analysis in kernel space. Kernel interaction by app is wrapped and handled by MAMBO.



MAMBO Repo

```
./mambo
    ├── api/
    ├── arch/
    |    └── ...
    ├── docker/
    ├── docs/
    |    └── ...
    ├── elf/
    ├── pie/
    ├── plugins/
    |    └── ...
    └── test/
         └── ...
    | dbm.c/h
    | plugins.h
    | signals.c
    | syscalls.c/h
    | traces.c
    | utils.S/h
```

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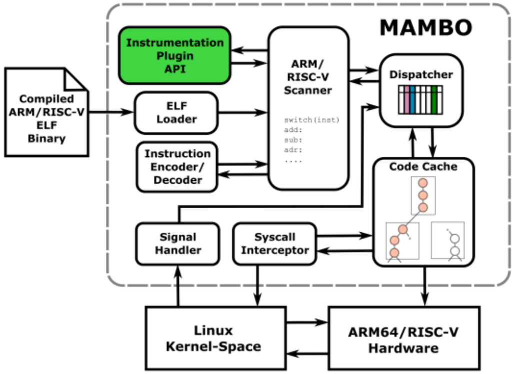
Introduction to MAMBO plugin API



MAMBO Plugins

- MAMBO Plugins use an event driven programming model
- Examples for the typical use case for plugins:
  - Code analysis
    - Building CFG
  - Code generation
    - Insertion of new functionality
  - Code modification
    - Reimplementation of library functions
    - Soft implementations of hardware instructions
  - Code instrumentation
    - Performance counters
    - Metrics on code hotspots
  - Runtime event handling
    - Tracking thread creation/destruction

Event Driven Programming Model

- User defined functions are registered as callbacks upon specific events.
- Internally MAMBO will execute callback functions when the event is encountered.
- Two categories of events:
  - Hosted application runtime events (need to be specially handled by MAMBO, e.g. system calls).
  - MAMBO scan-time events (most typically used for analysis and general instrumentation).
- Provides a simple way for a user to instrument/analyse their application.
  - Fine grained instrumentation (per-instruction).
  - Instrumentation on higher level abstractions, e.g:
    - thread creation/destruction.
    - calls to specific function symbols etc.

MAMBO API Event Flow

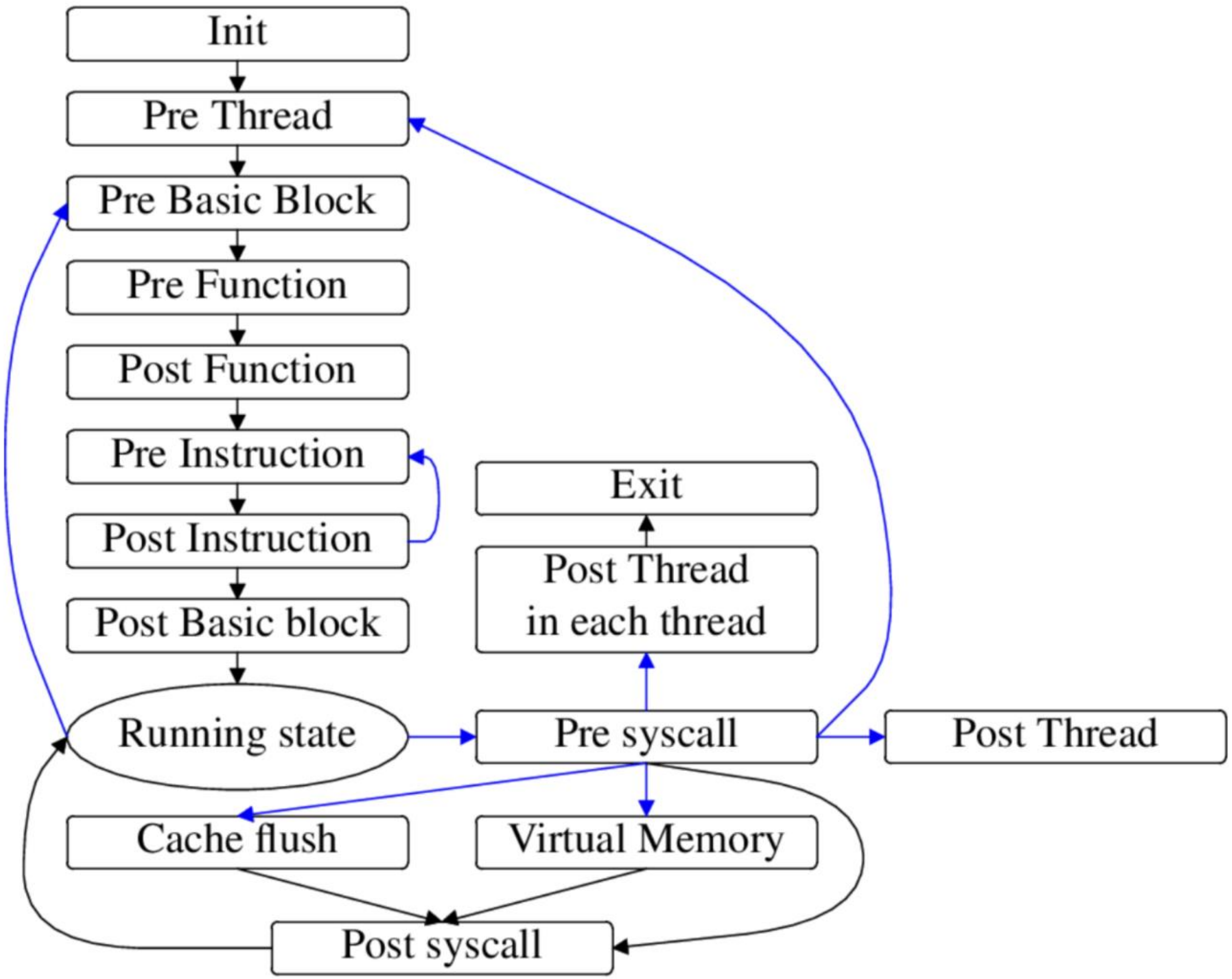


Image taken from: Gorgovan et al. Balancing Performance and Productivity for the Development of Dynamic Binary Instrumentation Tools: A Case Study on Arm Systems, p.3.

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MAMBO API

- MAMBO's API consists of different types of functions for users:
  - Constructor function.
  - Callback registering functions.
  - Code analysis functions:
    - Get branch types.
    - Get addresses and fields.
  - Code instrumentation functions:
    - Set registers.
    - Perform memory operations (load/store).
    - Call user defined functions (C/ASM).
    - Insert other instructions.
  - Data structure helpers:
    - Hash table support.
    - Get/set private MAMBO data.

Constructor Function

- Used to register the plugin in MAMBO.
  - Required before main MAMBO program runs (hence compiler attribute).
  - Callbacks should also be registered in here...
  - Allocation of the *context* for the plugin should happen here. You will need:

```
_attribute__((constructor)) void <plugin name>() {
    mambo_context * ctx = mambo_register_plugin();
    ...
    ...
}
```

`_attribute__((constructor))`

The constructor attribute causes the function to be called automatically before execution enters main(). […] Functions with these attributes are useful for initializing data that will be used implicitly during the execution of the program.

Source: https://gcc.gnu.org/onlinedocs/gcc-4.7.0/gcc/Function-Attributes.html

MAMBO Context

```
mambo_context * ctx = mambo_register_plugin();
```

– Context provides necessary data structures which the user needs to analyse/instrument the code. Some useful fields are:

```
ctx->code.read_address // The untranslated application address of an instruction.
ctx->code.write_p      // The current code cache address to place the next instruction.
ctx->code.inst         // The enum of the decoded instruction.

// Thread private data can be stored and retrieved with these functions.
void * mambo_get_thread_plugin_data(mambo_context *ctx);
int mambo_set_thread_plugin_data(mambo_context *ctx, void *data);
```

Callback Registering Functions

– Used to call your own functions when a given event happens at scan/runtime (see plugin_support.h):

```
// Call <user function> before every instruction is scanned at SCAN-TIME.
int mambo_register_pre_inst_cb(mambo_context *ctx, &<user function> );

// Call <user function> before every basic block is SCAN-TIME.
int mambo_register_pre_basic_block_cb(mambo_context *ctx,
    &<user function> );

// Call <user function> after every thread is destroyed at RUNTIME.
int mambo_register_post_thread_cb(mambo_context *ctx, &<user function> );

// Call <user function> before a syscall is executed at RUNTIME.
int mambo_register_pre_syscall_cb(mambo_context *ctx, &<user function> );
```

Callback Registering Functions

– Used to call your own functions when a given event happens at scan/runtime (see plugin_support.h):

```
// Call <user fn pre> before and <user fn post> after a function with
symbol fn_name is scanned at SCAN-TIME.
int mambo_register_function_cb(
    mambo_context *ctx,
    char *fn_name,
    & <user fn pre> ,
    & <user fn post> ,
    int max_args);
```

Code Analysis Functions

– Used to help analyse code that triggered the callback functions (see plugin_support.h).

```
// is the inst a branch? is it direct, indirect, etc?
mambo_branch_type mambo_get_branch_type(mambo_context *ctx);

// is it a conditionally executed instruction?
mambo_cond mambo_get_cond(mambo_context *ctx);

bool mambo_is_load(mambo_context *ctx);
bool mambo_is_store(mambo_context *ctx);

// if load or store, what size of data does it access?
int mambo_get_ld_st_size(mambo_context *ctx);

// what's the size of the instruction word? 2 / 4 bytes for Thumb
int mambo_get_inst_len(mambo_context *ctx);
```

Code Analysis Functions

– Used to help analyse code that triggered the callback functions (see plugin_support.h).

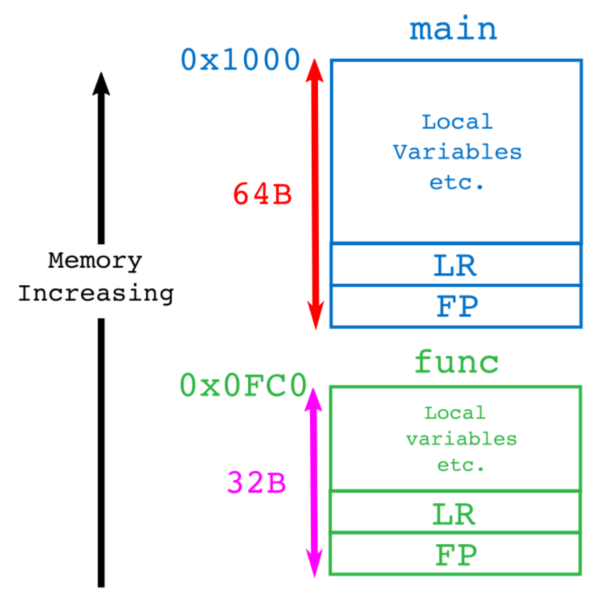
```
int plugin_pre_inst_handler(mambo_context *ctx) {
    mambo_branch_type type = mambo_get_branch_type(ctx);
    if (type & BRANCH_RETURN) {
        // Procedure return instruction
    } else if (type & BRANCH_DIRECT) {
        // Direct branch instruction }
    else if (type & BRANCH_INDIRECT) {
        // Indirect branch instruction
    }
}
```

AARCH64 Assembly / ABI Recap

- Register file comprised of 32 registers (X0-X31).
  - Stack pointer (SP) = X31.
  - Link Register (LR) = X30.
  - Frame Pointer (FP) = X29.
- Arguments to/return values from function calls placed in X0-X7.
- Caller saved X9-X15.
- Callee saved X19-X28.
- Function prologue
  - Push LR & FP, first shifting stack pointer accordingly
- Function epilogue
  - Pop LR & FP, unwinding stack frame

```
main:
     stp  x29, x30, [sp, #-64]!
     mov  x29, sp
     ...
     bl  func
     ...

func:
     stp  x29, x30, [sp, #-32]
     ...
     ldp  x29, x30, [sp], #32
     ret
```



Code Instrumentation Functions

- Used to insert new code into the instruction stream of the basic block in the code cache.
- Some are safe (preserves stack and register state).
- Some are unsafe (you need to preserve stack/register integrity yourself).
- See helpers.h

```
void emit_counter64_incr(mambo_context *ctx, void *counter,
    unsigned incr);
void emit_push(mambo_context *ctx, uint32_t regs);
void emit_pop(mambo_context *ctx, uint32_t regs);
void emit_set_reg(mambo_context *ctx, enum reg reg,
    uintptr_t value);
void emit_fcall(mambo_context *ctx, void *function_ptr);
int  emit_safe_fcall(mambo_context *ctx, void *function_ptr,
    int argno);
int  emit_indirect_branch_by_spc(mambo_context *ctx, enum reg reg);
```

Hash Map Helper

- There is a hash map helper that can be used when instrumenting, to quickly store data and associate with particular code regions etc.
- Useful in the context of binary instrumentation, since lookup at runtime should be fast.

```c
int mambo_ht_init(mambo_ht_t *ht, size_t initial_size,
    int index_shift, int fill_factor, bool allow_resize);

int mambo_ht_add_nolock(mambo_ht_t *ht, uintptr_t key,
    uintptr_t value);

int mambo_ht_add(mambo_ht_t *ht, uintptr_t key, uintptr_t value);

int mambo_ht_get_nolock(mambo_ht_t *ht, uintptr_t key,
    uintptr_t *value);

int mambo_ht_get(mambo_ht_t *ht, uintptr_t key, uintptr_t *value);
```

Plugin API Scan-Time vs. Runtime

– Important to remember. Most common mistake when first writing plugins:

C:

```c
uint64_t run_many_times(uint64_t num) {
  return num * num;
}
```

ARM64:

```
run_many_times:
0x8000 sub sp, sp, #16
0x8004 str x0, [sp, 8]
0x8008 ldr x0, [sp, 8]
0x800C mul x0, x0, x0
0x8010 add sp, sp, 16
0x8014 ret
```

Plugin API Scan-Time vs. Runtime

```
char* message = "We are here\n";

int pre_inst_callback(mambo_context ctx*){
  if(ctx->code.read_address == 0x8000) {
        printf(message);
  }
  return 0;
}
```

```
run_many_times:
0xFC7000 sub sp, sp, #16
0xFC7004 str x0, [sp, 8]
0xFC7008 ldr x0, [sp, 8]
0xFC700C mul x0, x0, x0
0xFC7010 add sp, sp, 16
0xFC7014 ret
```

```
Output:
We are here!
```

```
char* message = "We are here!\n";

int pre_inst_callback(mambo_context ctx*) {
  if(ctx->code.read_address == 0x8000) {
    emit_push(ctx, (1 << 0));
    emit_set_reg(ctx, reg0, message);
    emit_safe_fcall(ctx, my_print_fn, 1);
    emit_pop(ctx, (1 << 0));
  }
return 0;
}
```

```
run_many_times:
0xFC7000 str x0, [sp,#8]
0xFC7014 mov x0, &message
0xFC7018 bl my_print_fn
0xFC7000 ldr x0, [sp,#-8]
0xFC7004 sub sp, sp, #16
0xFC7008 str x0, [sp, 8]
0xFC700C ldr x0, [sp, 8]
0xFC7010 mul x0, x0, x0
0xFC701c add sp, sp, 16
0xFC7020 ret
```

```
Output:
We are here!
We are here!
We are here!
We are here!
...
```

Coffee Break (30 min)

SET UP MAMBO!

IT TAKES 30 - 60 MIN WITH QEMU!

http://tinyurl.com/mambo-docker-setup

MAMBO use-case and example plugin

The following code example can be found at:

https://github.com/beehive-lab/mambo/blob/master/plugins/

Example Plugin: Branch Counter

1. Build the constructor and add required data structures.

```
#ifdef PLUGINS_NEW
...

__attribute__((constructor)) void branch_count_init_plugin() {
  mambo_context *ctx = mambo_register_plugin();
  assert(ctx != NULL);

  mambo_register_pre_inst_cb(ctx, &branch_count_pre_inst_handler);
  mambo_register_pre_thread_cb(ctx, &branch_count_pre_thread_handler);
  mambo_register_post_thread_cb(ctx, &branch_count_post_thread_handler);
  mambo_register_exit_cb(ctx, &branch_count_exit_handler);

  setlocale(LC_NUMERIC, "");
}

...
#endif
```

Example Plugin: Branch Counter

1. Build the constructor and add required data structures.

```
#ifdef PLUGINS_NEW
...

struct br_count {
  uint64_t direct_branch_count;
  uint64_t indirect_branch_count;
  uint64_t return_branch_count;
};

struct br_count global_counters;

...
#endif
```

Example Plugin: Branch Counter

2. Create pre_thread handler to set up initial state.

```
#ifdef PLUGINS_NEW
...

int branch_count_pre_thread_handler(mambo_context *ctx) {
  struct br_count *counters = mambo_alloc(ctx, sizeof(struct br_count));
  assert(counters != NULL);
  mambo_set_thread_plugin_data(ctx, counters);

  counters->direct_branch_count = 0;
  counters->indirect_branch_count = 0;
  counters->return_branch_count = 0;
}

...
#endif
```

Example Plugin: Branch Counter

3. Create pre_inst handler which has the core function of the plugin.

```
#ifdef PLUGINS_NEW
...

int branch_count_pre_inst_handler(mambo_context *ctx) {
  struct br_count *counters = mambo_get_thread_plugin_data(ctx);
  uint64_t *counter = NULL;

  mambo_branch_type type = mambo_get_branch_type(ctx);
  if (type & BRANCH_RETURN) {
    counter = &counters->return_branch_count;
  } else if (type & BRANCH_DIRECT) {
    counter = &counters->direct_branch_count;
  } else if (type & BRANCH_INDIRECT) {
    counter = &counters->indirect_branch_count;
  }

  if (counter != NULL) {
    emit_counter64_incr(ctx, counter, 1);
  }
}
...
#endif
```

Example Plugin: Branch Counter

4. Create post_thread handler which clears up after program execution.

```
#ifdef PLUGINS_NEW
...

int branch_count_post_thread_handler(mambo_context *ctx) {
  struct br_count *counters = mambo_get_thread_plugin_data(ctx);

  fprintf(stderr, "Thread: %d\n", mambo_get_thread_id(ctx));
  print_counters(counters);
  atomic_increment_u64(&global_counters.direct_branch_count,
                       counters->direct_branch_count);
  atomic_increment_u64(&global_counters.indirect_branch_count,
                       counters->indirect_branch_count);
  atomic_increment_u64(&global_counters.return_branch_count,
                       counters->return_branch_count);
  mambo_free(ctx, counters);
}

...
#endif
```

Example Plugin: Branch Counter

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5. Create exit handler which displays results before termination.

```
#ifdef PLUGINS_NEW
...

void print_counters(struct br_count *counters) {
  fprintf(stderr, "  direct branches: %'" PRIu64 "\n",
   counters->direct_branch_count);
  fprintf(stderr, "  indirect branches: %'" PRIu64 "\n",
   counters->indirect_branch_count);
  fprintf(stderr, "  returns: %'" PRIu64 "\n",
   counters->return_branch_count);
}

int branch_count_exit_handler(mambo_context *ctx) {
  fprintf(stderr, "Total:\n");
  print_counters(&global_counters);
}

...
#endif
```

lantj@lantj: /mnt/josh_stuff/mambo_tutorial/mambo ⌥⌘1

lantj@softwood: ~ (-zsh) ⌘1 | ...ambo_tutorial/mambo (ssh) ⌘2 | ...ddc: ~/riscv (com.docker.cli) ⌘3 | tmux ⌘4

```
lantj@lantj:~$ 
```

```
[0] 0:bash  1:bash  2:bash  3:vim  4:bash- 5:bash*                   "lantj" 15:27 11-Jan-24
```

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SimAcc: A Configurable Simulator for customised accelerators on SoCs with FPGAs.

SimAcc: A Configurable Cycle-Accurate Simulator for Customized Accelerators on CPU-FPGAs SoCs
https://ieeexplore.ieee.org/document/8735519

Search Wikipedia
Search

Multi-tool

Article Talk

From Wikipedia, the free encyclopedia

A **multi-tool** (or **multitool**) is a hand tool that combines several individual functions in a single unit. The smallest are credit-card or key sized units designed for carrying in a wallet or on a keyring, but others are designed to be carried in a trouser pocket or belt-mounted pouch.

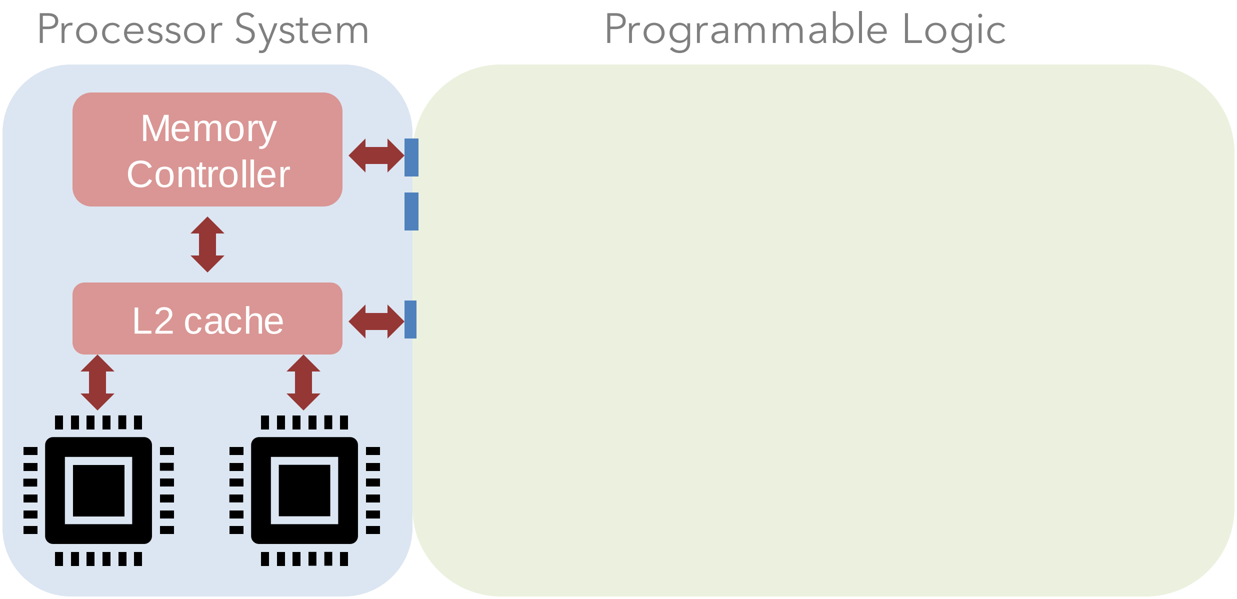
Motivation.

A trend for System-on-Chips is to include application specific accelerators on the die. However:

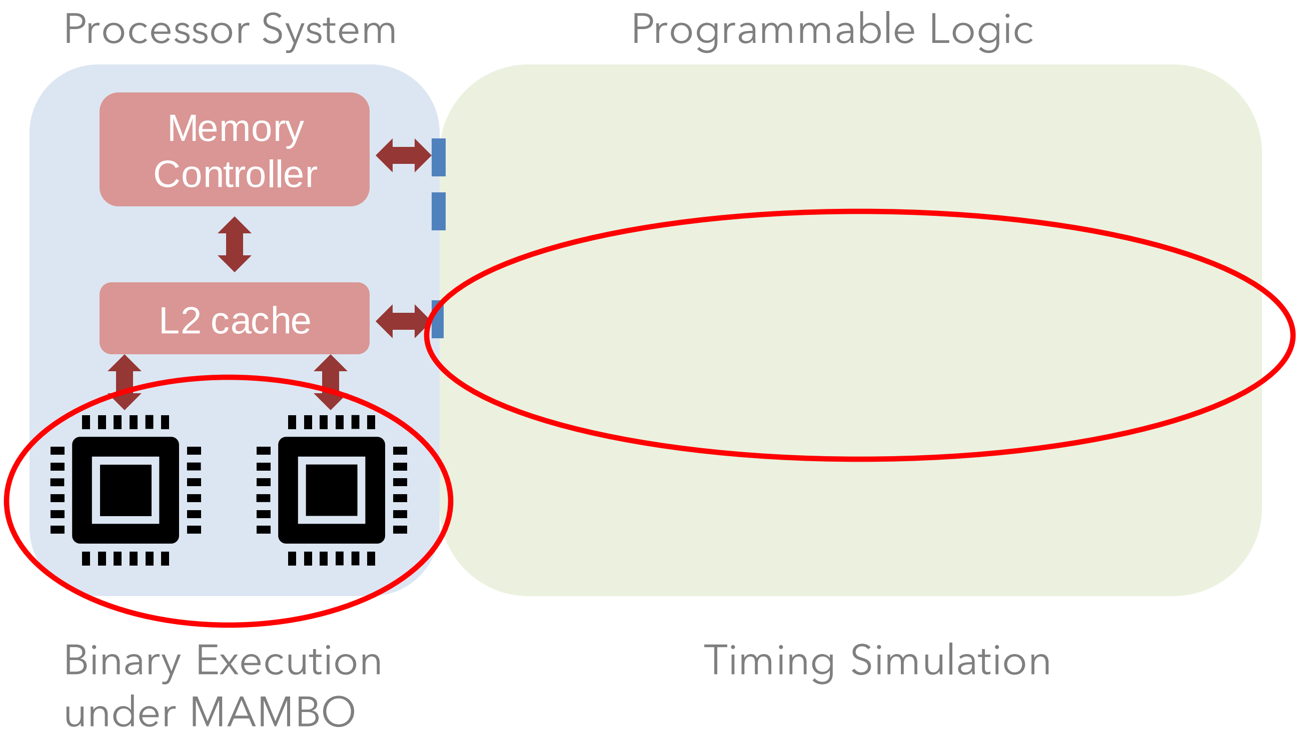
- Could we design a simulation infrastructure for **fast** computer architecture simulation and **prototyping of accelerator IP** on SoCs with FPGAs?

- How do **hardware accelerators interact** with the processors of a system and what is the **impact** on overall performance?

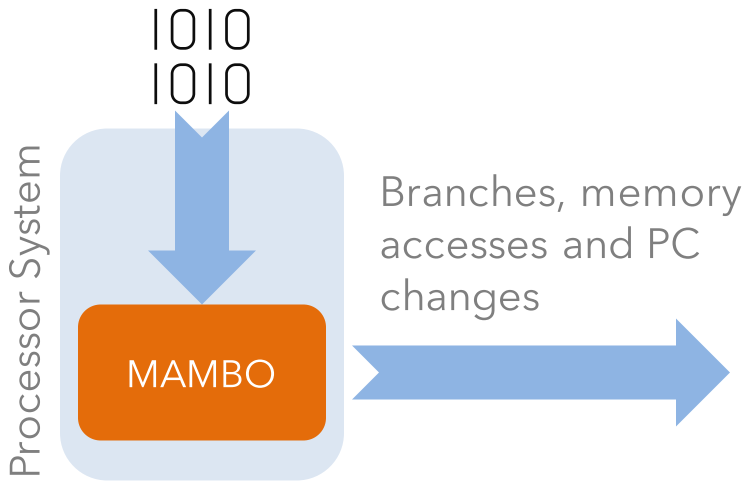
Simulation Infrastructure.



Simulation Infrastructure.

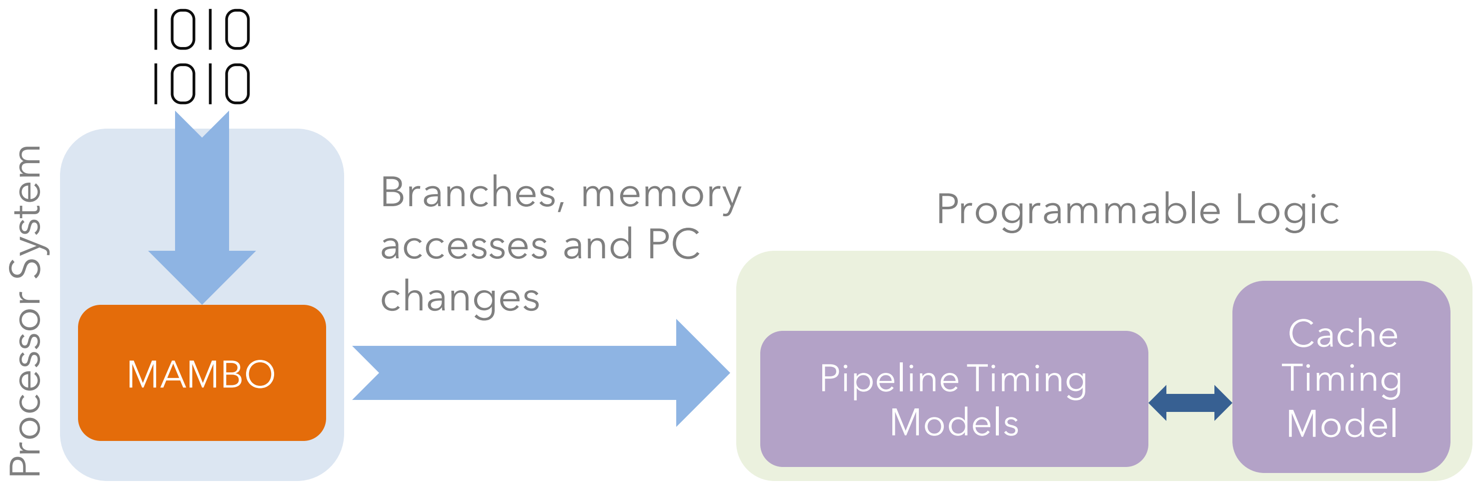


Simulation Infrastructure.



MAMBO plugin consists of a set of callbacks (are executed at various points of the program execution) and drives the hardware models on the Programmable Logic Part of the host platform.

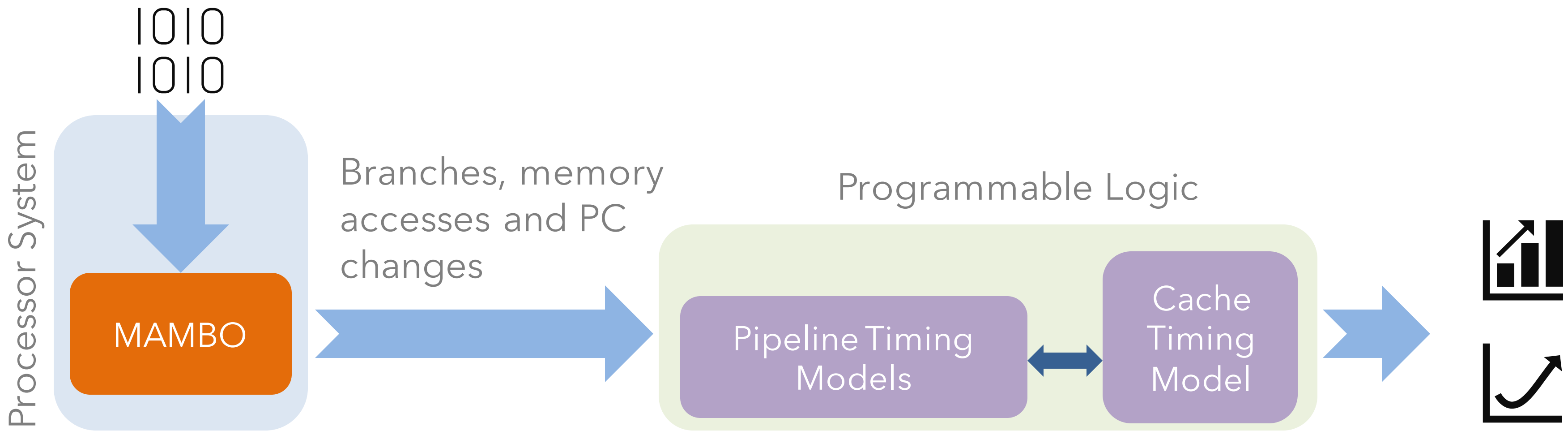
Simulation Infrastructure.



- Pipeline Model (inspired by Arm Cortex-A9)
    - Re-order buffer, register renaming module, branch prediction models, Branch Target Buffer (BTB), return address stack (RAS), and LD/ST queue.

- Cache System Model
    - It gathers statistics about the behaviour of a cache system. The model stores only address tags and states for cache lines.

Simulation Infrastructure.



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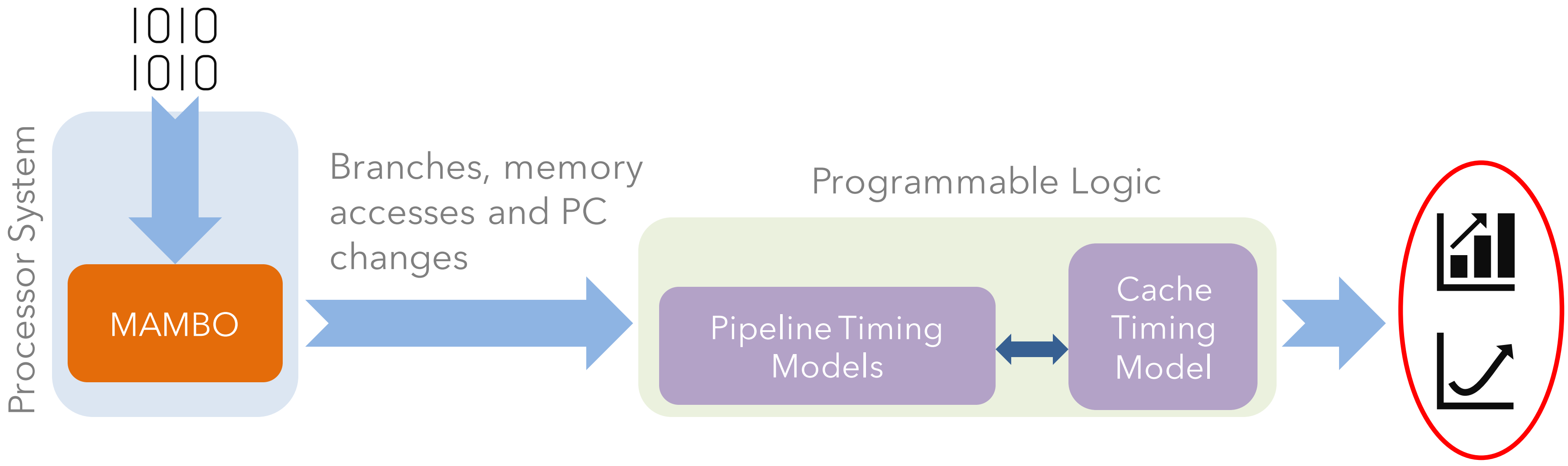

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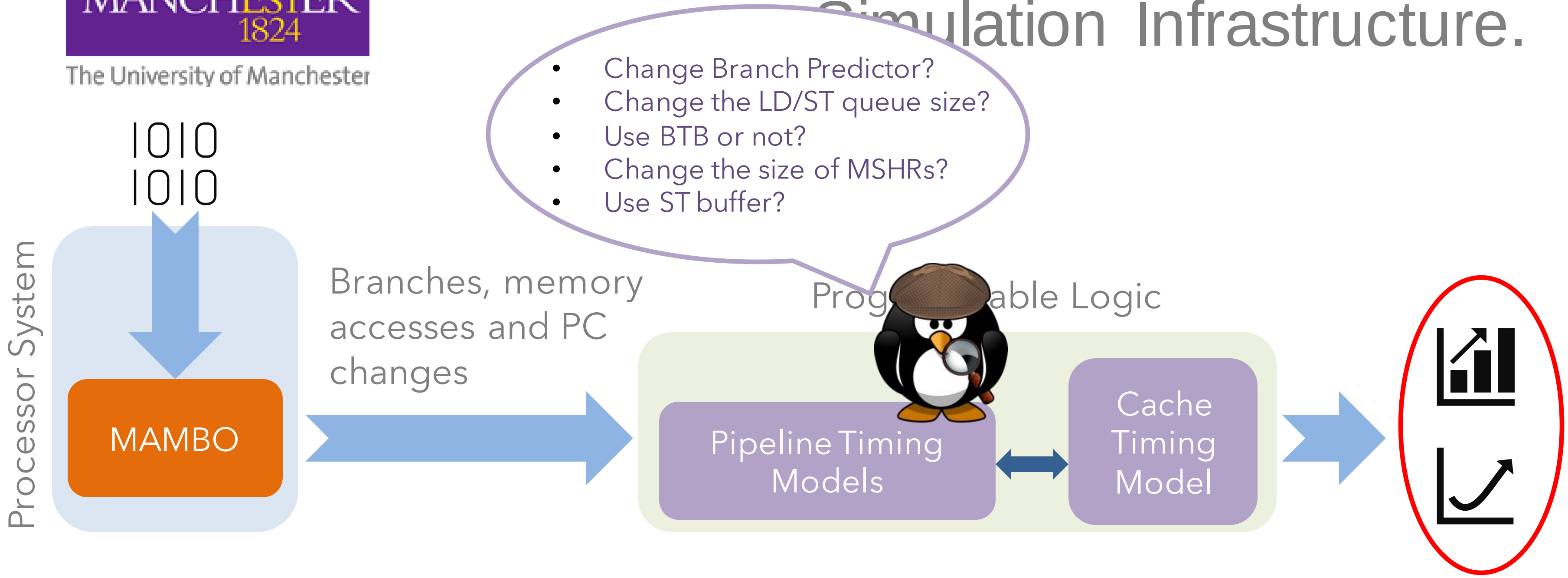

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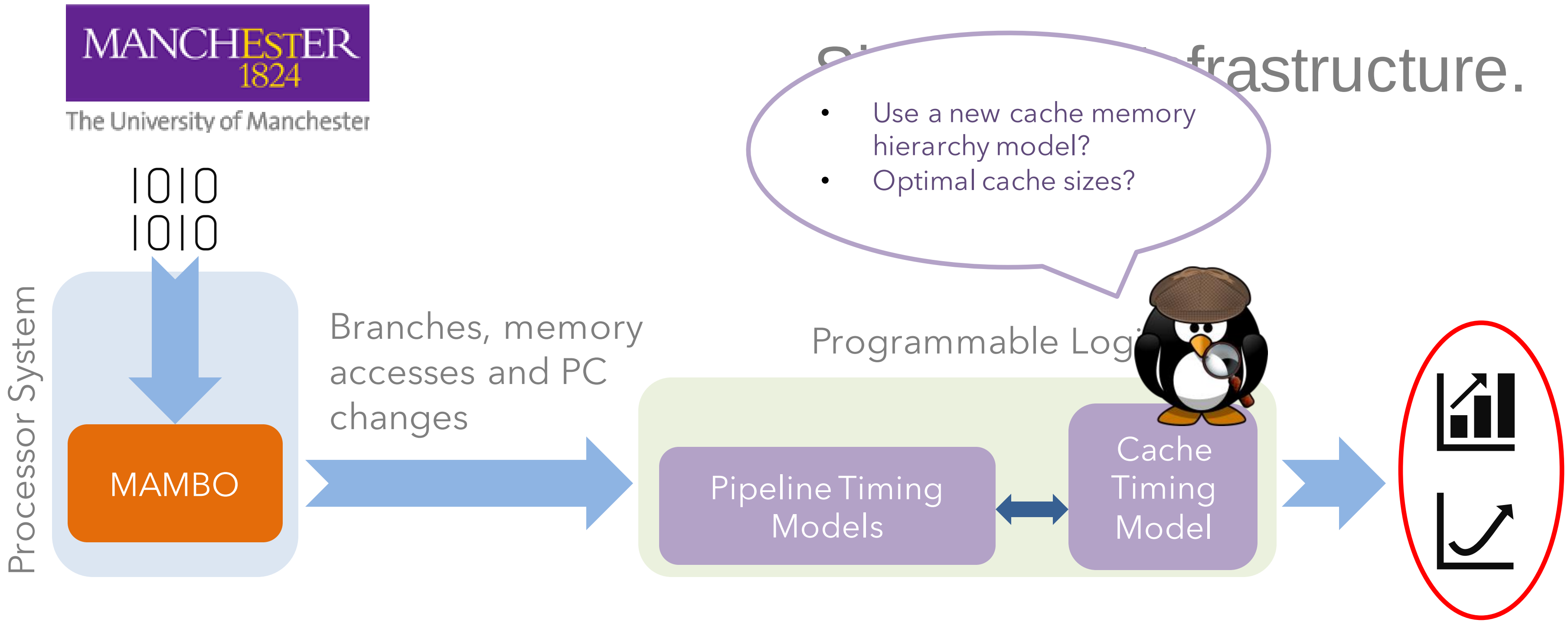

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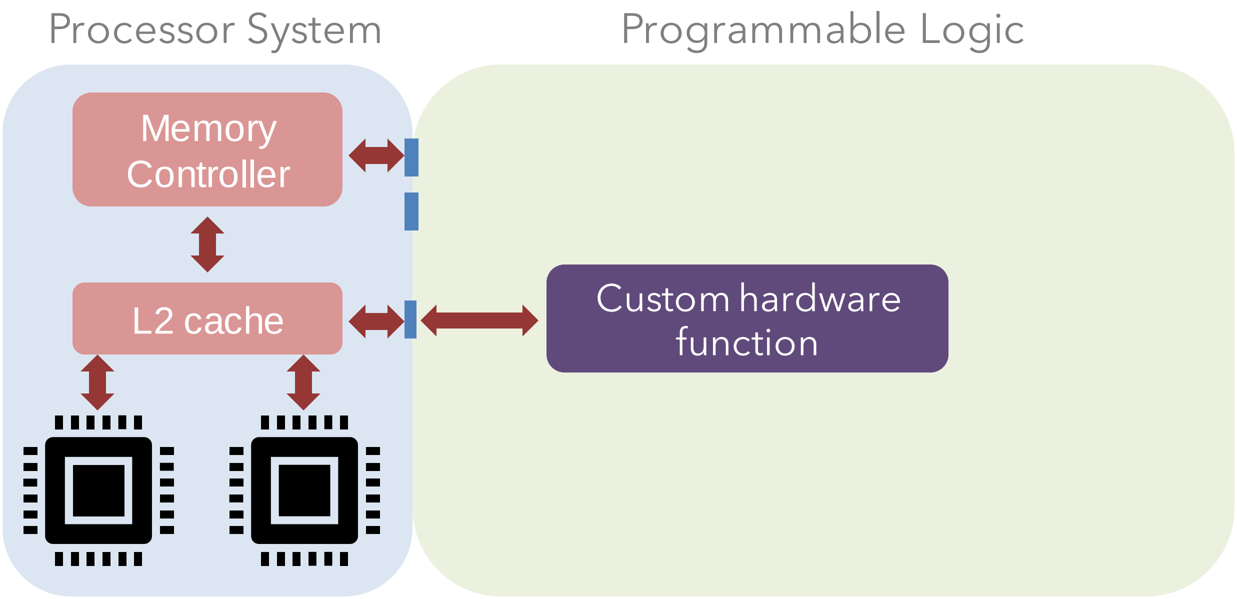
Simulation of Accelerated Apps.



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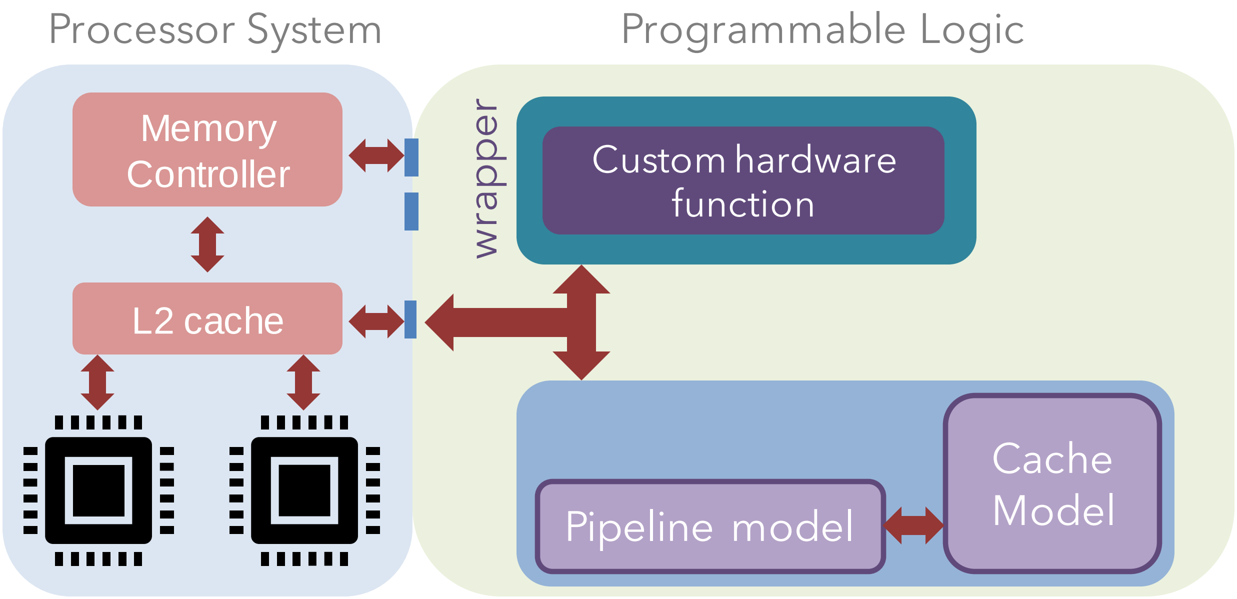
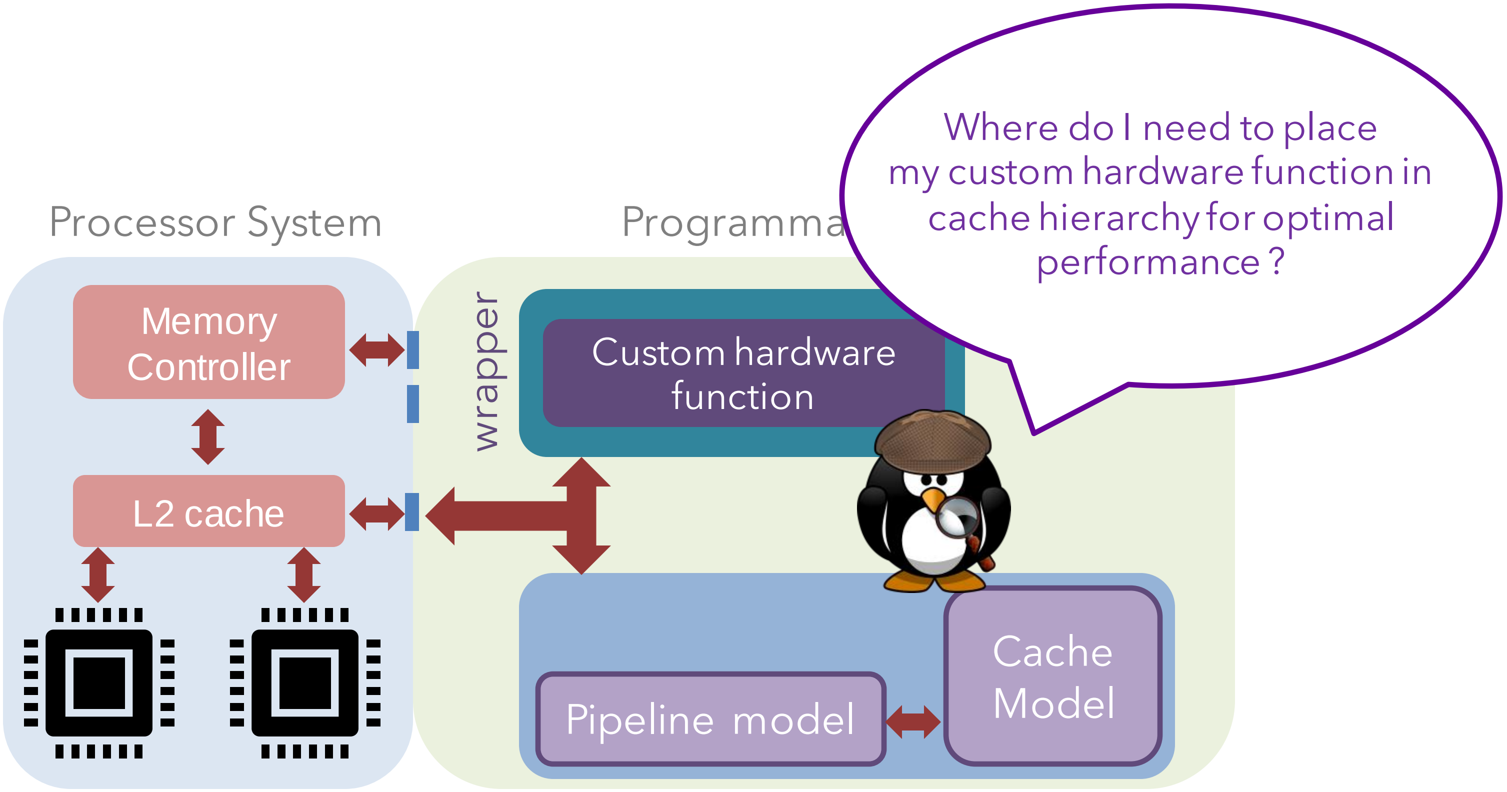
Simulation of Accelerated Apps.



Simulation of Accelerated Apps.



Hands On MAMBO session

Hands on MAMBO Session

Lab script:

Docs/ in MAMBO Repository
http://tinyurl.com/mambo-tutorial

Follow the instructions in the document

4 Main Exercises + Introduction + Extras

IMPORTANT!

PLEASE ASK US QUESTIONS!

MAMBO Roadmap

- Foster an open-source community
  - Collaborations/Contributions welcome
- Improve Documentation
- More tools
  - data race detector
  - call graph
- Keep up with Arm and RISC-V
- Current research projects
  - fast architectural simulation
  - cybersecurity
  - binary lifting

Thanks to the Digital Secure by Design programme

End of the tutorial

MAMBO Tutorial at HiPEAC 2024 - Feedback Form