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MAMBO
Dynamic Binary Modification for RISC-V

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Introduction to Dynamic Binary Modification (DBM) and MAMBO

What is DBM / DBI / DBT?

What is DBM?

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Example DBM / DBI / DBT

Valgrind

QEMU

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What is DBM / DBI / DBT?

- **D**ynamic - Working at runtime
- **B**inary - Natively compiled user-space code
- **M**odification - Alteration of applications

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What is DBM / DBI / DBT?

- **D**ynamic - Working at runtime
- **B**inary - Natively compiled user-space code
- **M**odification - Alteration of applications

- **I**nstrumentation – Inserting additional functionality
- **T**ranslation- Translating one instruction set into another

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Uses of DBM / DBI / DBT tools

- Program analysis
  - Callgrind (Valgrind)
- Memory error detection / debugging
  - Memcheck (Valgrind), Dr. Memory (DynamoRIO), Memcheck (MAMBO)
- Dynamic binary translation
  - QEMU, Apple Rosetta, TANGO

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Why MAMBO?

- Optimized for RISC-V 64-bit, ARM 32-bit & ARM 64-bit
  - Low overhead
  - **Only available DBM optimized for RISC-V**
- Low complexity
  - Relatively small codebase (~20k LoC)
- Simple plugin API
  - Architecture agnostic helper functions for portable plugins
- Not a toy

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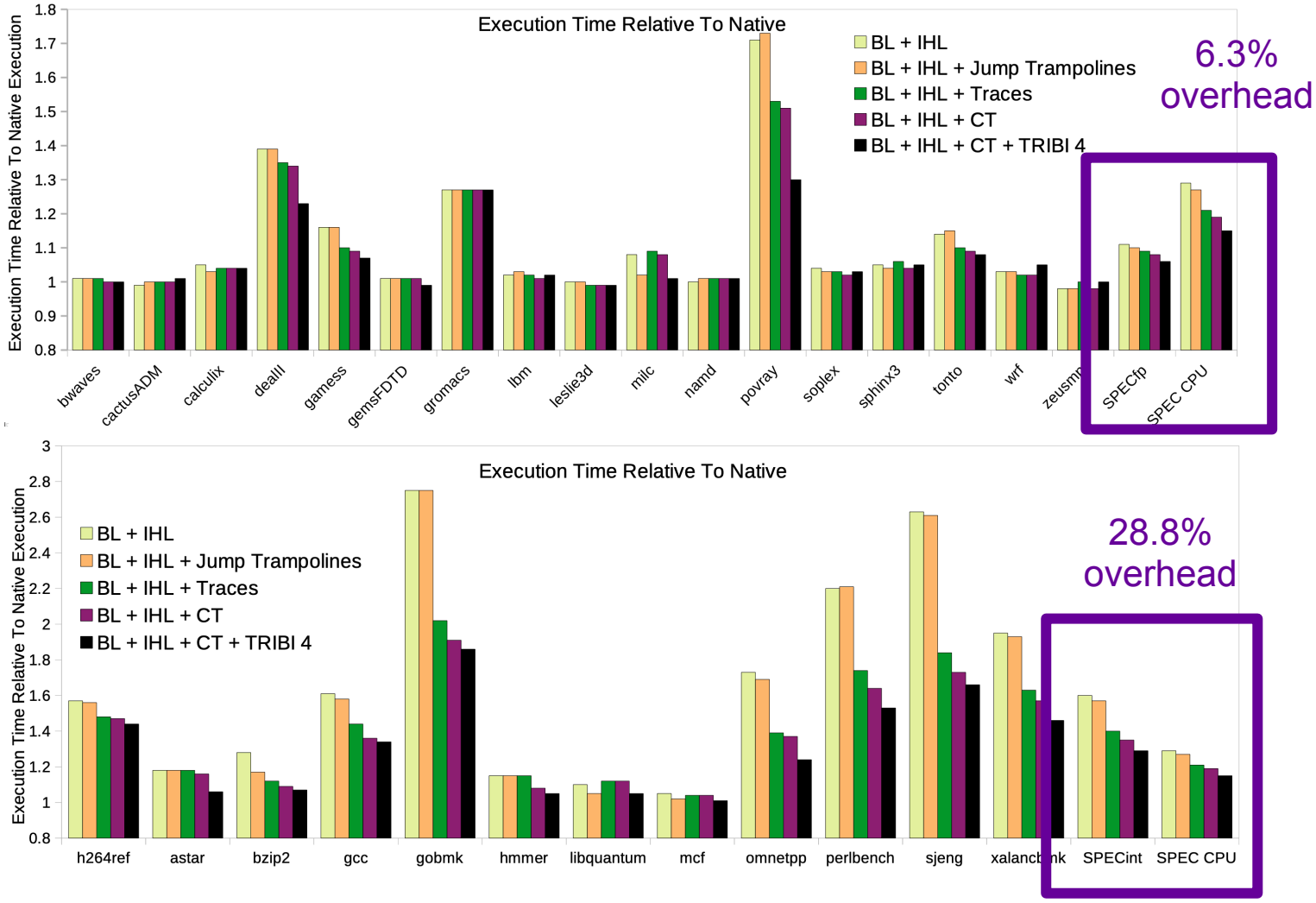
Why MAMBO on RISC-V?



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.

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MAMBO Architecture

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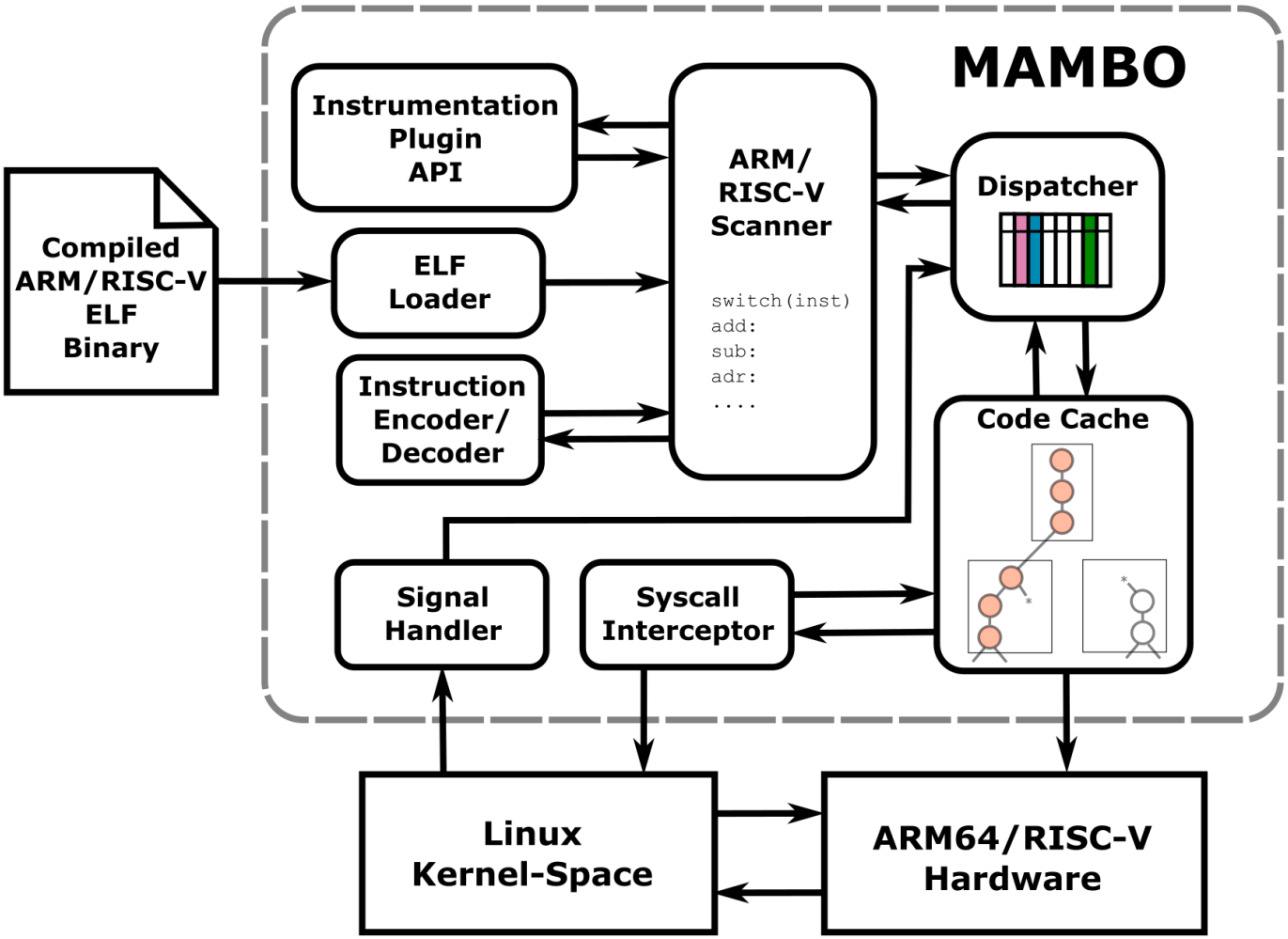
MAMBO Architecture



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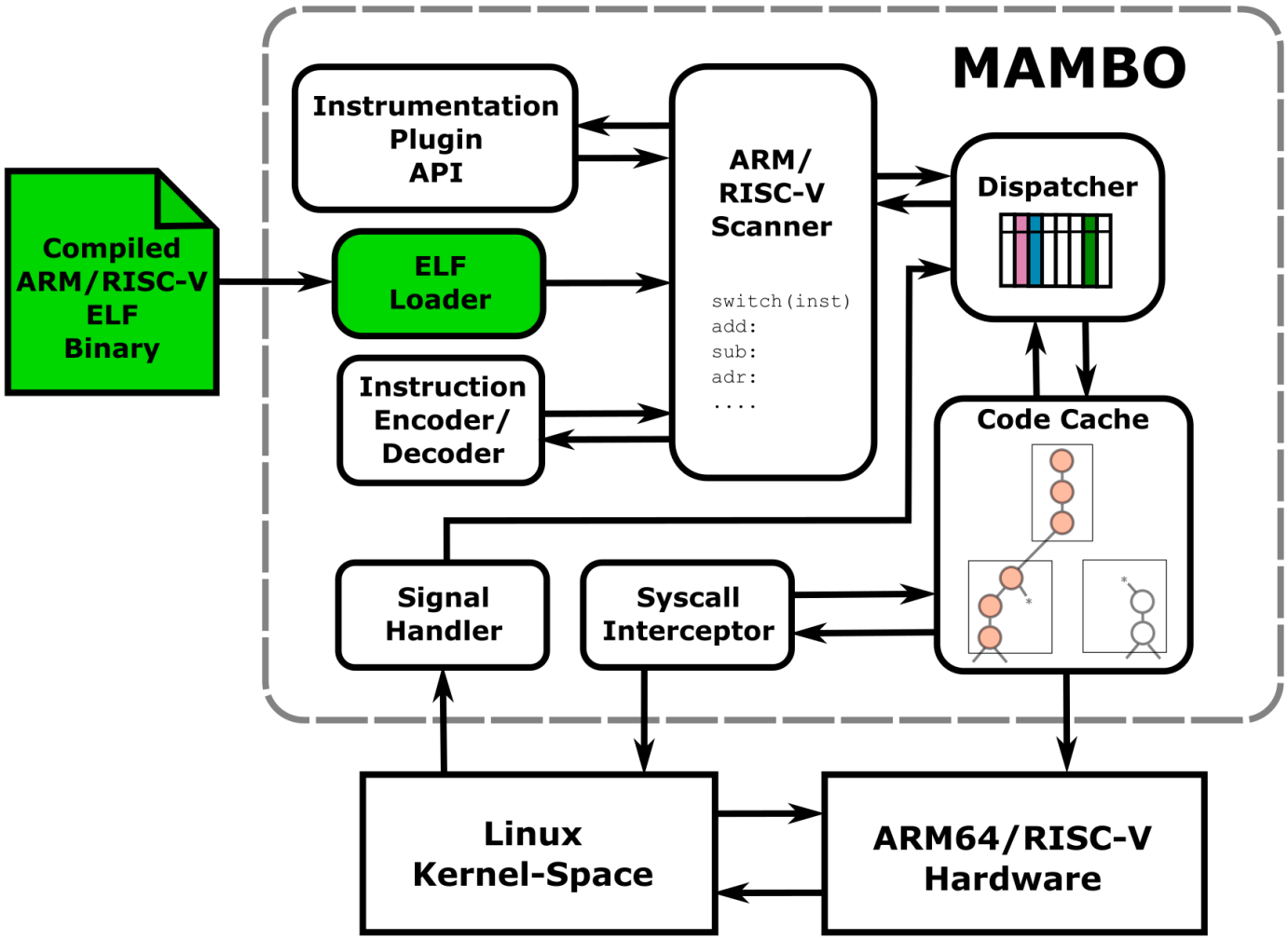
ELF Loading



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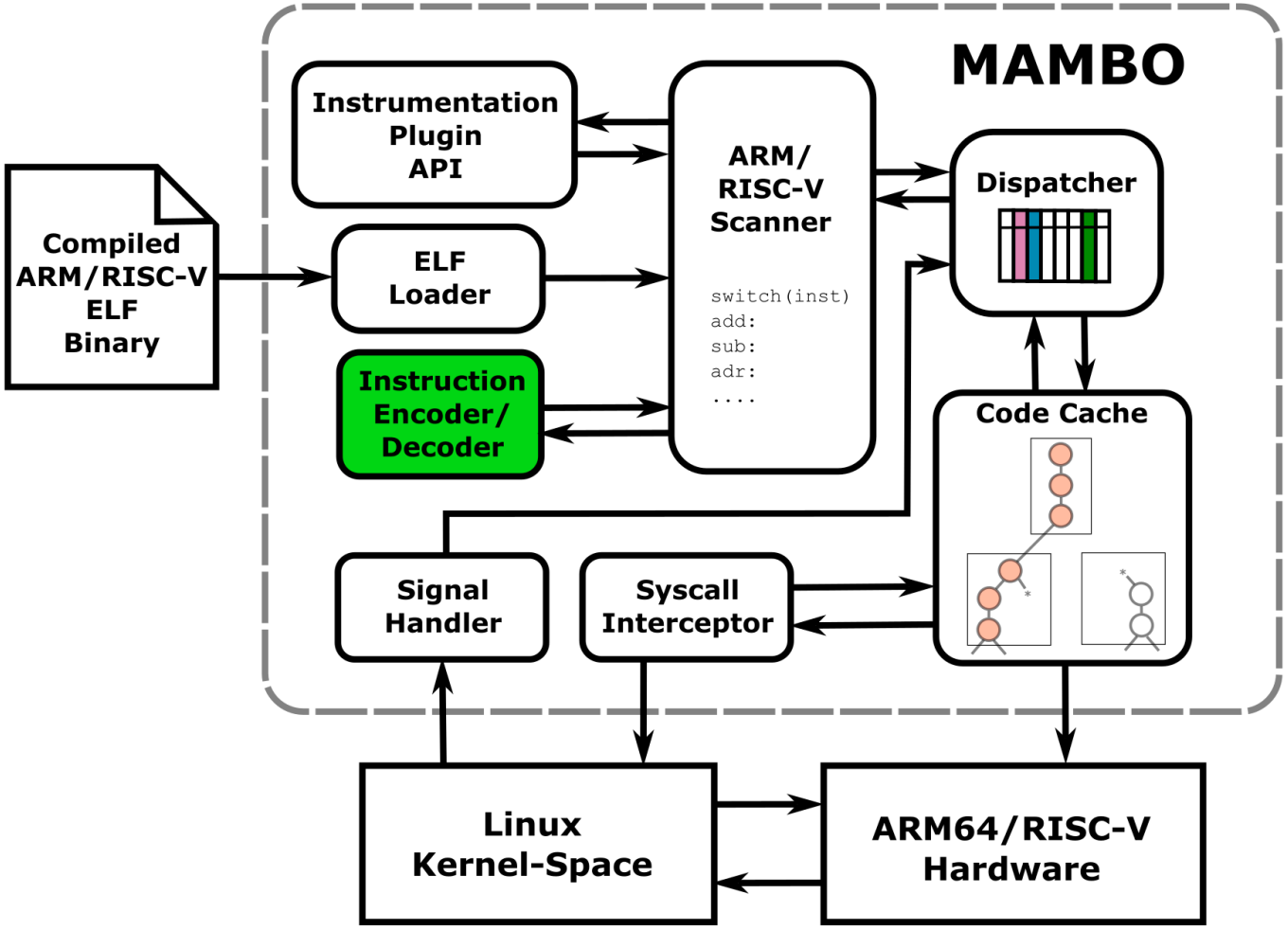
Instruction Encoder / Decoder



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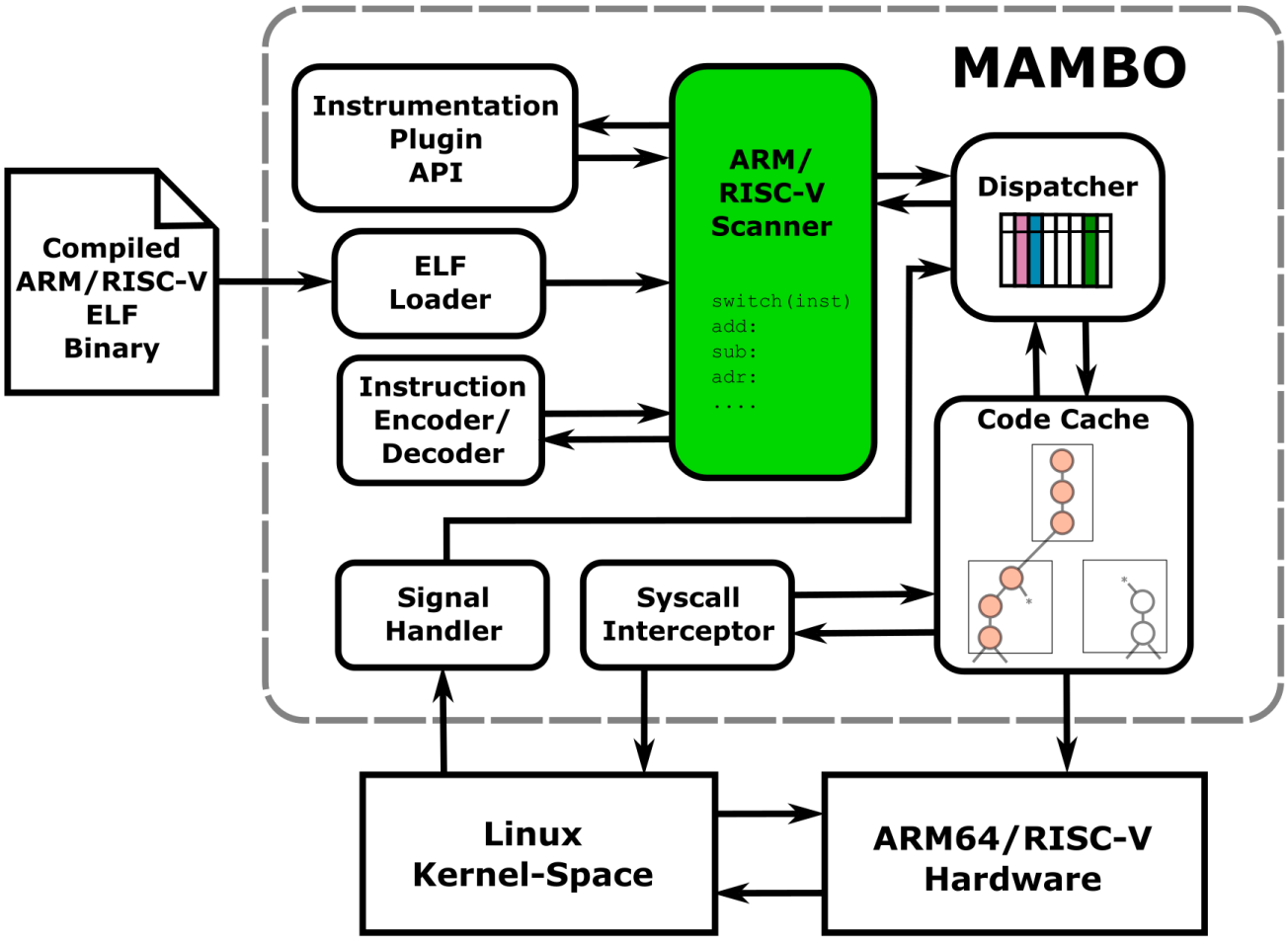
Basic Block Scanning



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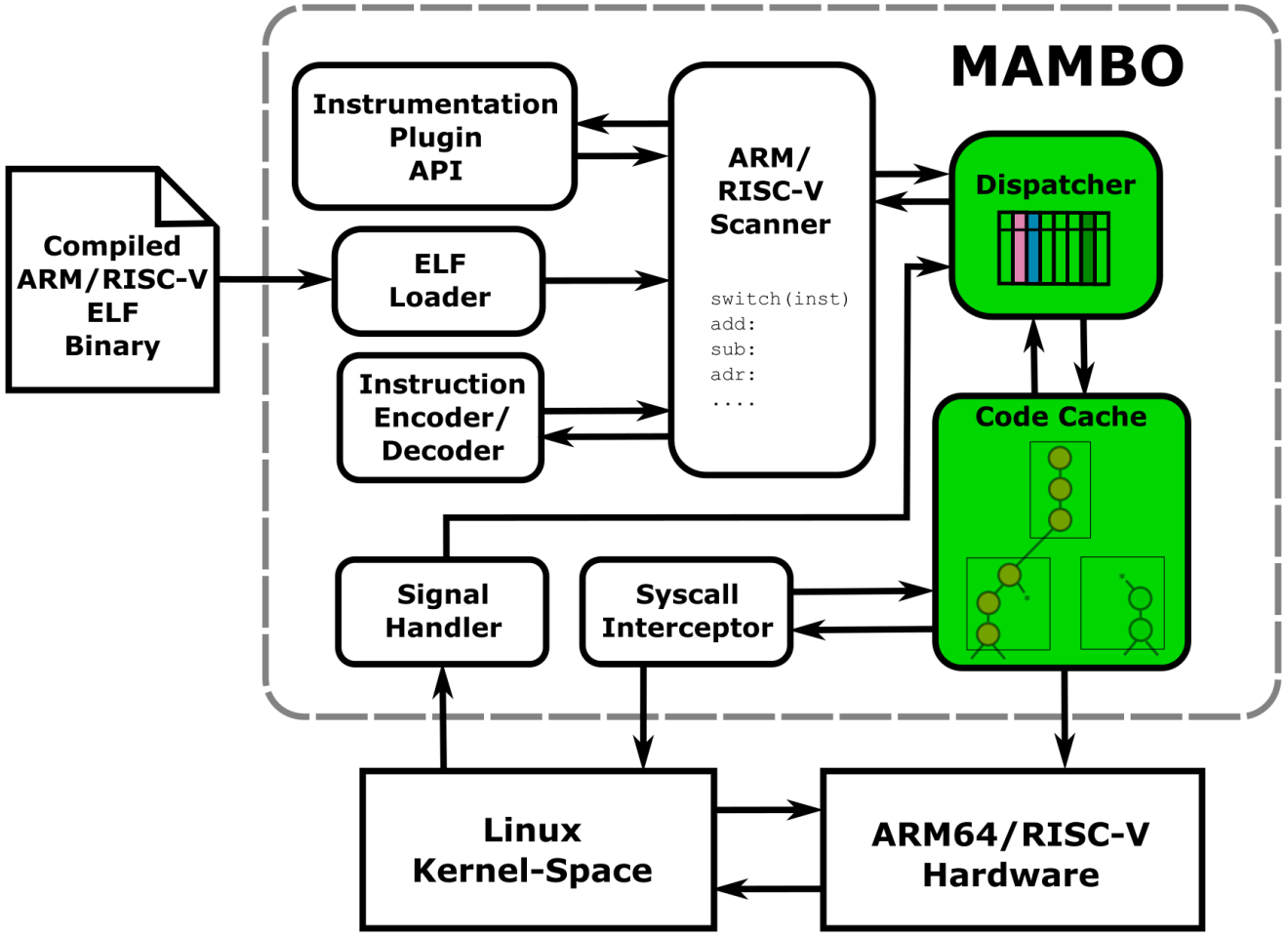
Dispatch and Code-Cache



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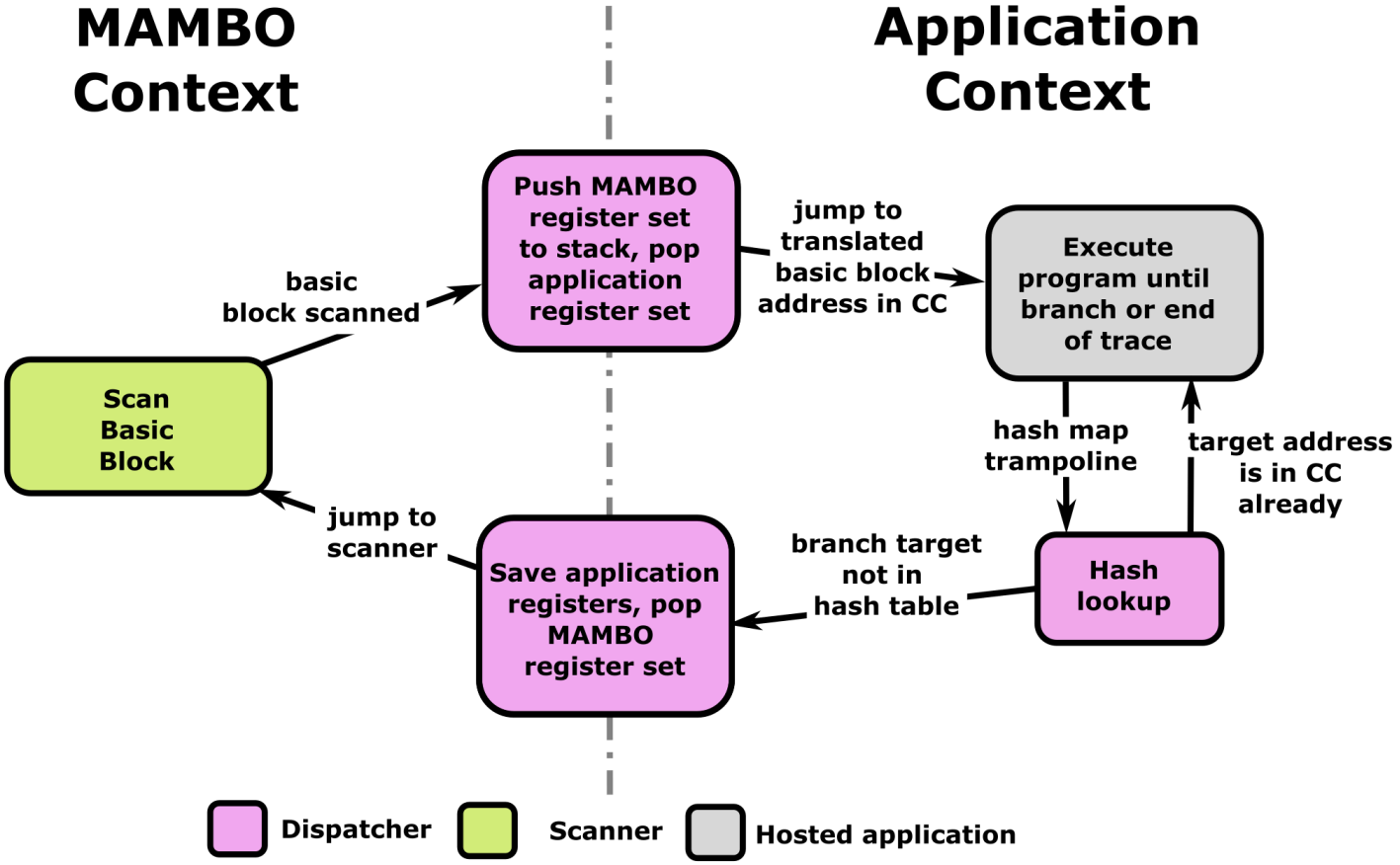
Dispatch and Code-Cache



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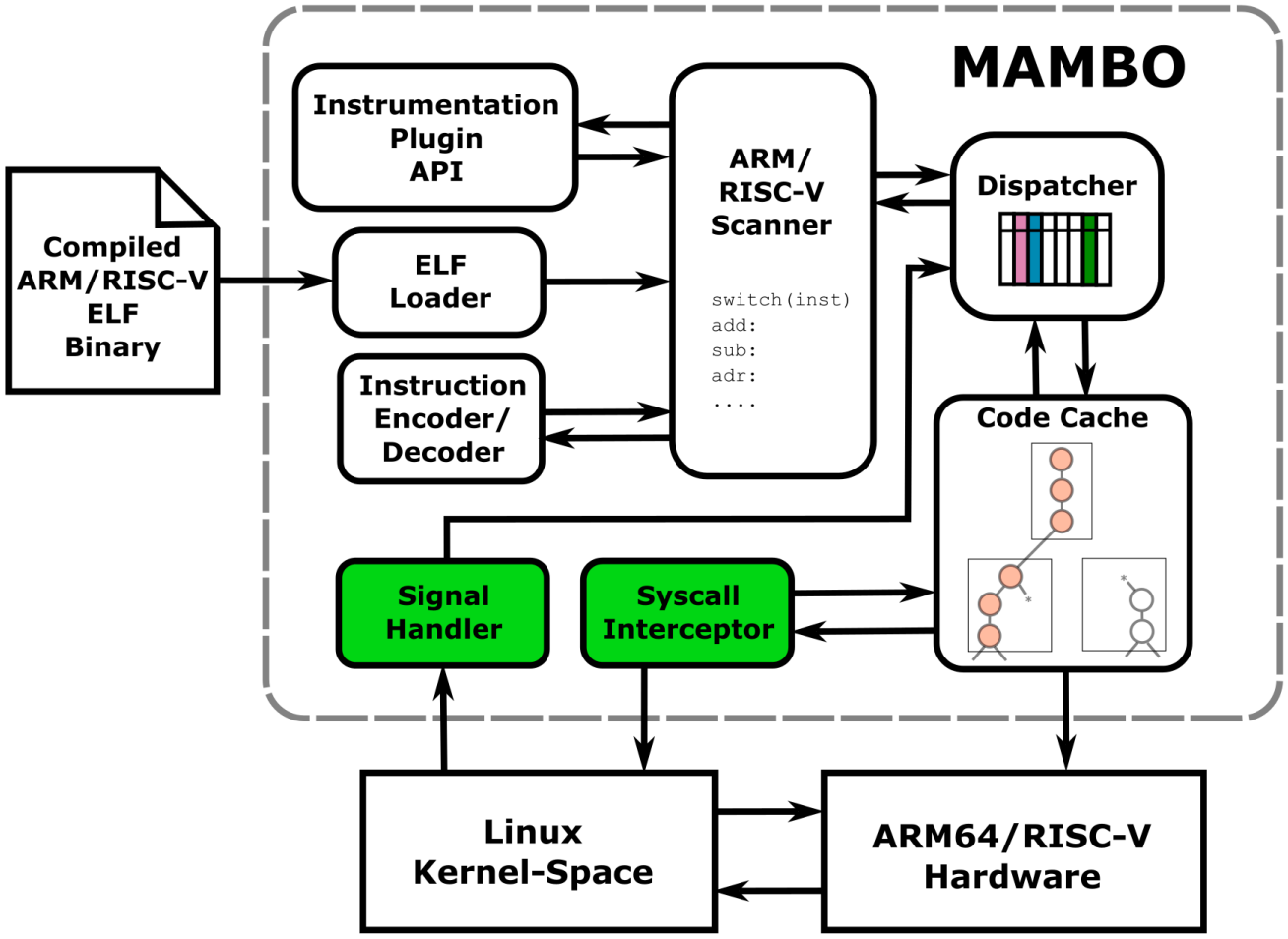
Kernel Interaction



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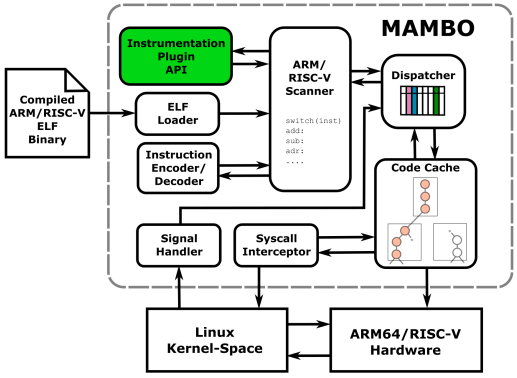
Introduction to MAMBO plugin API



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MAMBO Plugins

Example use cases for plugins:

- Code analysis (e.g., building CFG)
- Code generation (e.g., insertion of new functionality)
- Code modification (e.g., reimplementation of library functions)
- Code instrumentation (e.g., performance counters and metrics)
- Runtime event handling (e.g., tracking thread creation/destruction)

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Event Driven Programming Model

- User defined functions are registered as callbacks
- MAMBO executes callbacks when the event is encountered
- Two categories of events:
  - Hosted application runtime events (e.g. system calls).
  - MAMBO scan-time events (used for analysis and instrumentation)
- Fine-grained (e.g., per-instruction) and coarse-grained (e.g., thread creation/destruction) instrumentation

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Event Points

PRE-INSTRUCTION

```
ld a0, -24(s0)
```

POST-INSTRUCTION

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Event Points

PRE-BASIC BLOCK

PRE-INSTRUCTION

```
ld a0, -24(s0)
```

POST-INSTRUCTION

```
ld a0, -24(s0)
mul a0, a0, a0
ld ra, 24(sp)
ld s0, 16(sp)
addi sp, sp, 32
ret
```

POST-BASIC BLOCK

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Event Points

PRE-INSTRUCTION

```
ld a0, -24(s0)
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POST-INSTRUCTION

PRE-BASIC BLOCK

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ld a0, -24(s0)
mul a0, a0, a0
ld ra, 24(sp)
ld s0, 16(sp)
addi sp, sp, 32
ret
```

POST-BASIC BLOCK

PRE-THREAD

```
addi sp, sp, -32
sd ra, 24(sp)
sd s0, 16(sp)
addi s0, sp, 32
sd a0, -24(s0)
ld a1, -24(s0)
.Lpcrel_hi0:
auipc a0, %pcrel_hi(.L.str)
addi a0, a0, %pcrel_lo(.Lpcrel_hi0)
call printf@plt
ld a0, -24(s0)
mul a0, a0, a0
ld ra, 24(sp)
ld s0, 16(sp)
addi sp, sp, 32
ret
```

POST-THREAD

PRE-THREAD

```
addi sp, sp, -32
sd ra, 24(sp)
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POST-THREAD

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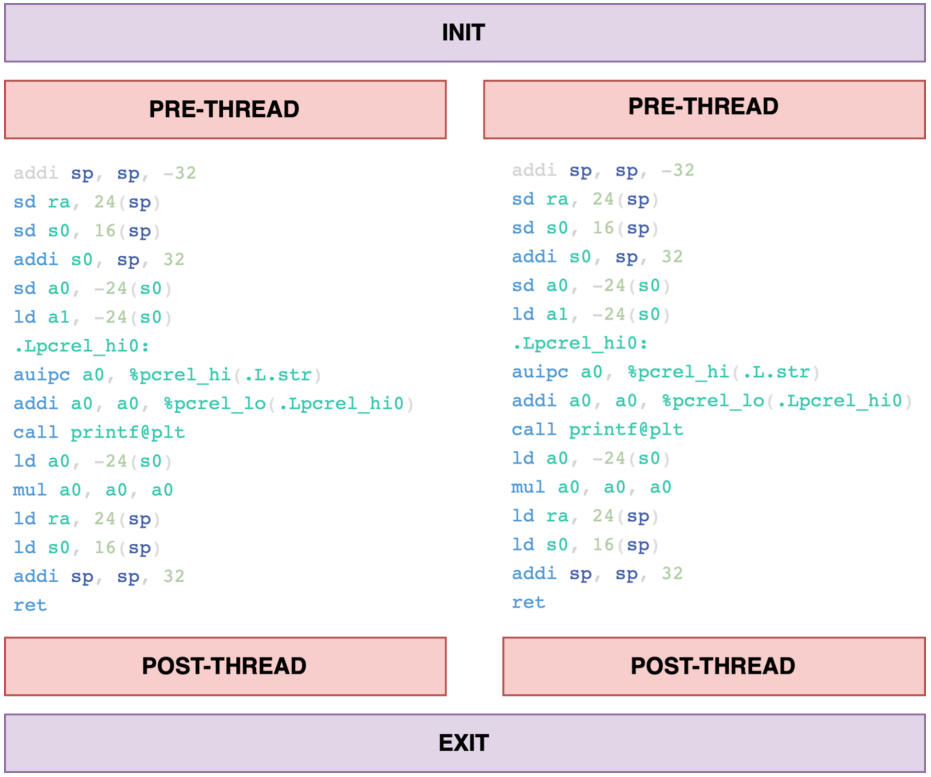

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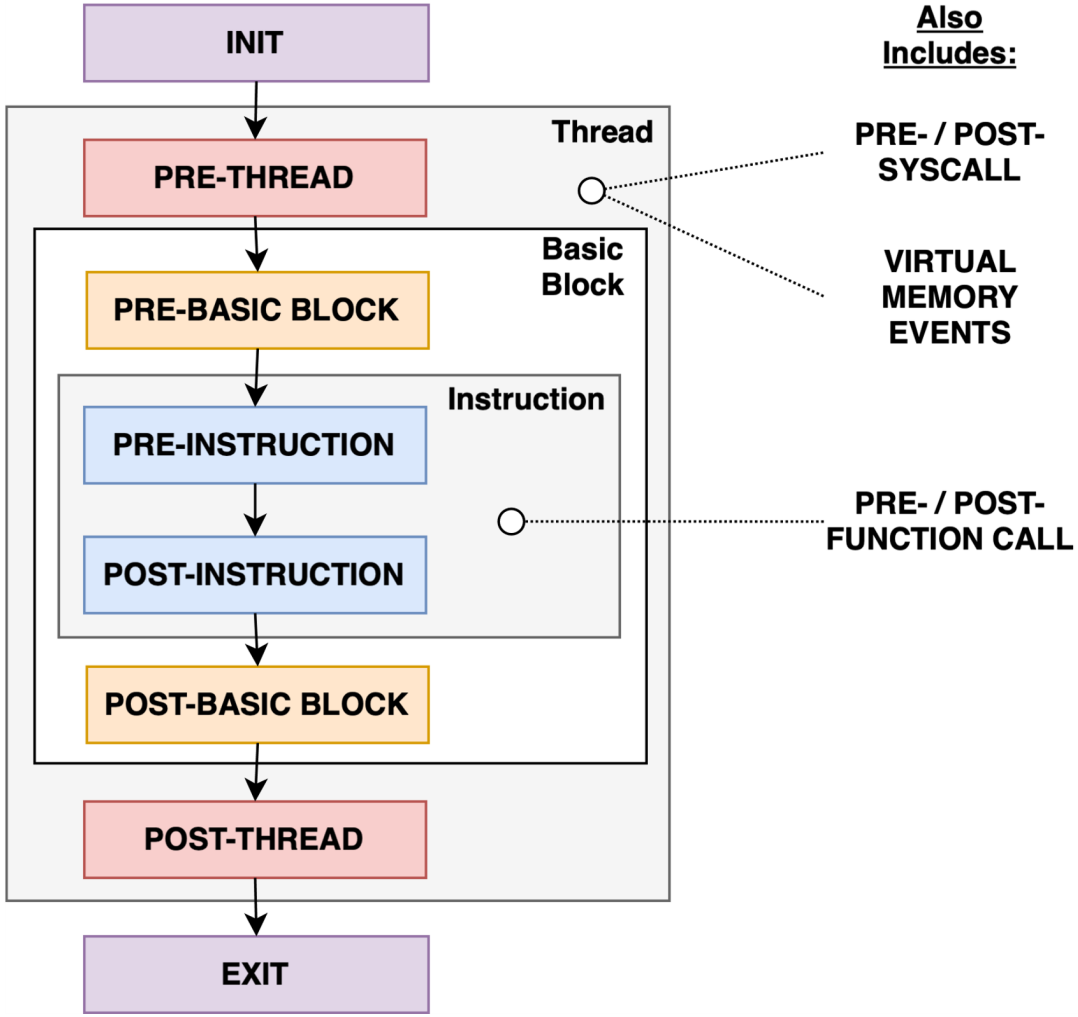
MAMBO Event Flow



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MAMBO API

- Callback registering functions
- Code analysis
- Instrumentation functions
- Various helper functions

Both architecture dependent and independent functions

Initialisation Functions Example

1) Initialise plugin

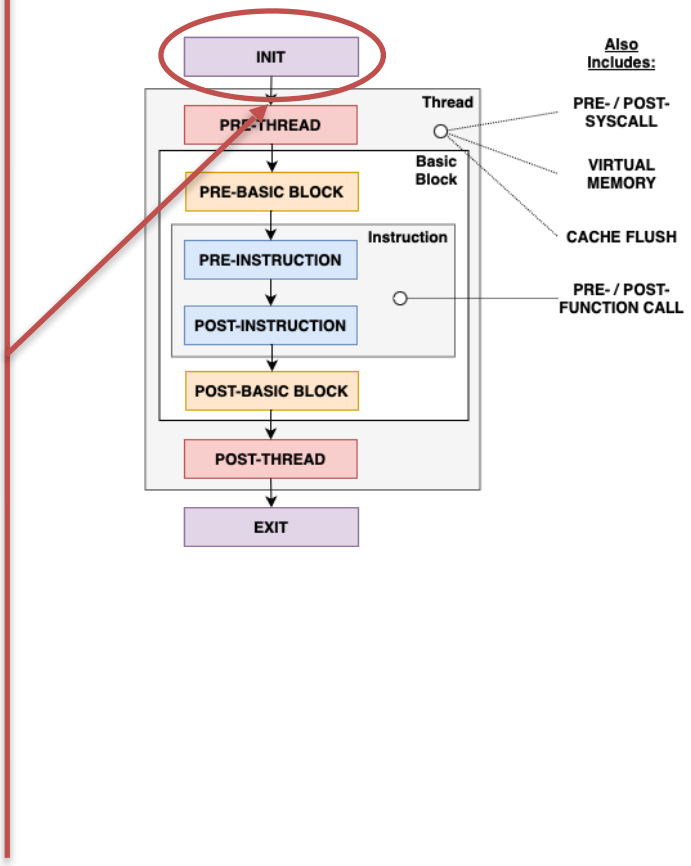
```
__attribute__((constructor))
void <plugin name>() {
    mambo_context * ctx =
        mambo_register_plugin();
    ...
    ...
}
```

2) Register callbacks (examples)

```
int mambo_register_pre_inst_cb(
    mambo_context *ctx,
    &<user function> );

int mambo_register_pre_basic_block_cb(
    mambo_context *ctx,
    &<user function> );

int mambo_register_post_thread_cb(
    mambo_context *ctx,
    &<user function> );
```



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Initialisation Functions Signature

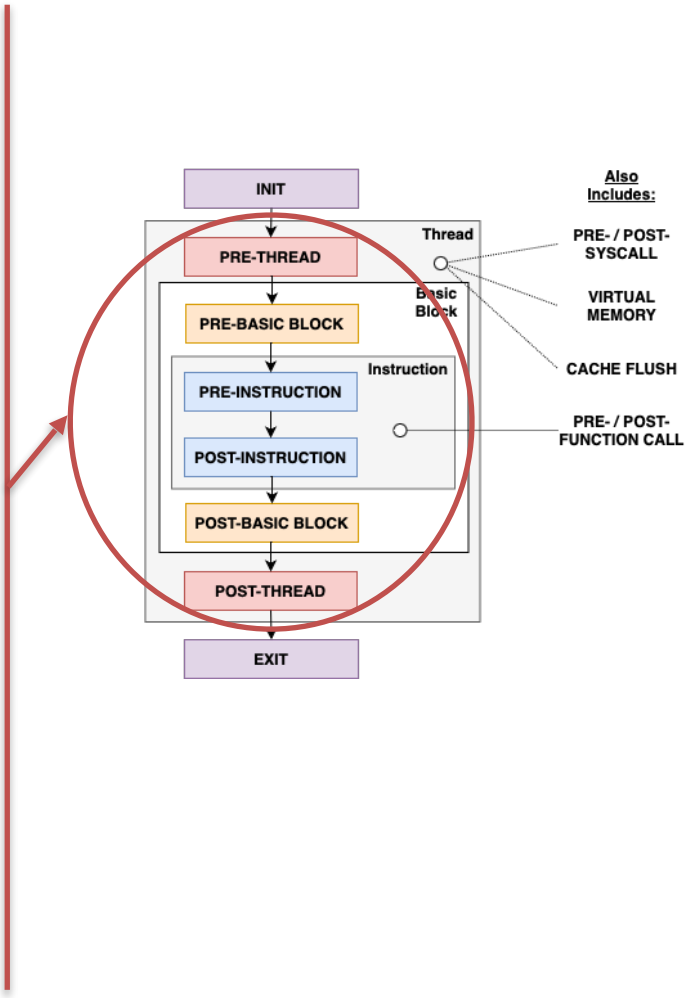
Code Analysis Functions

Code analysis (examples)

```
mambo_branch_type
mambo_get_branch_type(mambo_context *ctx);

mambo_cond
mambo_get_cond(mambo_context *ctx);

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



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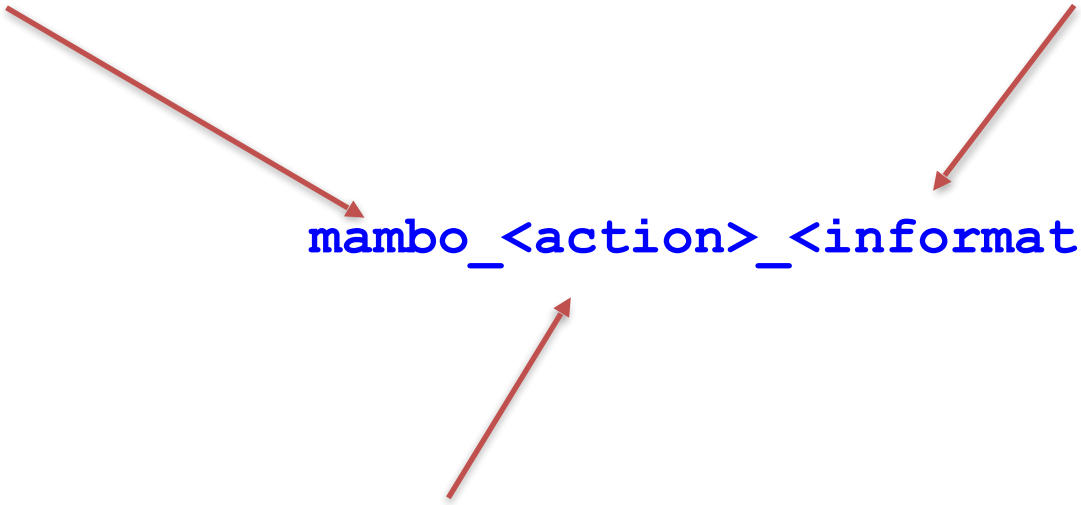
Analysis Functions Signature

"Namespace"

Type of information being accessed / modified



```
mambo_<action>_<information>
```

Access or set (`get` / `set` / `is`) current state of the execution

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Coding Our First Plugin - `branchplugin`

```
__attribute__((constructor))
void branchplugin_init() {
    mambo_context * ctx = mambo_register_plugin();

   mambo_register_pre_inst_callback(ctx, &branchplugin_pre_inst_handler);
}

int branchplugin_pre_inst_handler(mambo_context *ctx) {

    mambo_branch_type type = mambo_get_branch_type(ctx);

    if (type & BRANCH_RETURN) {
        // ...
    } else if (type & BRANCH_DIRECT) {
        // …
    }
    else if (type & BRANCH_INDIRECT) {
        // ...
    }
}
```

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Code Instrumentation Functions

Code instrumentations (examples)

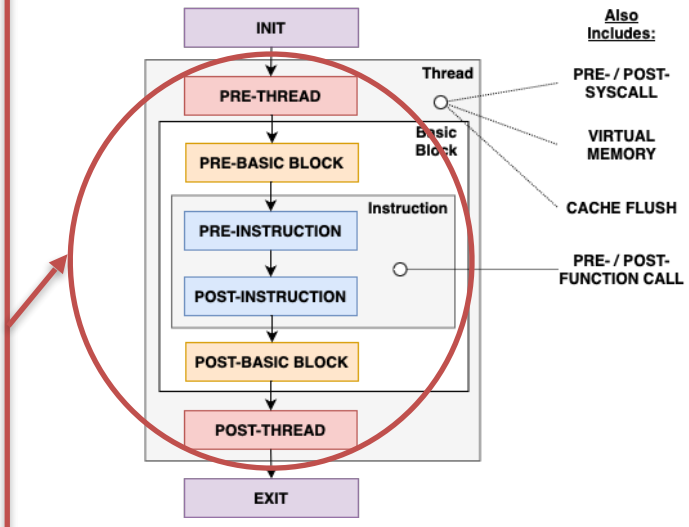
```
void emit_counter64_incr(
    mambo_context *ctx,
    void *counter,
    unsigned incr);

void emit_push(
    mambo_context *ctx, uint32_t regs);
void emit_pop(
    mambo_context *ctx, uint32_t regs);

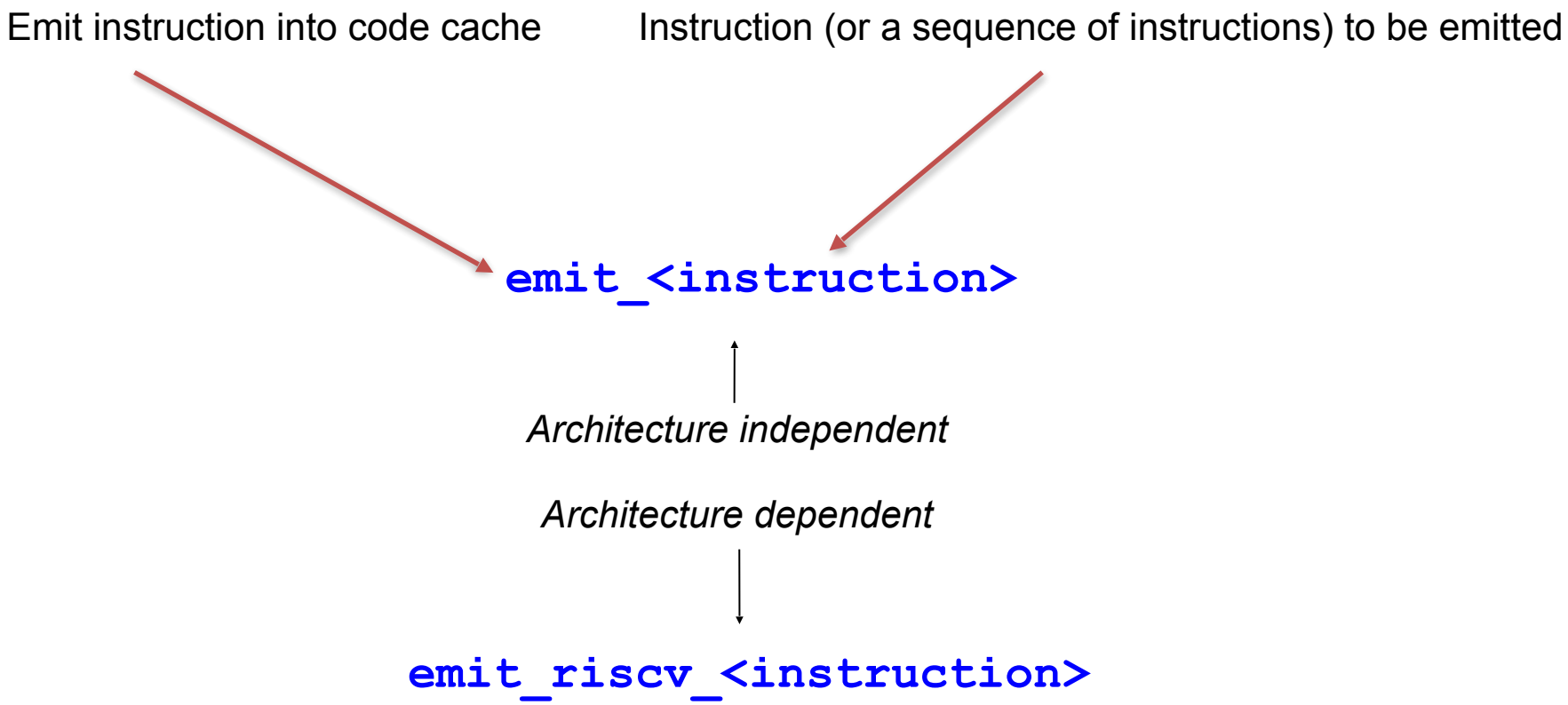
void emit_set_reg(
    mambo_context *ctx, enum reg reg,
    uintptr_t value);

void emit_fcall(
    mambo_context *ctx,
    void *function_ptr);

int  emit_safe_fcall(mambo_context *ctx,
void *function_ptr,
    int argno);
```



Instrumentation Functions Signature



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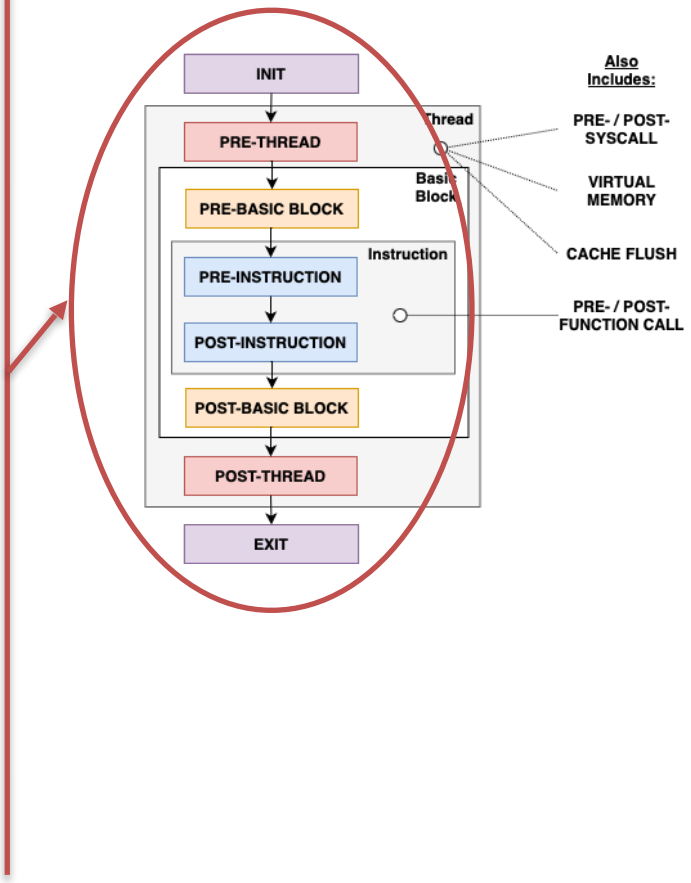
Additional Helper Functions

Additional Helpers (examples)

```
void mambo_alloc(
    mambo_context *ctx,
    size_t* size);
void mambo_free(
    mambo_context *ctx, void *ptr);

int mambo_ht_init(mambo_ht_t *ht,
    size_tinitial_size, int index_shift,
    int fill_factor, bool allow_resize);
int mambo_ht_add(mambo_ht_t *ht,
    uintptr_t key, uintptr_t value);
int mambo_ht_get(mambo_ht_t *ht,
    uintptr_t key, uintptr_t *value);

int get_symbol_info_by_addrl(
    uintptr_t addr, char **sym_name,
    void **start_addr, char **filename);
```



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Plugin API Scan-Time vs. Runtime

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

C:

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

RISC-V:

```
                run_many_times:
0x8000          mul a0, a0, a0
0x8004          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   mul a0, a0, a0
0xFC7004   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   addi sp, sp, -8
0xFC7004   sd a0, 0(sp)
0xFC7008   auipc x0, &message
0xFC700B   jal my_print_fn
0xFC7010   ld a0, 0(sp)
0xFC7014   addi sp, sp, 8
0xFC7018   mul a0, a0, a0
0xFC701B   ret
```

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

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MAMBO Example Plugin

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The following code example can be found at

BEEHIVE-LAB > MAMBO > PLUGINS

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LIVE DEMO

(NOTE: VIM RUNS UNDER RISC-V MAMBO)

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Lessons Learned from RISC-V Port

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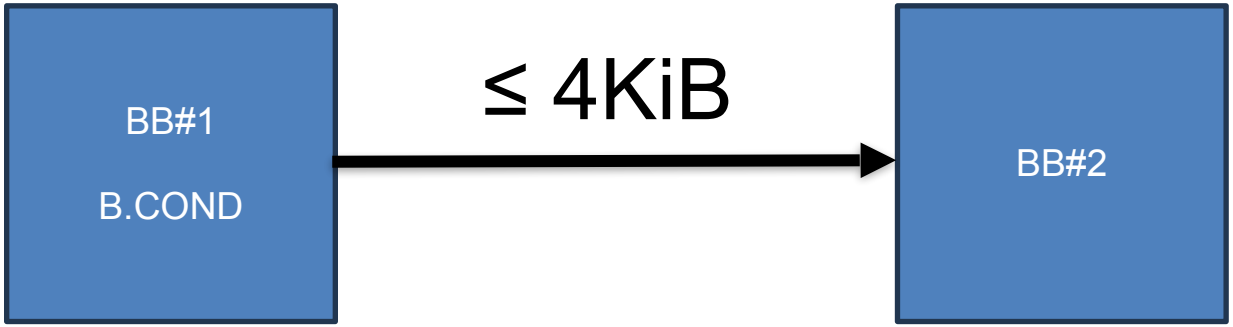
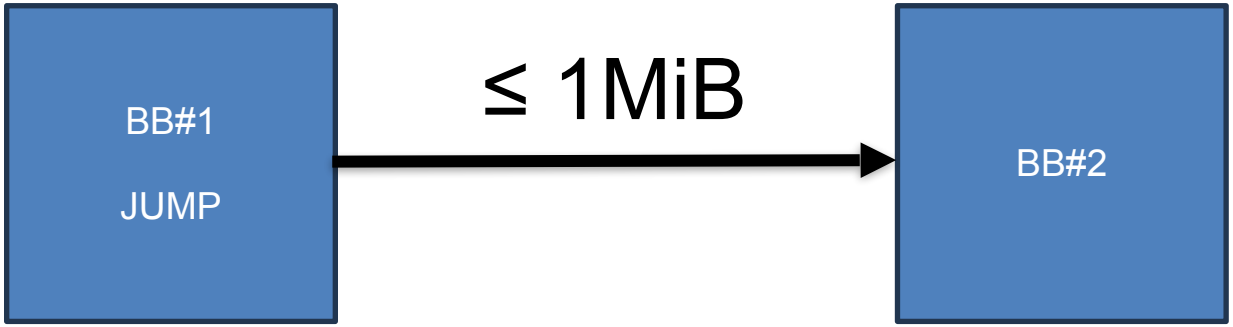
Lessons Learned From RISC-V Port

Conditional Branch Range:



Direct Jump Range:



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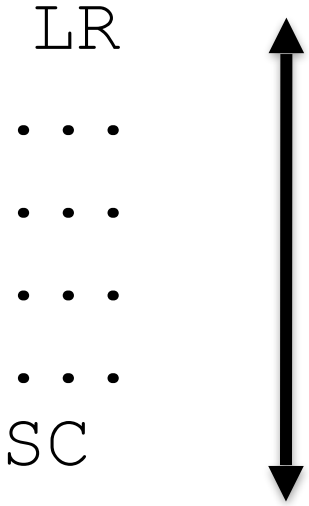
Lessons Learned From RISC-V Port

Atomic Load Reserved/Store Conditional:



✔ At most 16 integer instructions between

✘ Other loads and stores between

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Lessons Learned From RISC-V Port

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MAMBO Roadmap

- Foster an open-source community
  - Collaborations/Contributions welcome
- Improve Documentation
- More tools
  - Data race detector
  - Call graph generator
- Keep up with RISC-V (and ARM)
- Current research projects
  - Fast architectural simulation
  - Cybersecurity
  - Binary lifting

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CODE OPEN SOURCE ON GITHUB

BEEHIVE-LAB / MAMBO

(APACHE 2.0 LICENSE)

Thanks!

MoatE (10017512) and Soteria (75243)