CompCertX:

Verified Separate Compilation for Compositional Verification of Layered Systems

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August 24, 2015

Motivation

How to build reliable & secure ***system software stacks****?*

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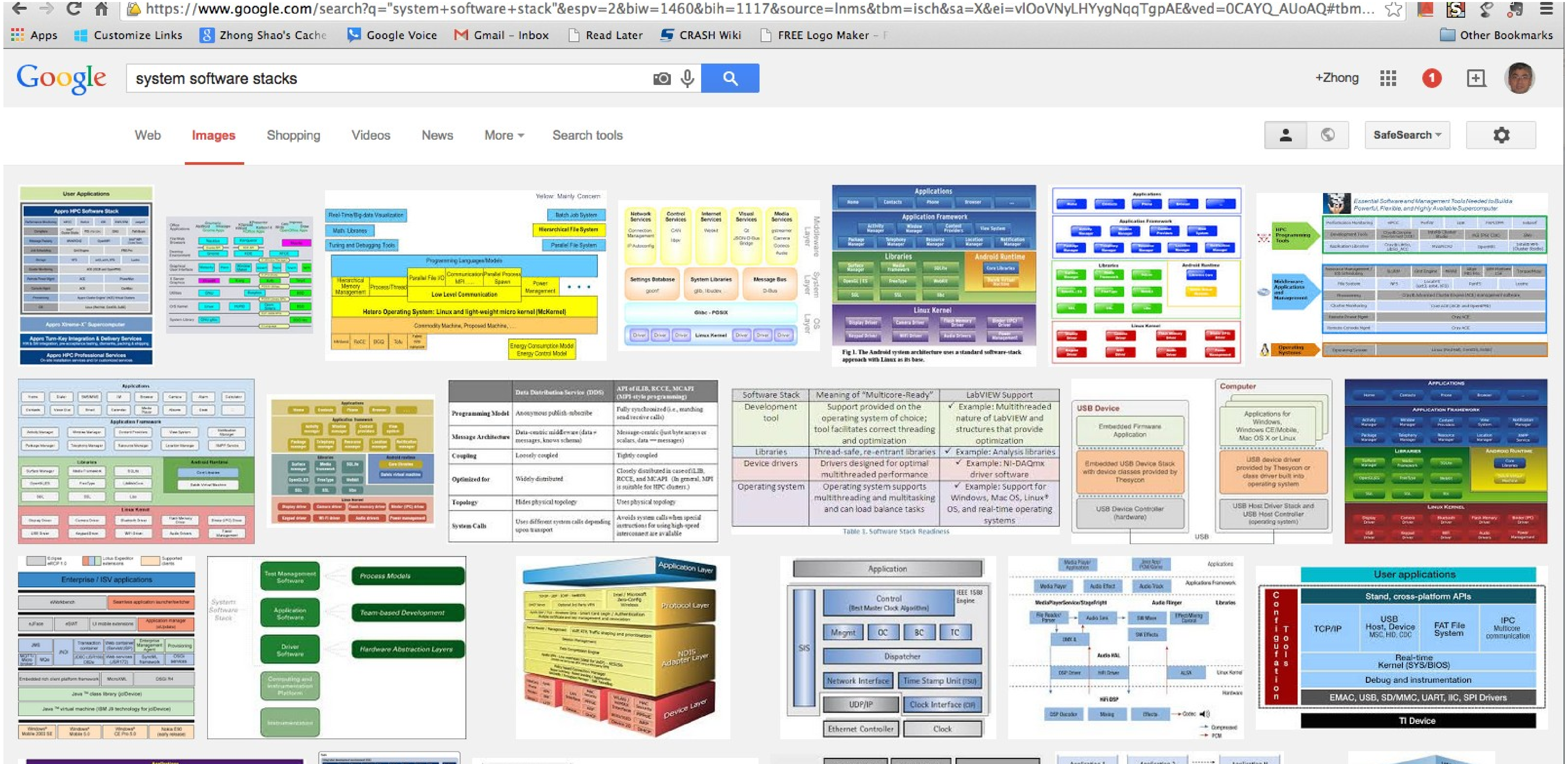
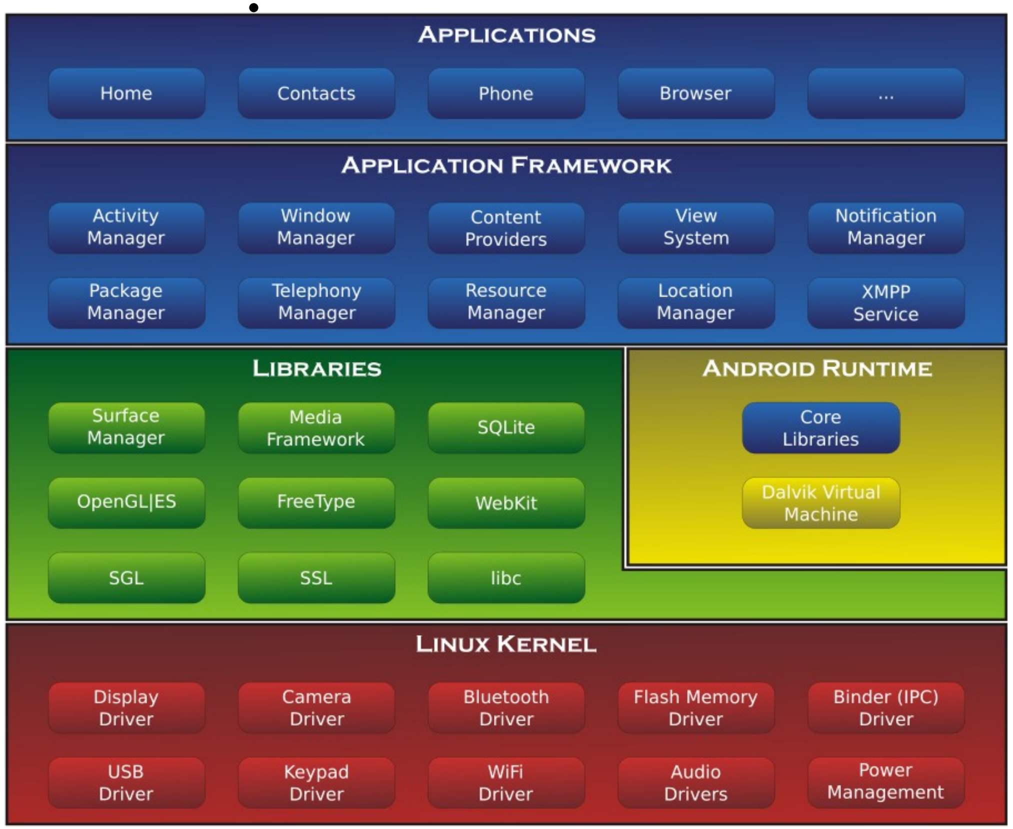
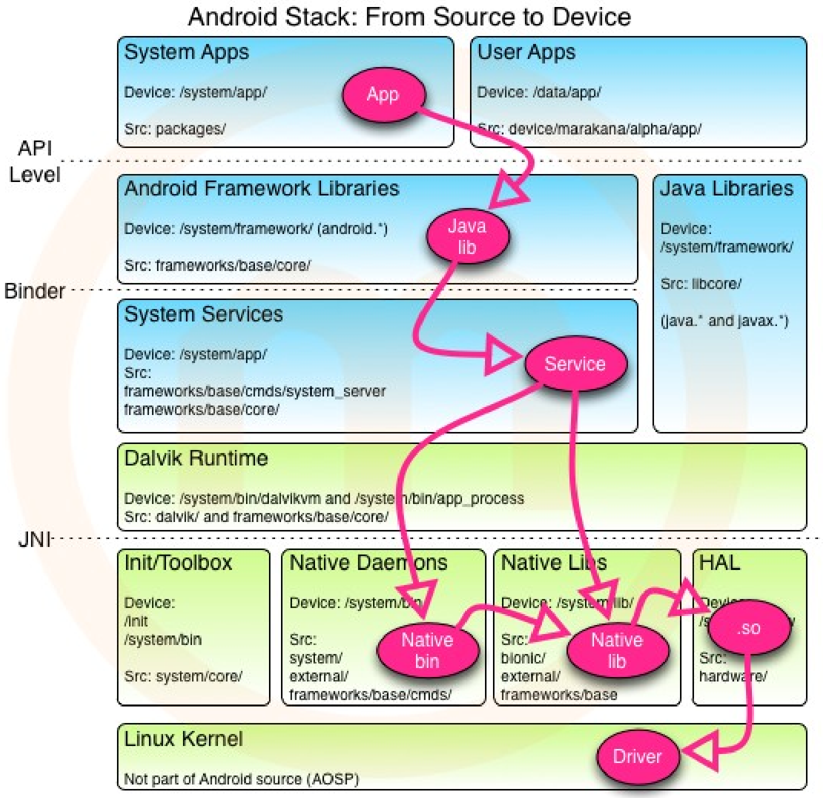


Motivation

Android architecture & system stack

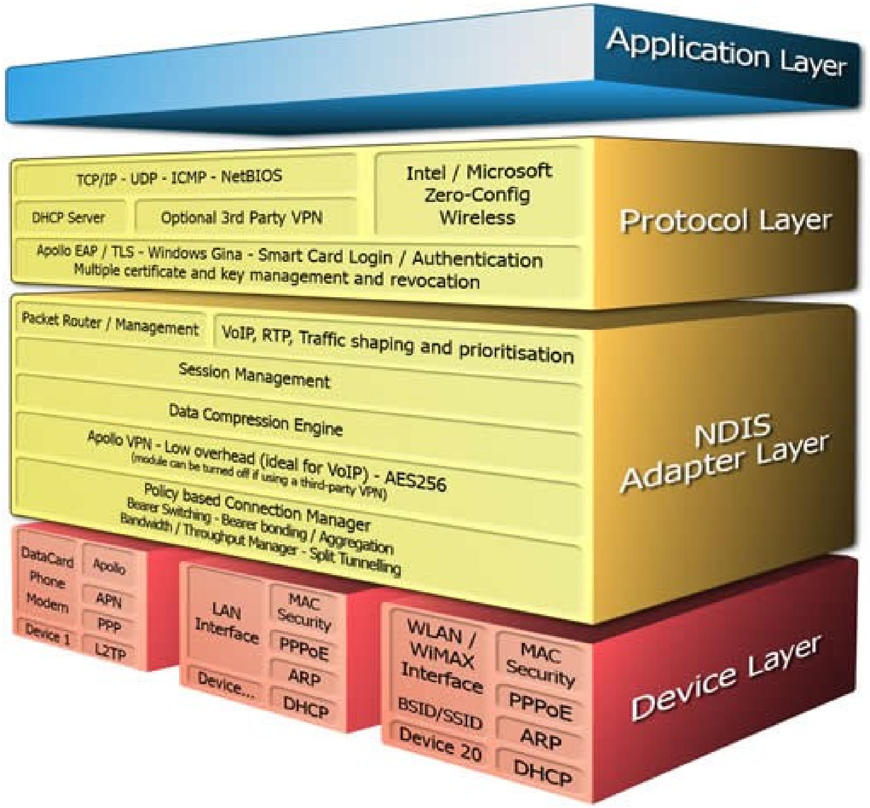
From https://thenewcircle.com/s/post/1031/android_stack_source_to_device &
http://en.wikipedia.org/wiki/Android_(operating_system)





Motivation

Apollo Mobile Communication Stack
http://www.layer2connections.com/apollo_clients.html



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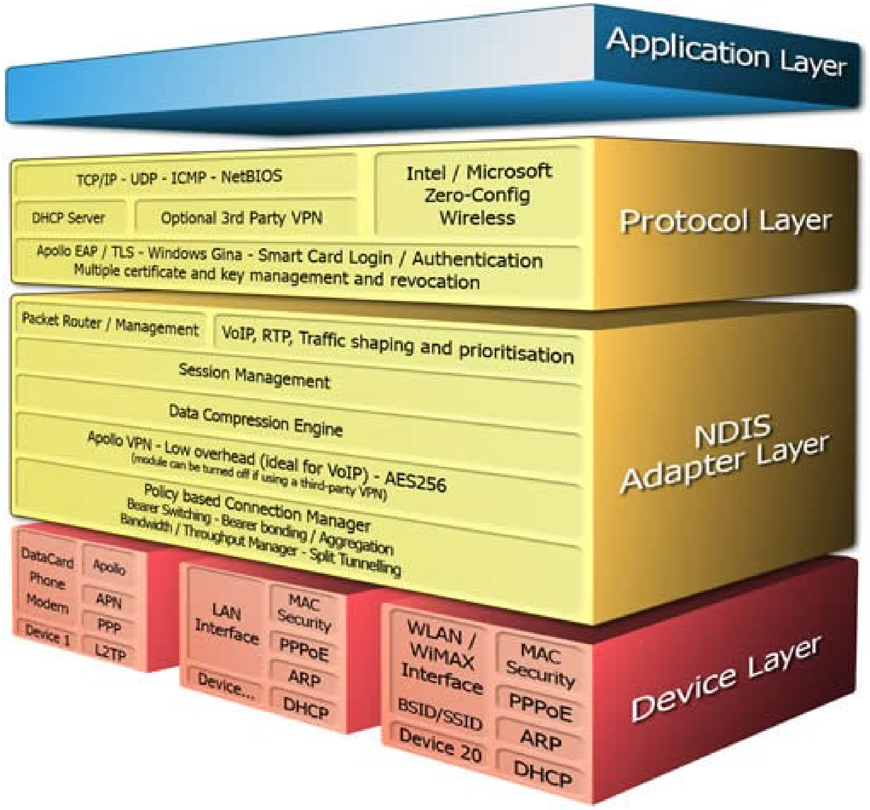
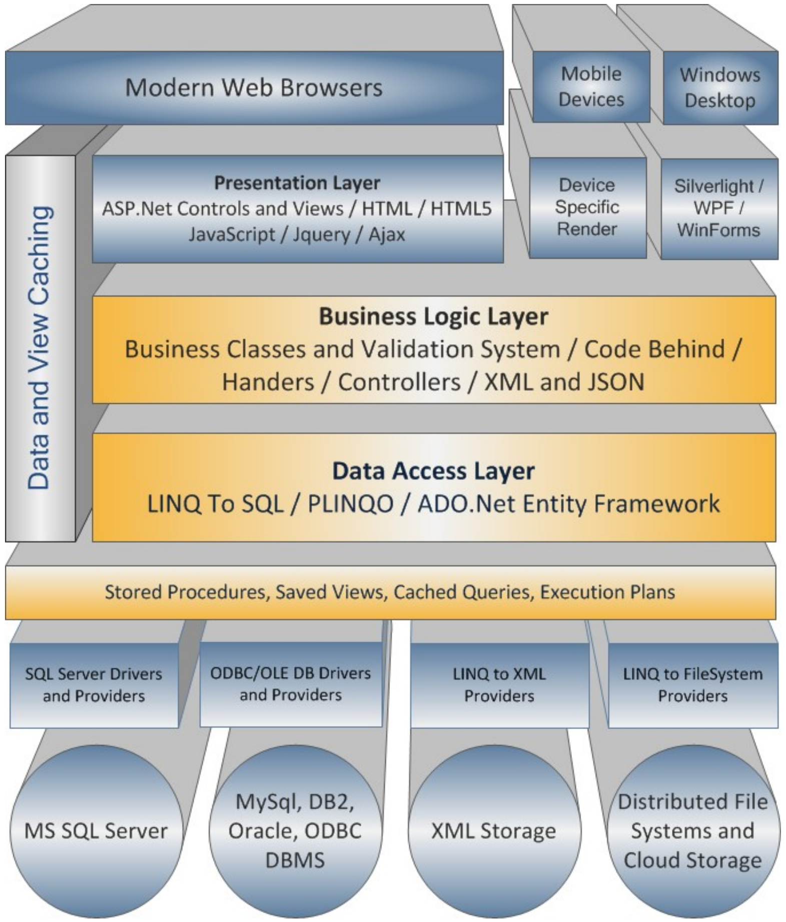


Web Application Development Stack
http://www.brightware.co.uk/Technology.aspx



Motivation (cont’d)

- Common themes: all system stacks are built based on abstraction, modularity, and layering
- Abstraction layers are ubiquitous!

Motivation (cont'd)

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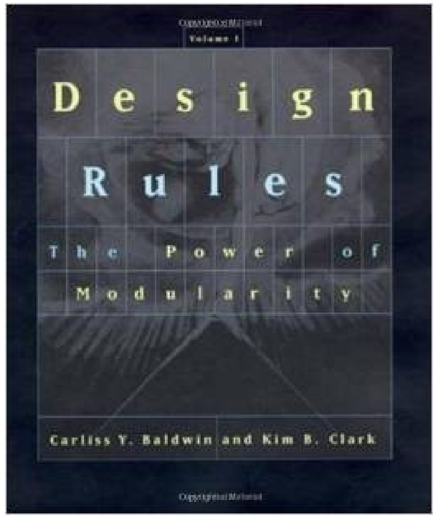
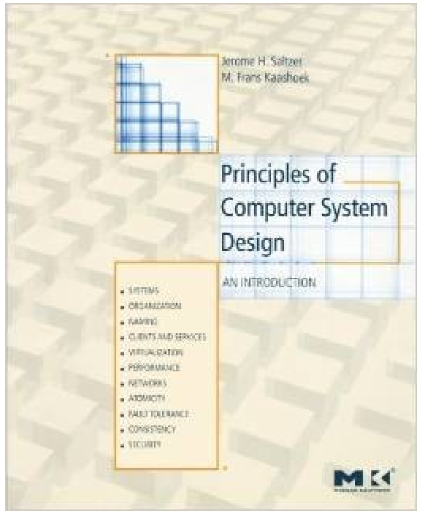
- Abstraction layers are ubiquitous!

Such use of abstraction, modularity, and layering is "**the key factor that drove the computer industry toward today's explosive levels of innovation and growth** because *complex products can be built from smaller subsystems that can be designed independently yet function together as a whole."*

Baldwin & Clark " Design Rules: Volume 1, The Power of Modularity", MIT Press, 2000





Problems

- What is an ***abstraction layer***?
- How to formally ***specify*** an abstraction layer?
- How to ***program***, ***verify***, and ***compile*** each layer?
- How to ***compose*** abstraction layers?
- How to apply ***certified abstraction layers*** to build *reliable* and *secure* system software?

Our Contributions

- We introduce deep specification and present a language-based formalization of certified abstraction layer

- We developed new languages & tools in Coq
  - A formal layer calculus for composing certified layers
  - ClightX for writing certified layers in a C-like language
  - AsmX for writing certified layers in assembly
  - CompCertX that compiles ClightX layers into AsmX layers

- We built multiple certified OS kernels in Coq
  - mCertiKOS-hyper consists of 37 layers, took less than one-person-year to develop, and can boot Linux as a guest

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Example: Thread Queues

```
extern unsigned int dequeue(unsigned int);
extern void set_state(unsigned int, unsigned int);
extern void enqueue(unsigned int, unsigned int);

void thread_enqueue(unsigned int proc_index)
{
    set_state(proc_index, TSTATE_READY);
    enqueue(NUM_CHAN, proc_index);
}

void thread_wakeup(unsigned int chan_index)
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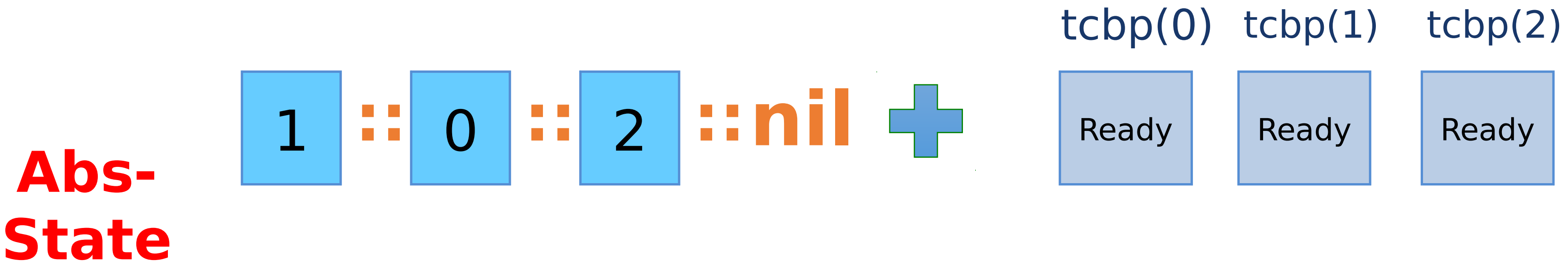
Layer primitives



Abs-State

1 :: 0 :: 2 ::nil +

tcbp(0)	tcbp(1)	tcbp(2)
Ready	Ready	Ready

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Client code

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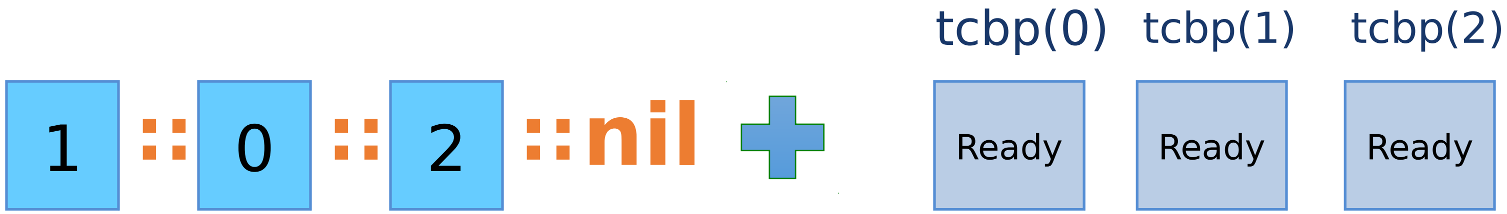

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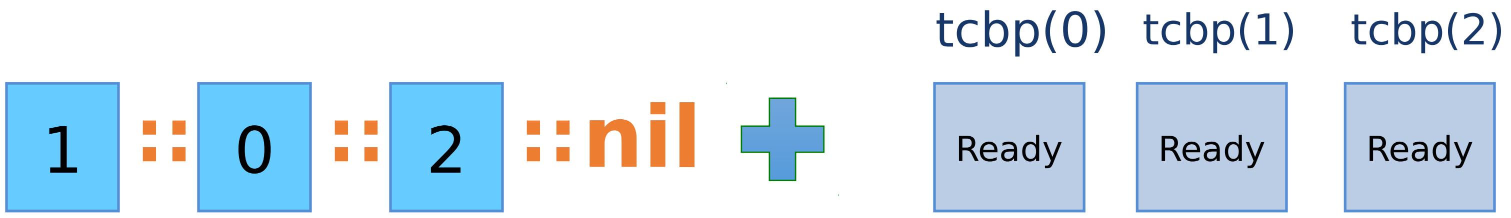

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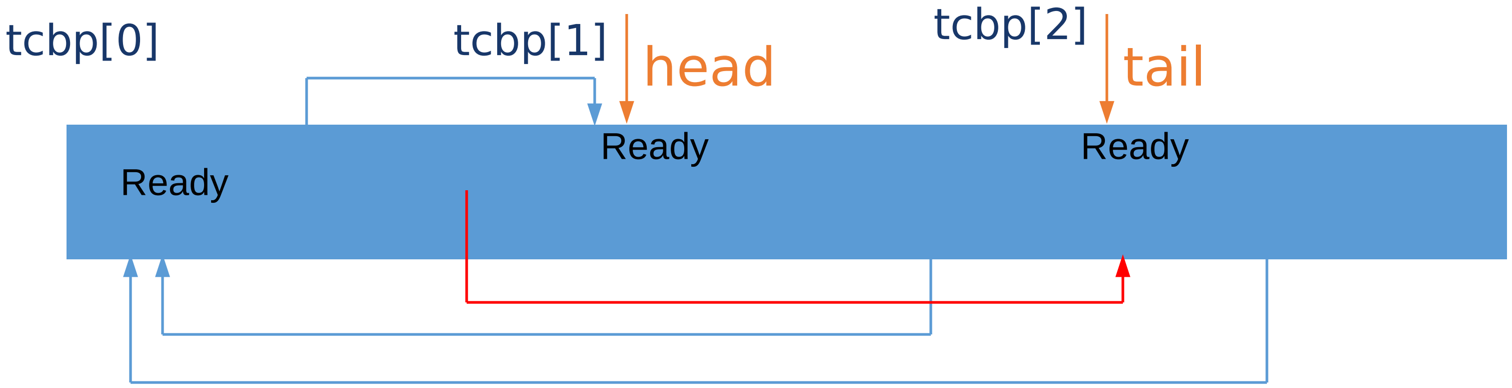
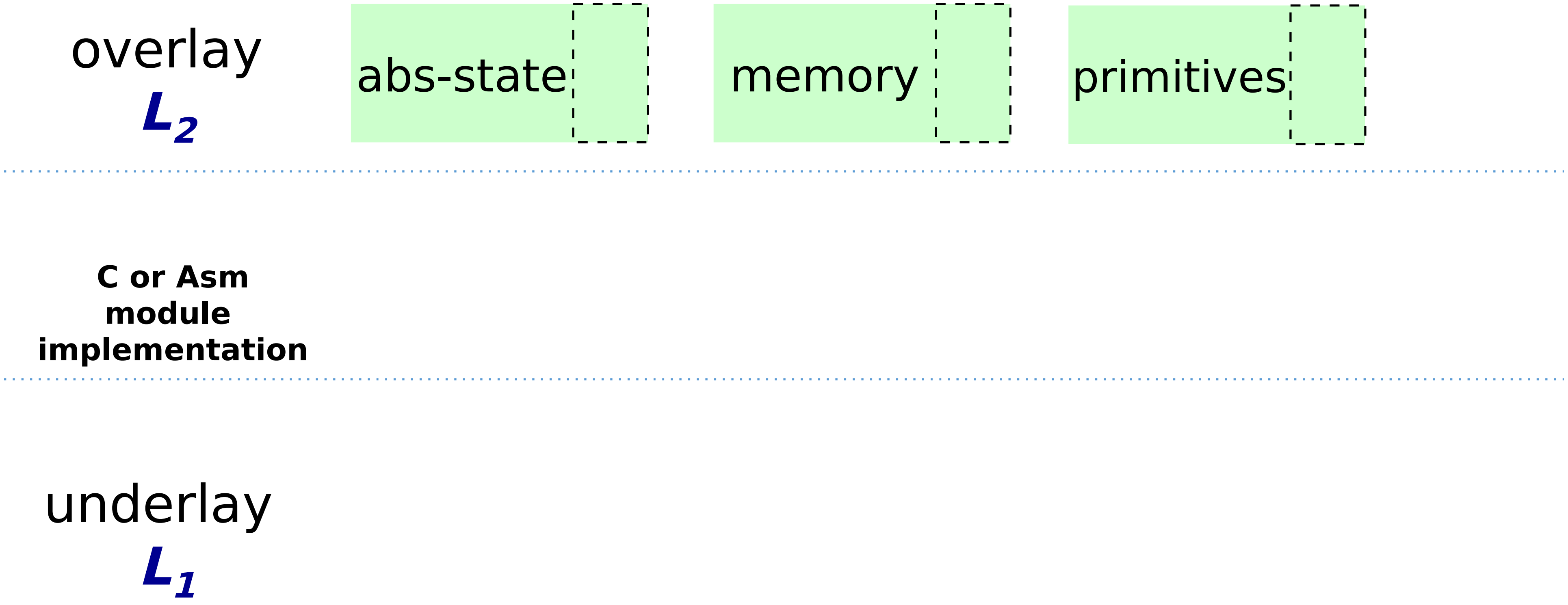
Concrete Memory



What is an Abstraction Layer?



overlay
L_2

abs-state

memory

primitives

C or Asm module implementation

underlay
L_1

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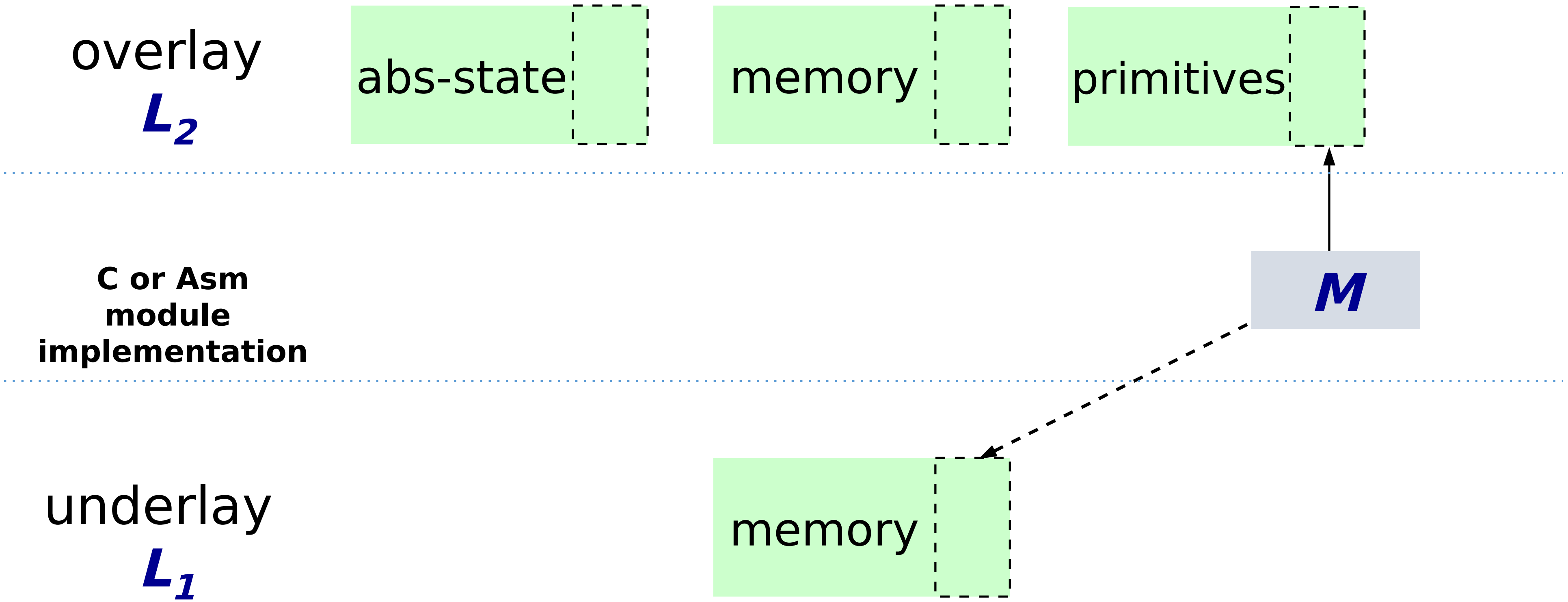

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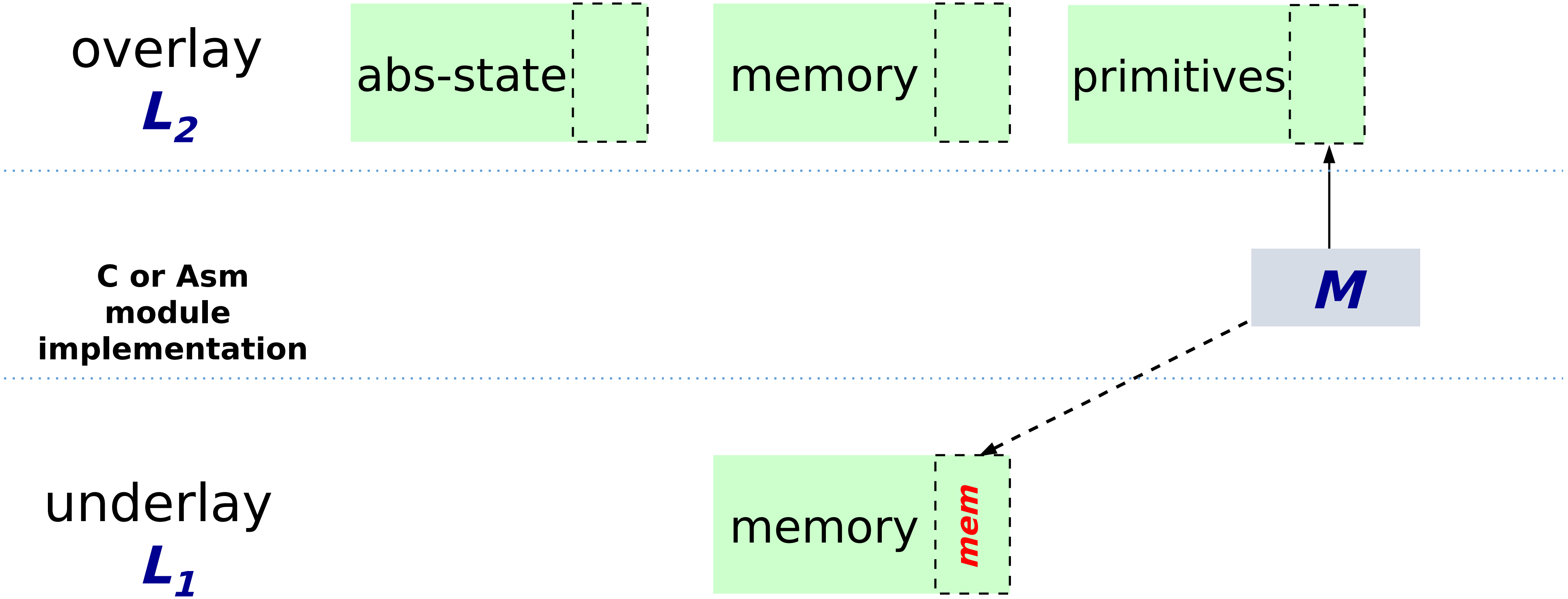

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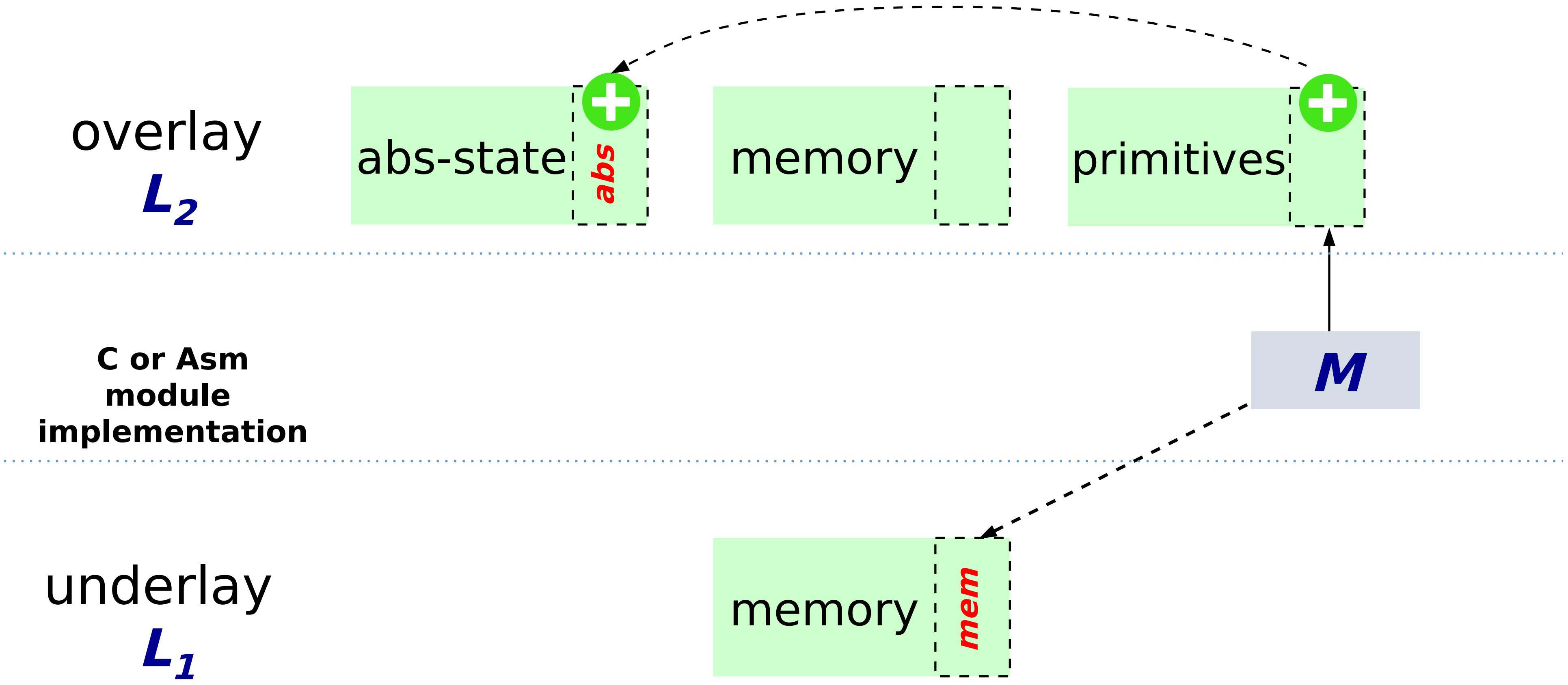

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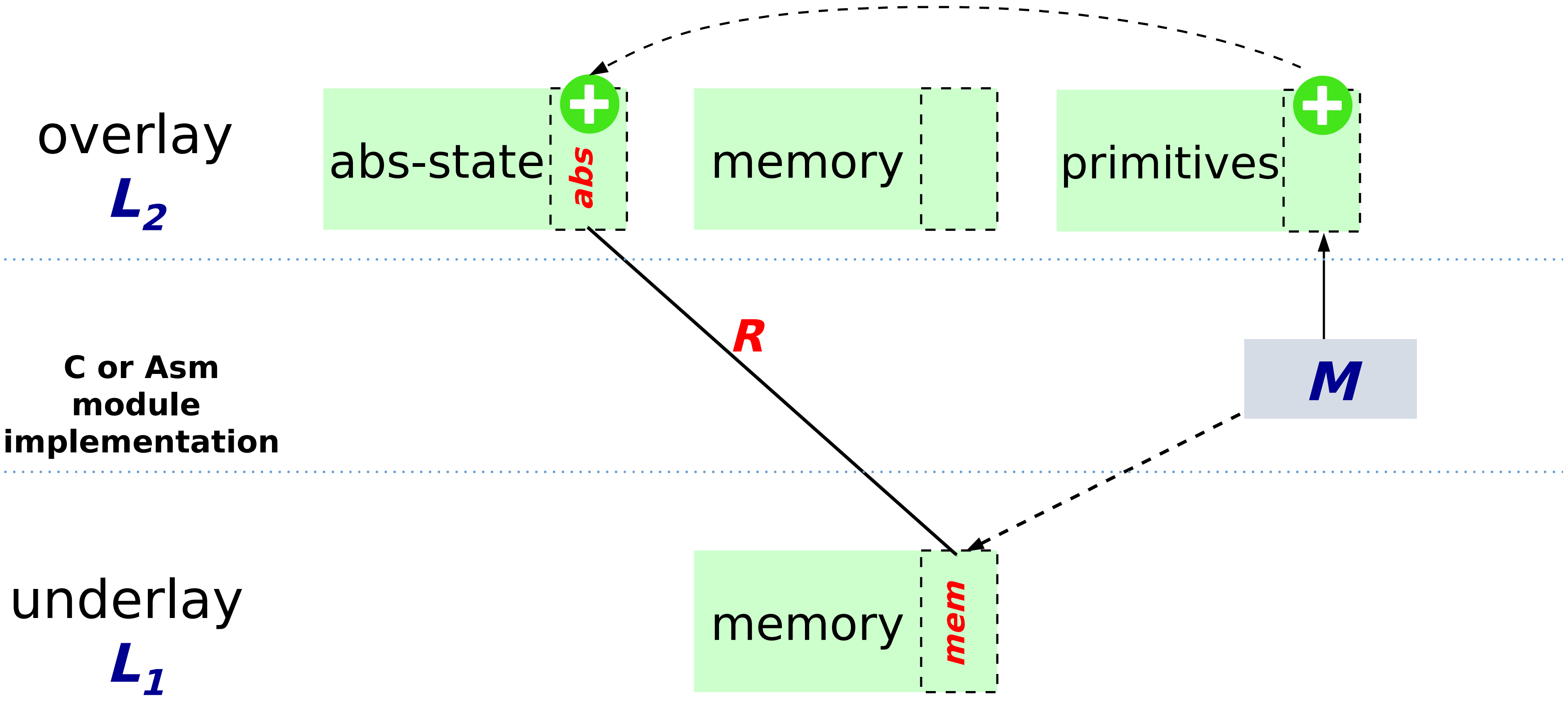

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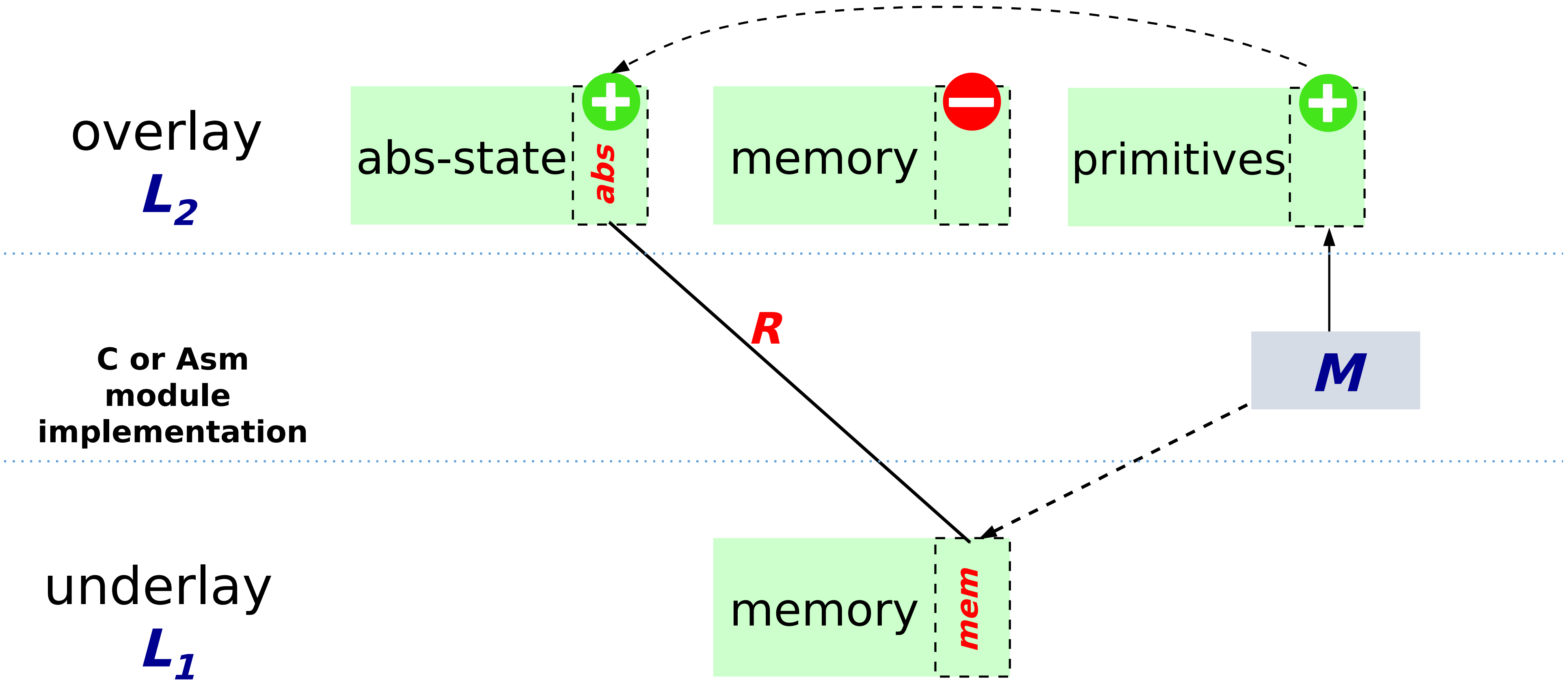

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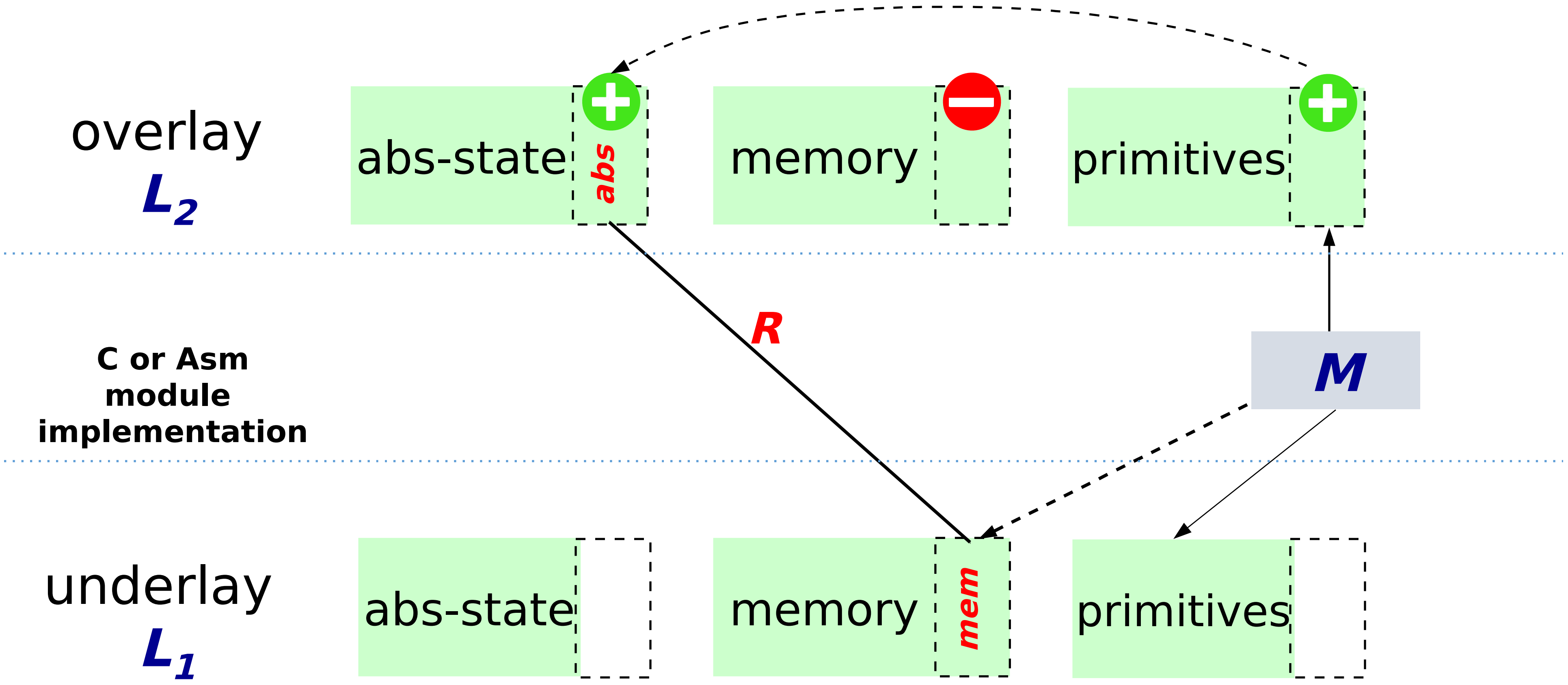
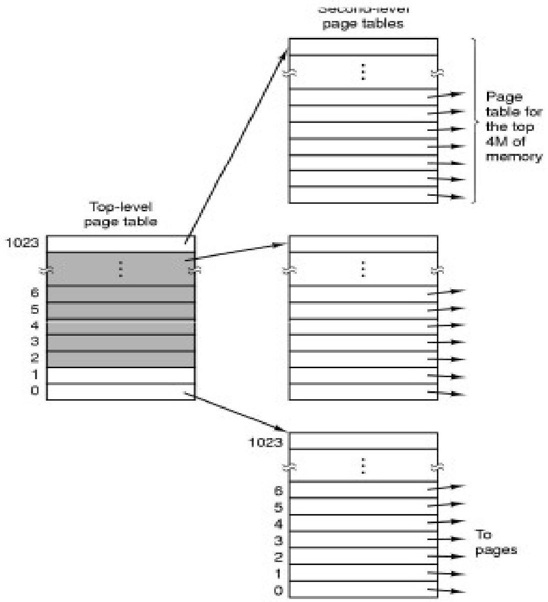


Example: Page Tables

concrete C types

```
struct PMap {
    char * page_dir[1024];
    uint  page_table[1024][1024];
};
```



abstract Coq spec

```
Inductive PTPerm: Type :=
     | PTP
     | PTU
     | PTK.

Inductive PTEInfo:=
     | PTEValid (v : Z) (p :  PTPerm)
     | PTEUnPresent.

Definition PMap := ZMap.t PTEInfo.
```

Example: Page Tables

abstract layer spec

abstract state ➕

PMap := ZMap.t PTEInfo
(* *vaddr ⇀ (paddr, perm)* *)

Invariants: kernel page table is a direct map; user parts are isolated

abstract primitives ➕
(Coq functions)

```
Definition page_table_init := …
Definition page_table_insert :=…
Definition page_table_rmv := …
Definition page_table_read := …
```

concrete C implementation

memory ➖

```
char * page_dir[1024];

uint page_table[1024][1024];
```

C functions

```
int page_table_init() { … }
int page_table_insert { … }
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```

Formalizing Abstraction Layers

What is a ***certified*** abstraction layer

(L_1, M, L_2) ?

C or Asm
implementation

module ***M*** with
concrete state: ***mem***

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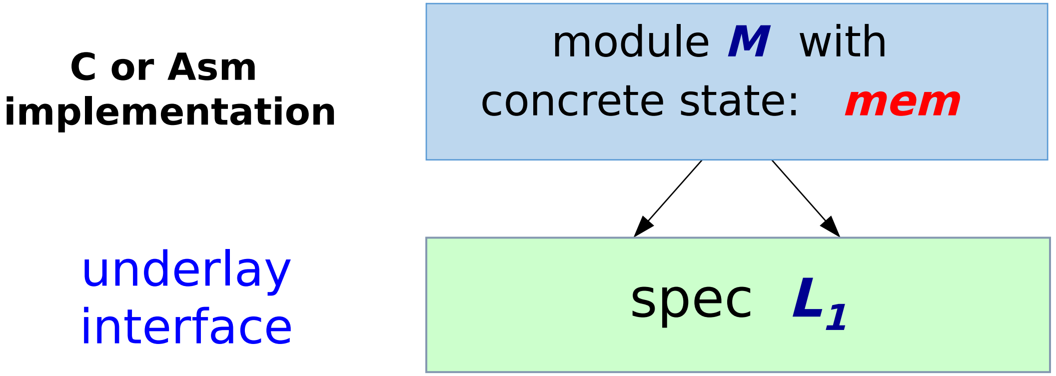

C or Asm implementation

module ***M*** with
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underlay interface

spec ***L_1***

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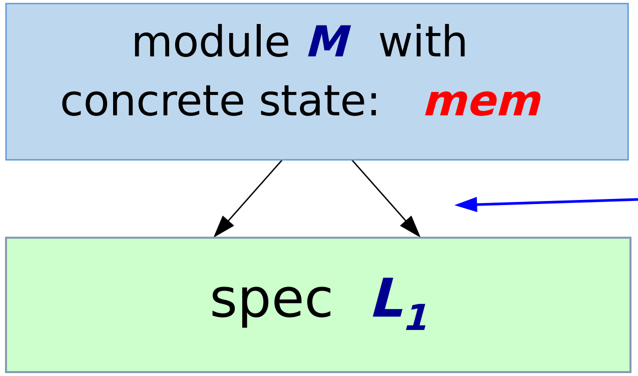

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calling abstract primitives in ***L_1***

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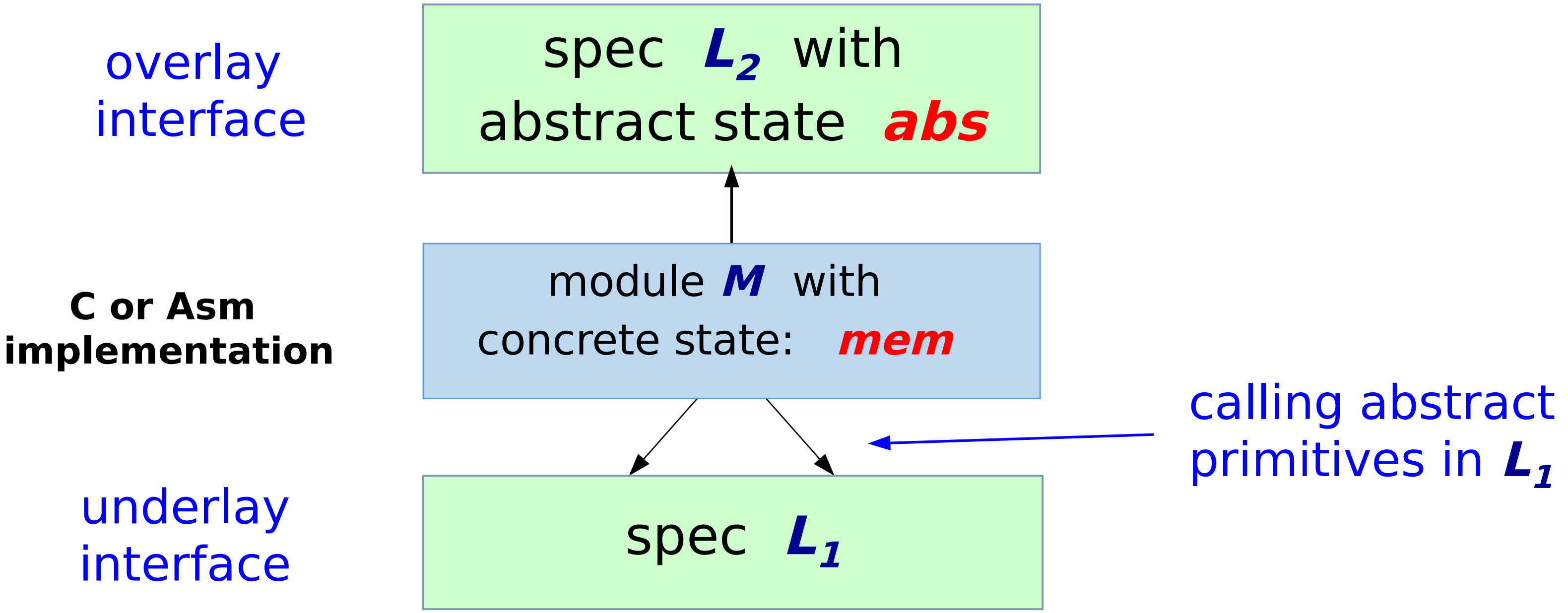

overlay
interface

spec L_2 with
abstract state ***abs***

C or Asm
implementation

module ***M*** with
concrete state: ***mem***

calling abstract
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underlay
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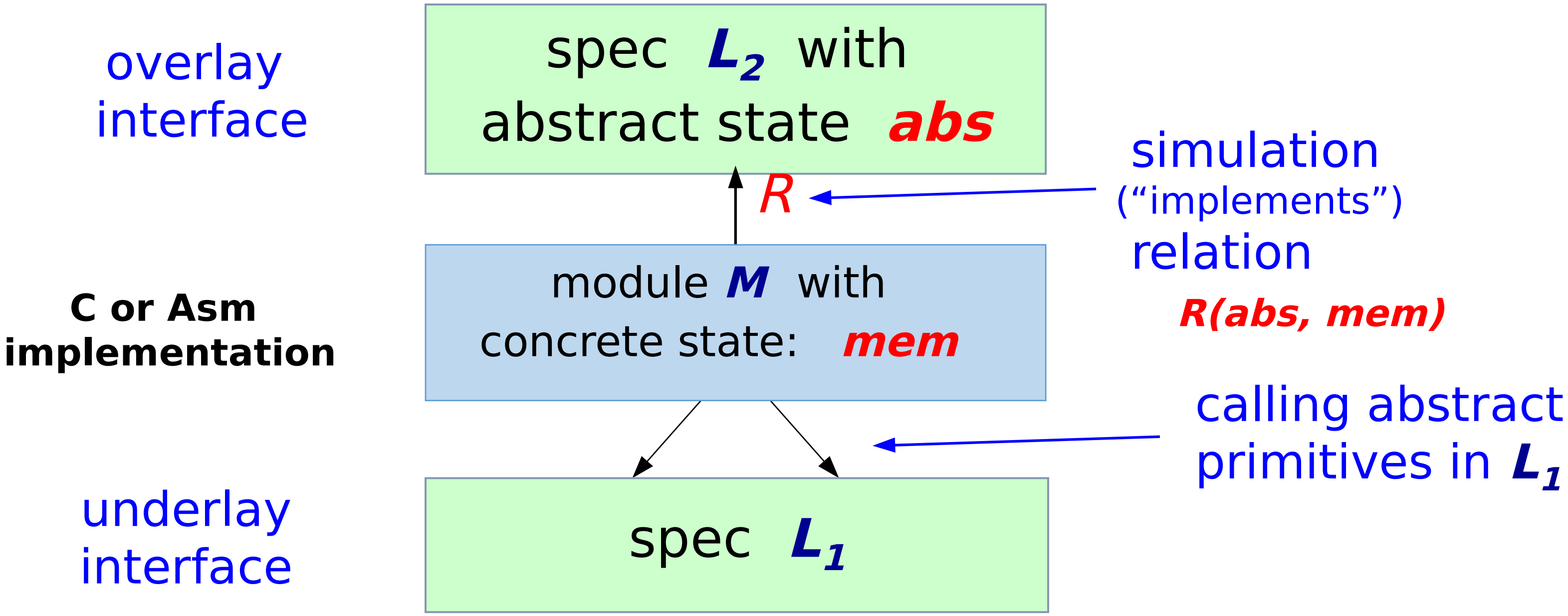

overlay interface

spec L_2 with abstract state ***abs***

R

simulation (“implements”) relation

R(abs, mem)

C or Asm implementation

module M with concrete state: ***mem***

calling abstract primitives in L_1

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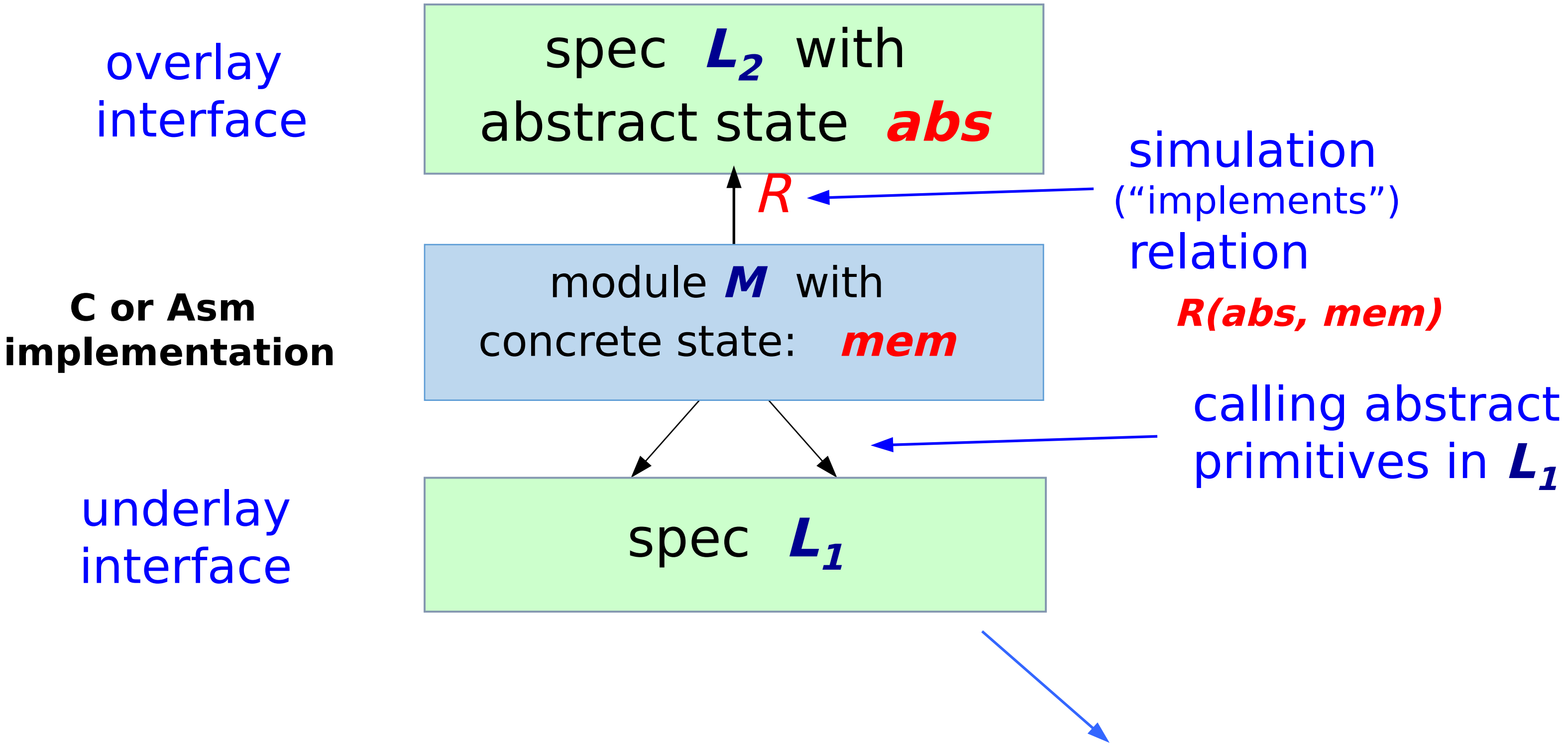

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Recorded as the *well-formed layer* judgment

$$\boxed{L_1 \vdash_R M : L_2}$$

Compositional Verification:
The "Implements" Simulation Relation

$L_1 \vdash_R M : L_2$ Defined as $L_2 \le_R [\![\; M \;]\!] \; L_1$

compositional
per-module
semantics
$[\![\, \bullet \,]\!]$

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for each function **f** in Dom(L_2)

$$\text{abs2} \xrightarrow{L_2(\mathbf{f})} \text{abs2}'$$

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$[\![\bullet]\!]$

for each function **f** in Dom($\boldsymbol{L_2}$)

$$\begin{tikzcd}
\text{abs2} \arrow[r, "\boldsymbol{L_2}\mathbf{(f)}"] \arrow[d, dash, "R"'] & \text{abs2'} \\
\text{mem1} &
\end{tikzcd}$$

Compositional Verification: The “Implements” Simulation Relation

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$\llbracket \bullet \rrbracket$

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compositional per-module semantics $[\![\bullet]\!]$

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\text{mem1} \arrow[r, dotted, "{[\![M]\!] (L_1)(\mathbf{f})}"'] & \text{mem1'}
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Forward Downward Simulation:

- Whenever L_2(**f**) takes abs2 to abs2’ in one step, and R(abs2, mem1) holds,
- then there exists mem1’ such that $[\![M]\!]$ (L_1)(**f**) takes mem1 to mem1’ in zero or more steps , and R(abs2’, mem1’) also holds.

Compositional Verification: The “Implements” Simulation Relation

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Forward Downward Simulation

Why is it enough?

Forward Downward Simulation:

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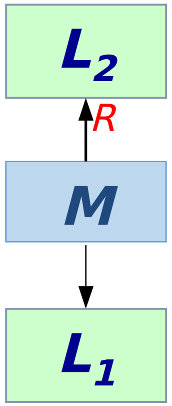
Deep Specification and Contextual Refinement

Our ultimate goal:

Making refinement "contextual" using the whole-program semantics $[\![\bullet]\!]$

$$\boxed{L_1 \models_R M : L_2}$$



L_2 is a **deep specification** of M over L_1

if under any valid program context P of L_2,

$[\![P \oplus M]\!] (L_1)$ and $[\![P]\!] (L_2)$ are

observationally equivalent

L_2 captures everything about running M over L_1

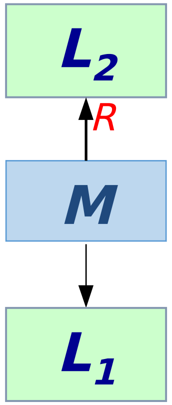
Soundness

Compositional Verification

$L_1 \vdash_R M : L_2$

Making refinement “contextual” using the whole-program semantics 【•】

$L_1 \models_R M : L_2$



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Reversing the Simulation Relation

$$\boxed{L_1 \vdash_R M : L_2} \longrightarrow \boxed{L_2 \leq_R [\![M]\!] L_1}$$

Reversing the Simulation Relation

$$L_1 \vdash_R M : L_2 \quad \longrightarrow \quad L_2 \leq_R \llbracket M \rrbracket \, L_1$$

$$\Big\downarrow \text{ Contextualize}$$

$\forall$ valid P:

$$\text{【} P \text{】}(L_2) \leq_R \text{【} P \oplus M \text{】}(L_1)$$

Reversing the Simulation Relation

$L_1 \vdash_R M : L_2$ → $L_2 \leq_R [\![M]\!] L_1$

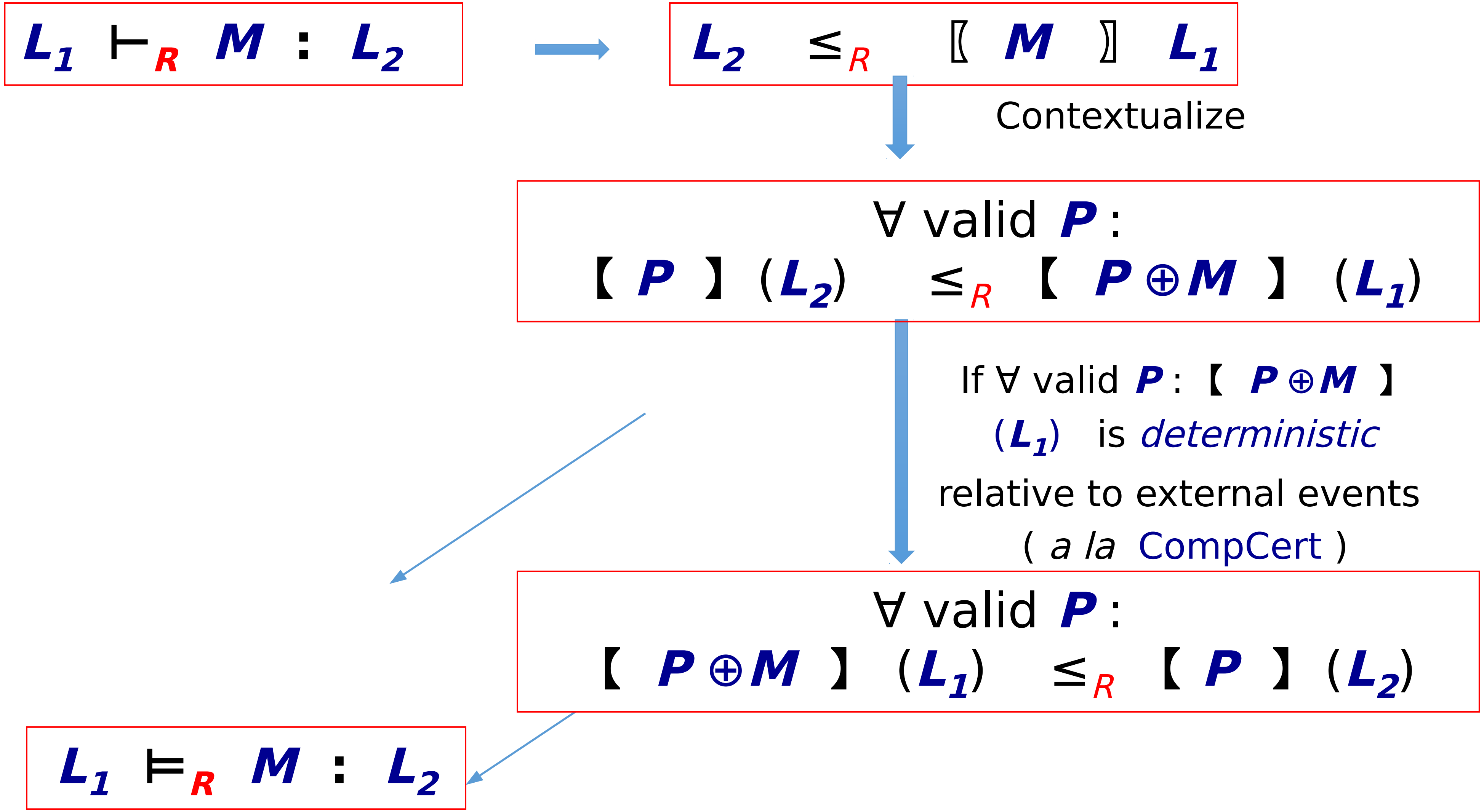
Contextualize

$$\forall \text{ valid } P : \\ 【P】(L_2) \leq_R 【P \oplus M】(L_1)$$

If ∀ valid P: $【P \oplus M】(L_1)$ is *deterministic* relative to external events (*a la* CompCert)

$$\forall \text{ valid } P : \\ 【P \oplus M】(L_1) \leq_R 【P】(L_2)$$

Reversing the Simulation Relation



$L_1 \vdash_R M : L_2$

$L_2 \leq_R [\![M]\!] \; L_1$

Contextualize

∀ valid P:

$[\![P]\!](L_2) \leq_R [\![P \oplus M]\!](L_1)$

If ∀ valid P: $[\![P \oplus M]\!](L_1)$ is *deterministic* relative to external events (*a la* CompCert)

∀ valid P:

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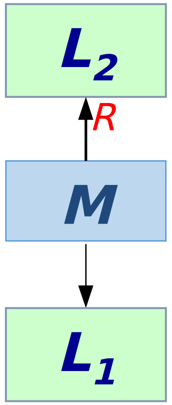
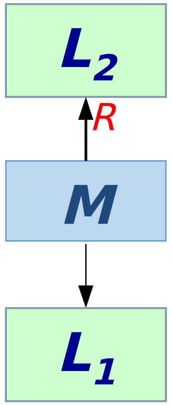
$L_1 \vDash_R M : L_2$

Why Deep Spec is Really Cool?



L_2 is a **deep specification** of M over L_1 if under any valid program context P of L_2, 【 $P \oplus M$ 】 (L_1) and 【 P 】 (L_2) are observationally equivalent

Why Deep Spec is Really Cool?



L_2 is a **deep specification** of M over L_1 if under any valid program context P of L_2, $\llbracket P \oplus M \rrbracket (L_1)$ and $\llbracket P \rrbracket (L_2)$ are observationally equivalent

Deep spec L_2 captures all we need to know about a layer M

- No need to ever look at M again!
- Any property about M can be proved using L_2 alone.

Implementation Independence : any two implementations of the same deep spec are *contextually equivalent*

POPL
2015
Mumbai, India
January 12-18

Our Contributions

- We introduce deep specification and present a language-based formalization of certified abstraction layer

- We developed new languages & tools in Coq
  - A formal layer calculus for composing certified layers
  - ClightX for writing certified layers in a C-like language
  - AsmX for writing certified layers in assembly
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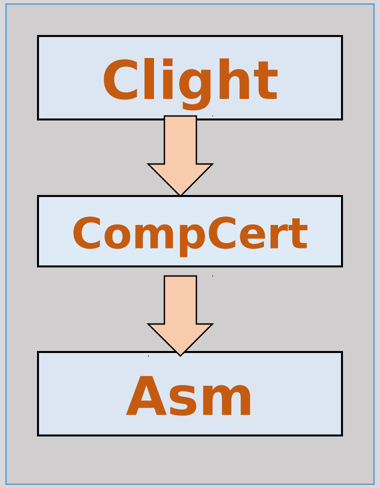
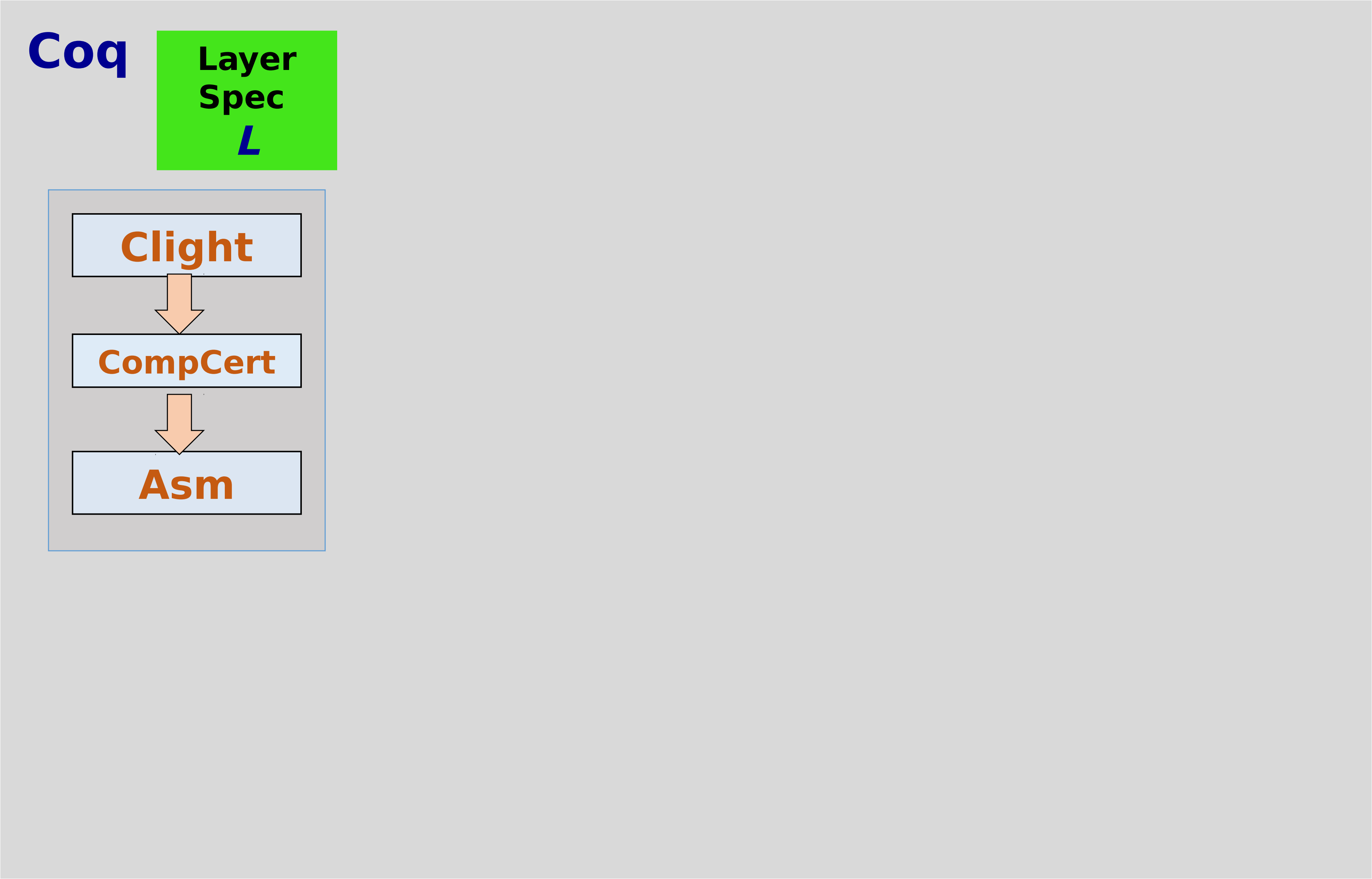
Coq

Coq



What We Have Done



Coq

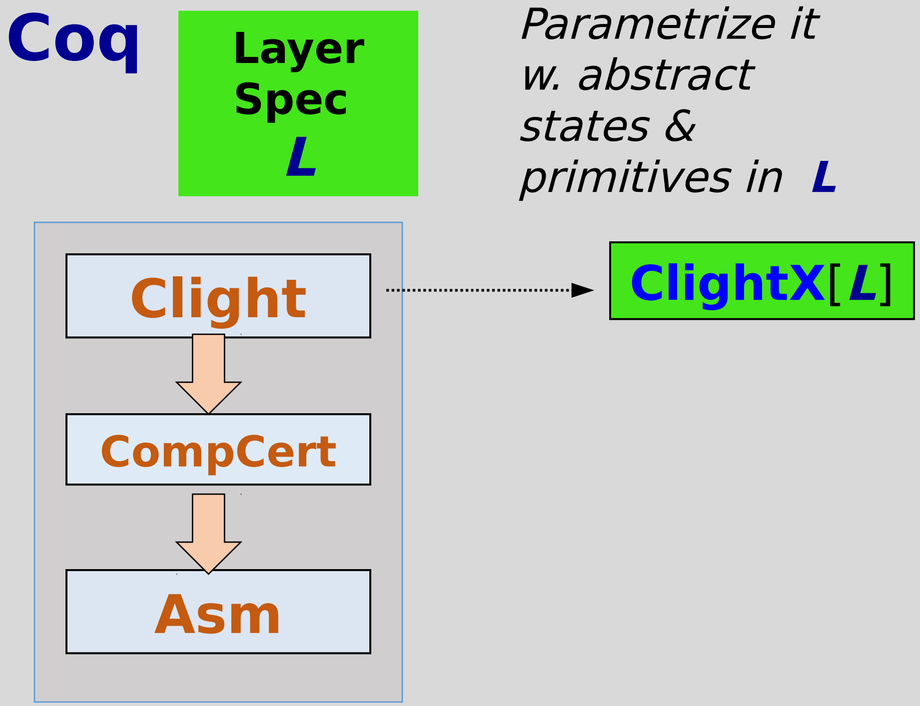
Layer Spec *L*

Clight

CompCert

Asm

What We Have Done



Coq

Layer Spec *L*

*Parametrize it w. abstract states & primitives in **L***

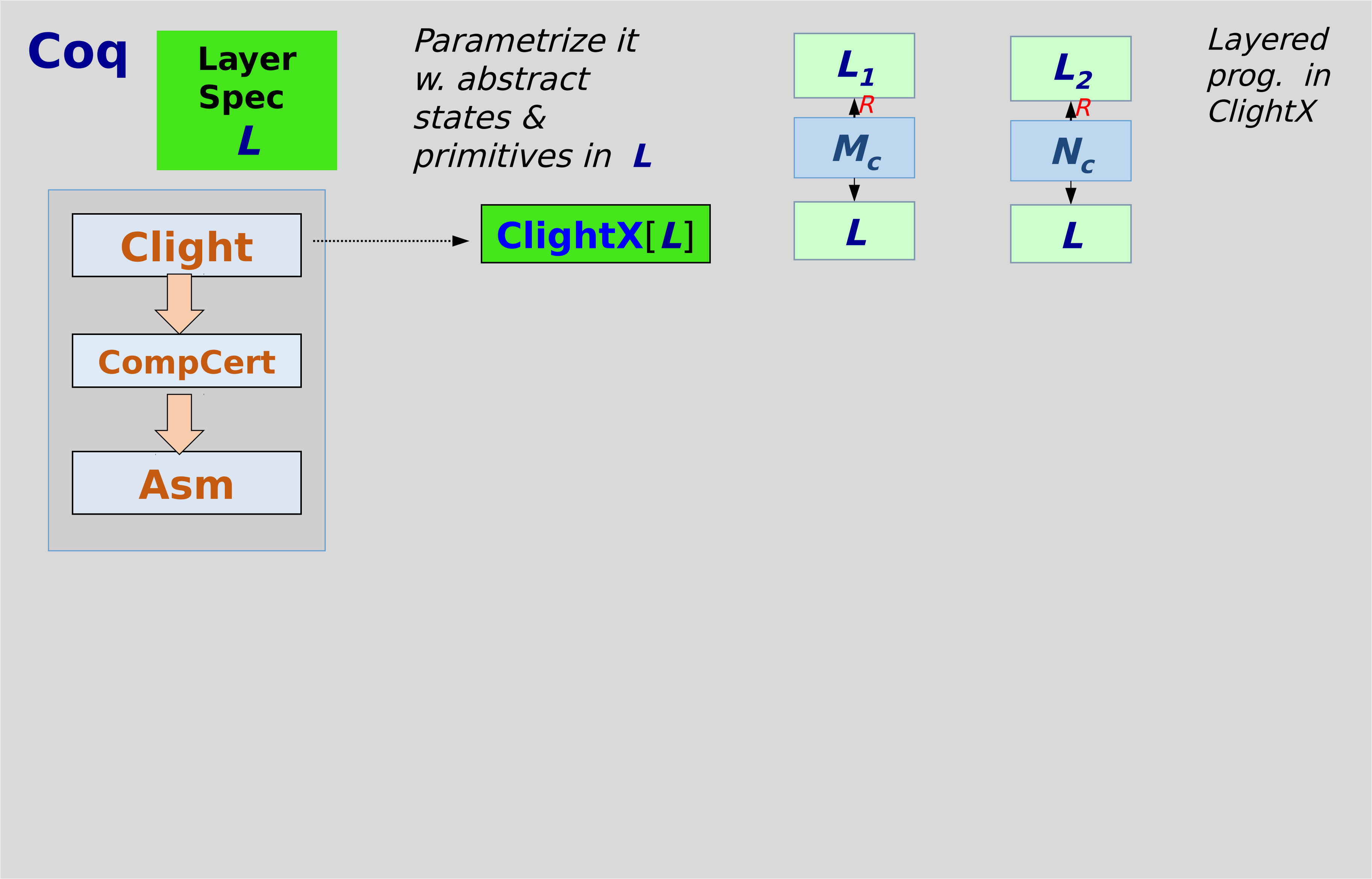
Clight

CompCert

Asm

ClightX[*L*]

What We Have Done



Coq

Layer Spec L

Parametrize it w. abstract states & primitives in L

Clight

CompCert

Asm

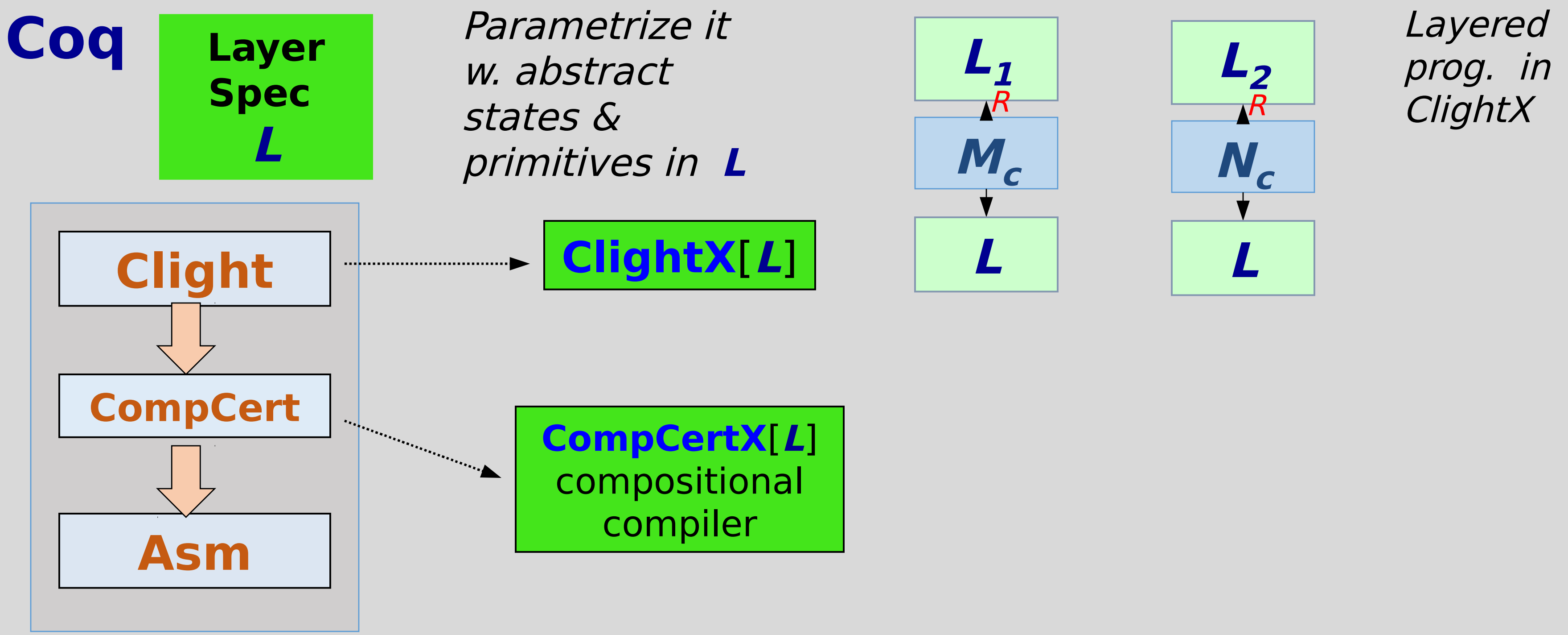
ClightX[L]

L_1
R
M_c
L

L_2
R
N_c
L

Layered prog. in ClightX

What We Have Done



Coq

Layer Spec
L

Parametrize it w. abstract states & primitives in ***L***

Clight

CompCert

Asm

ClightX[*L*]

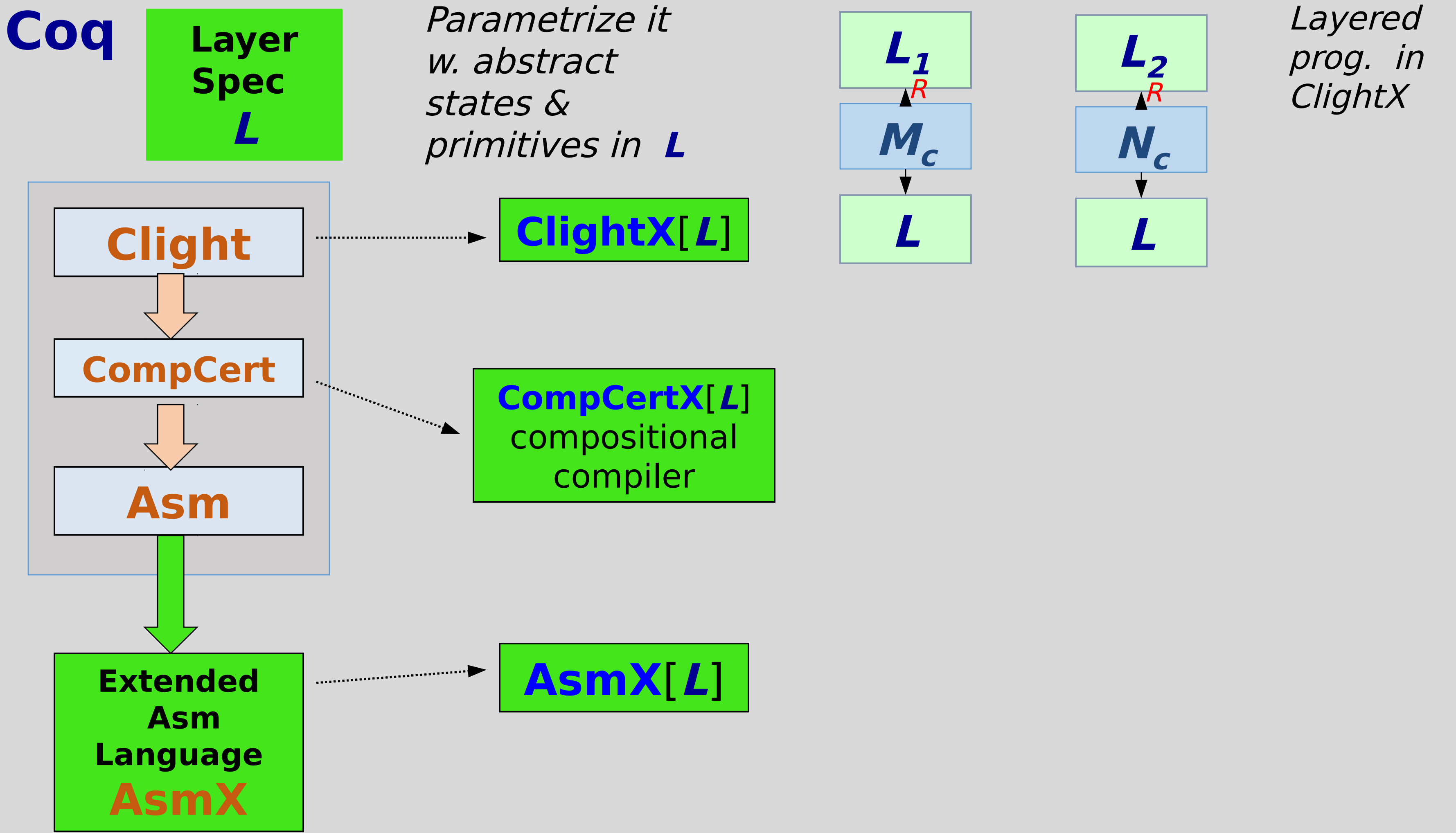
CompCertX[*L*]
compositional compiler

L_1
R
M_c
L

L_2
R
N_c
L

Layered prog. in ClightX

What We Have Done



Coq

Layer Spec
L

Parametrize it w. abstract states & primitives in ***L***

L_1 $\xleftarrow{R}$ M_c → L

L_2 $\xleftarrow{R}$ N_c → L

Layered prog. in ClightX

Clight → **ClightX[*L*]**

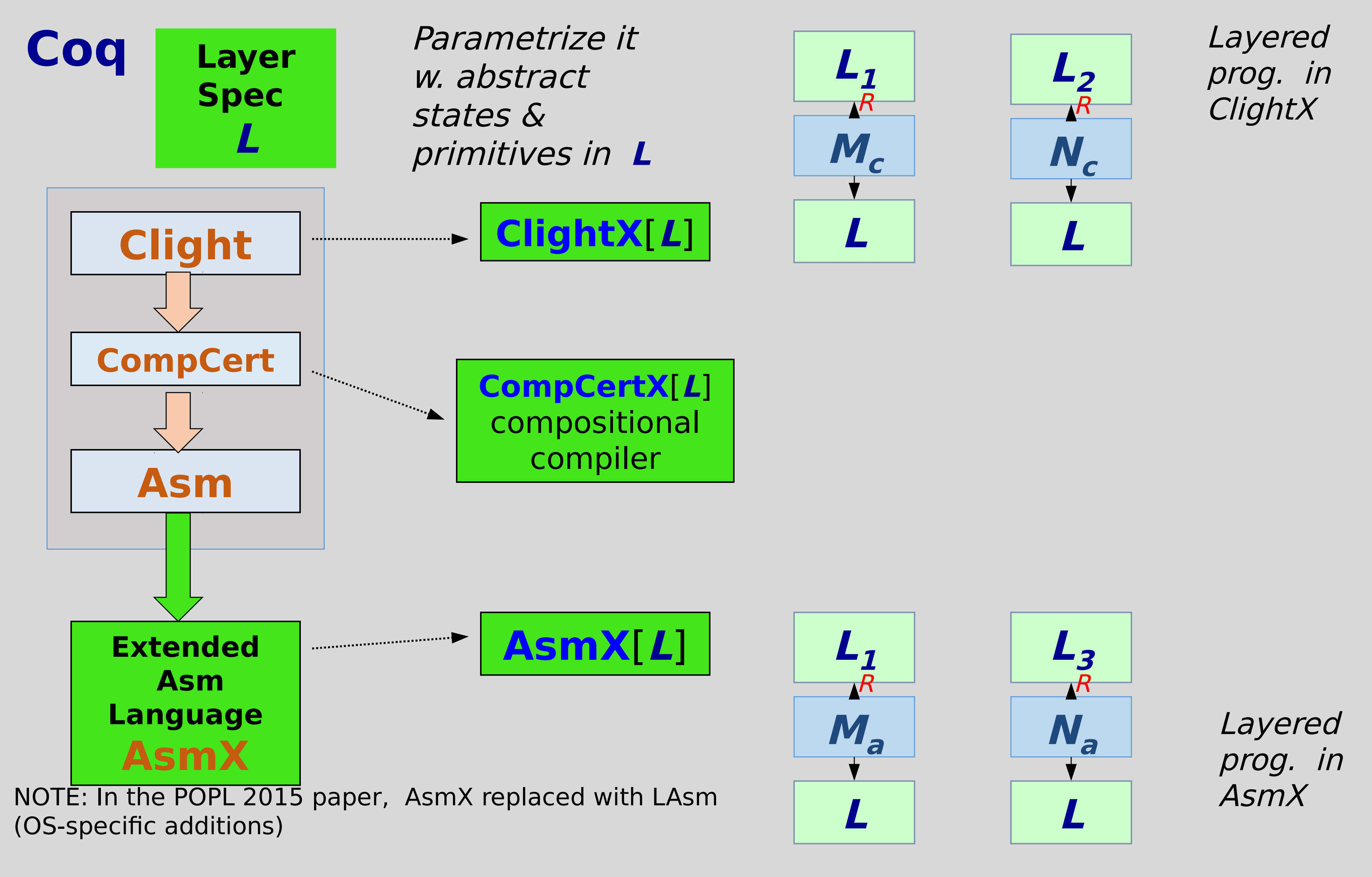
CompCert → **CompCertX[*L*]** compositional compiler

Asm

Extended Asm Language AsmX → **AsmX[*L*]**

NOTE: In the POPL 2015 paper, AsmX replaced with LAsm (OS-specific additions)

What We Have Done



Coq

Layer Spec *L*

*Parametrize it w. abstract states & primitives in **L***

Clight

CompCert

Asm

ClightX[*L*]

CompCertX[*L*] compositional compiler

Extended Asm Language AsmX

AsmX[*L*]

L_1 R M_c L

L_2 R N_c L

Layered prog. in ClightX

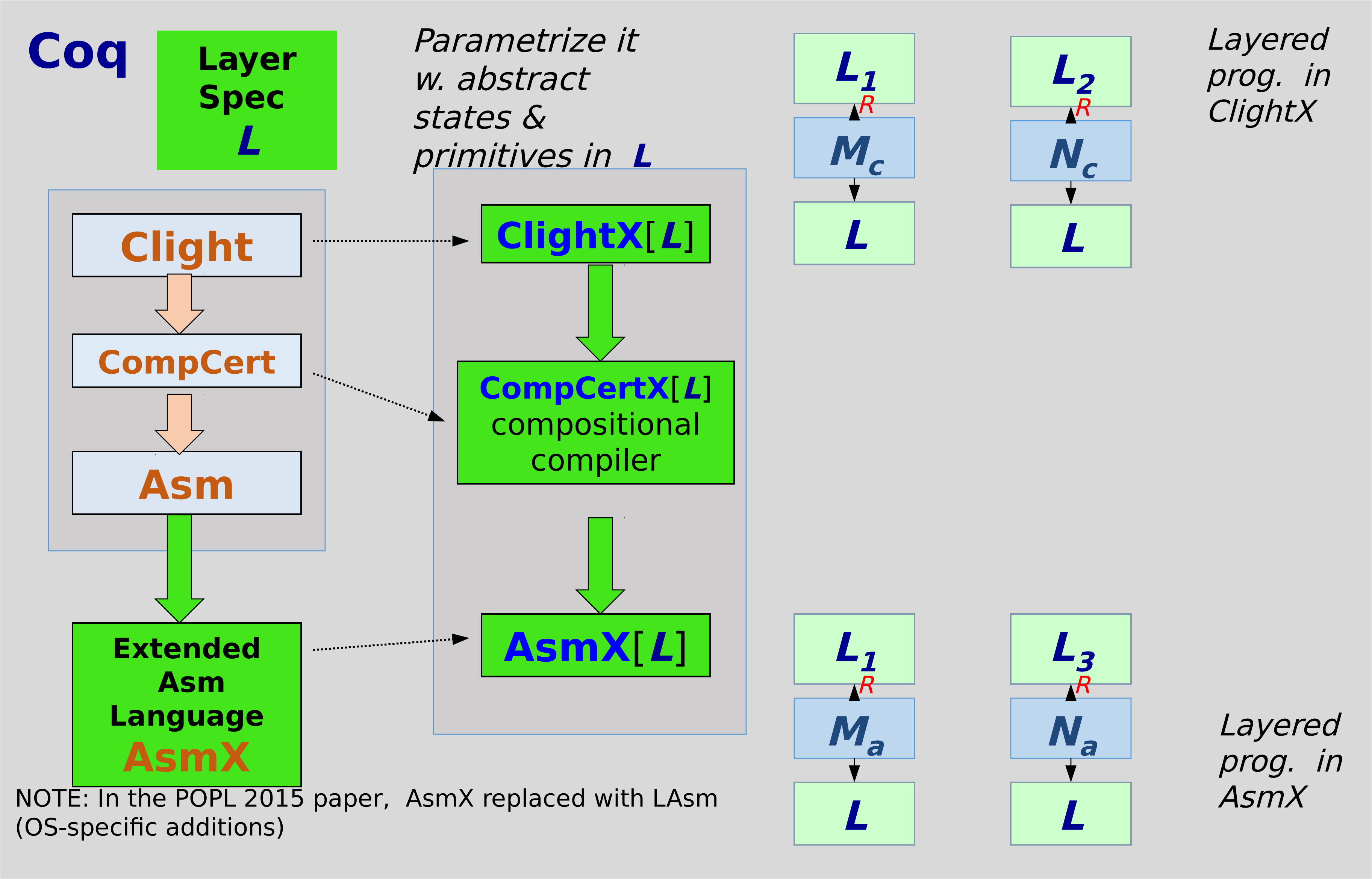
L_1 R M_a L

L_3 R N_a L

Layered prog. in AsmX

NOTE: In the POPL 2015 paper, AsmX replaced with LAsm (OS-specific additions)

What We Have Done



Coq

Layer Spec *L*

*Parametrize it w. abstract states & primitives in **L***

Clight

CompCert

Asm

Extended Asm Language AsmX

ClightX[*L*]

CompCertX[*L*] compositional compiler

AsmX[*L*]

L_1 $\xleftarrow{R}$ M_c → L

L_2 $\xleftarrow{R}$ N_c → L

Layered prog. in ClightX

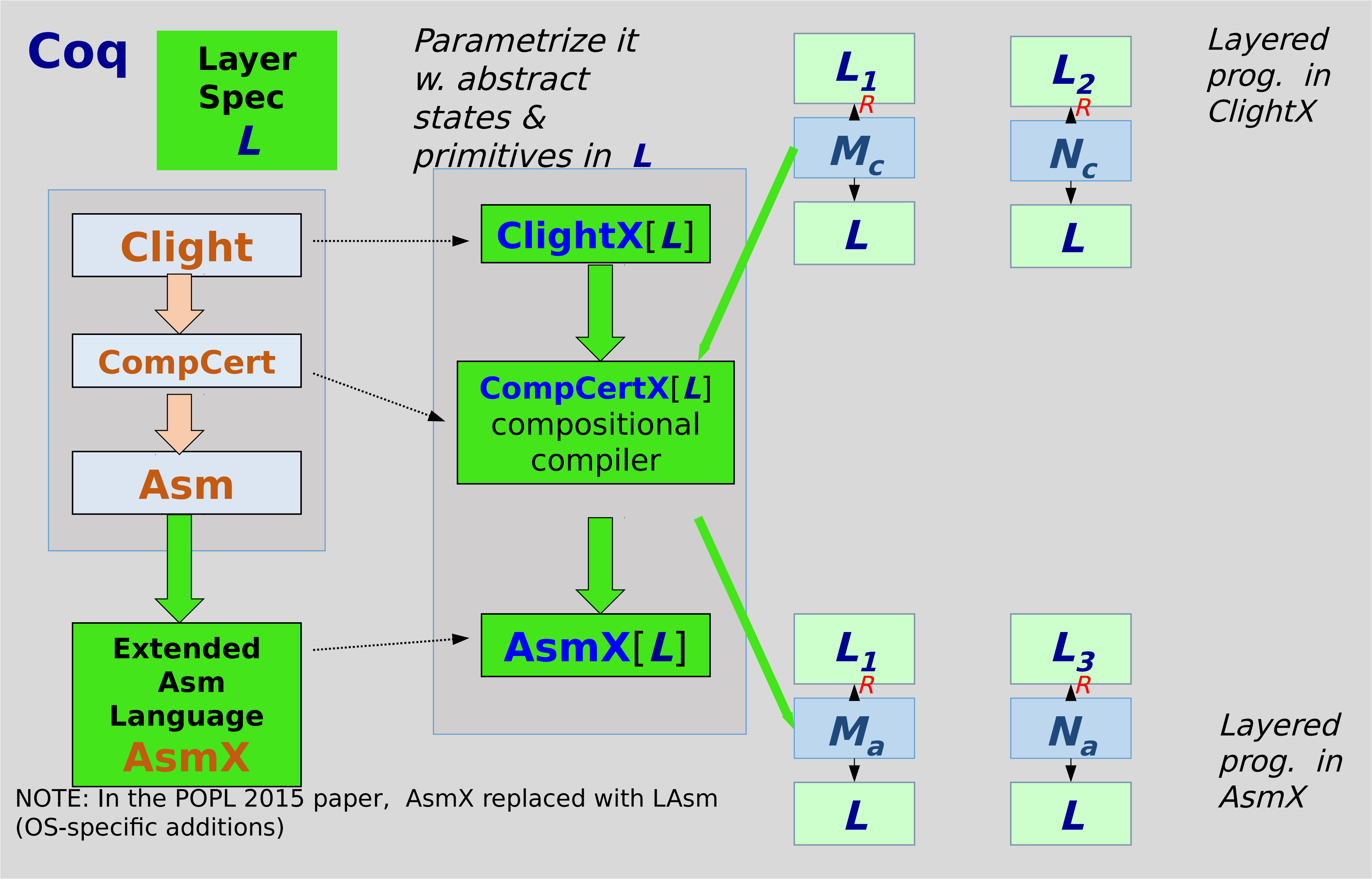
L_1 $\xleftarrow{R}$ M_a → L

L_3 $\xleftarrow{R}$ N_a → L

Layered prog. in AsmX

NOTE: In the POPL 2015 paper, AsmX replaced with LAsm (OS-specific additions)

What We Have Done



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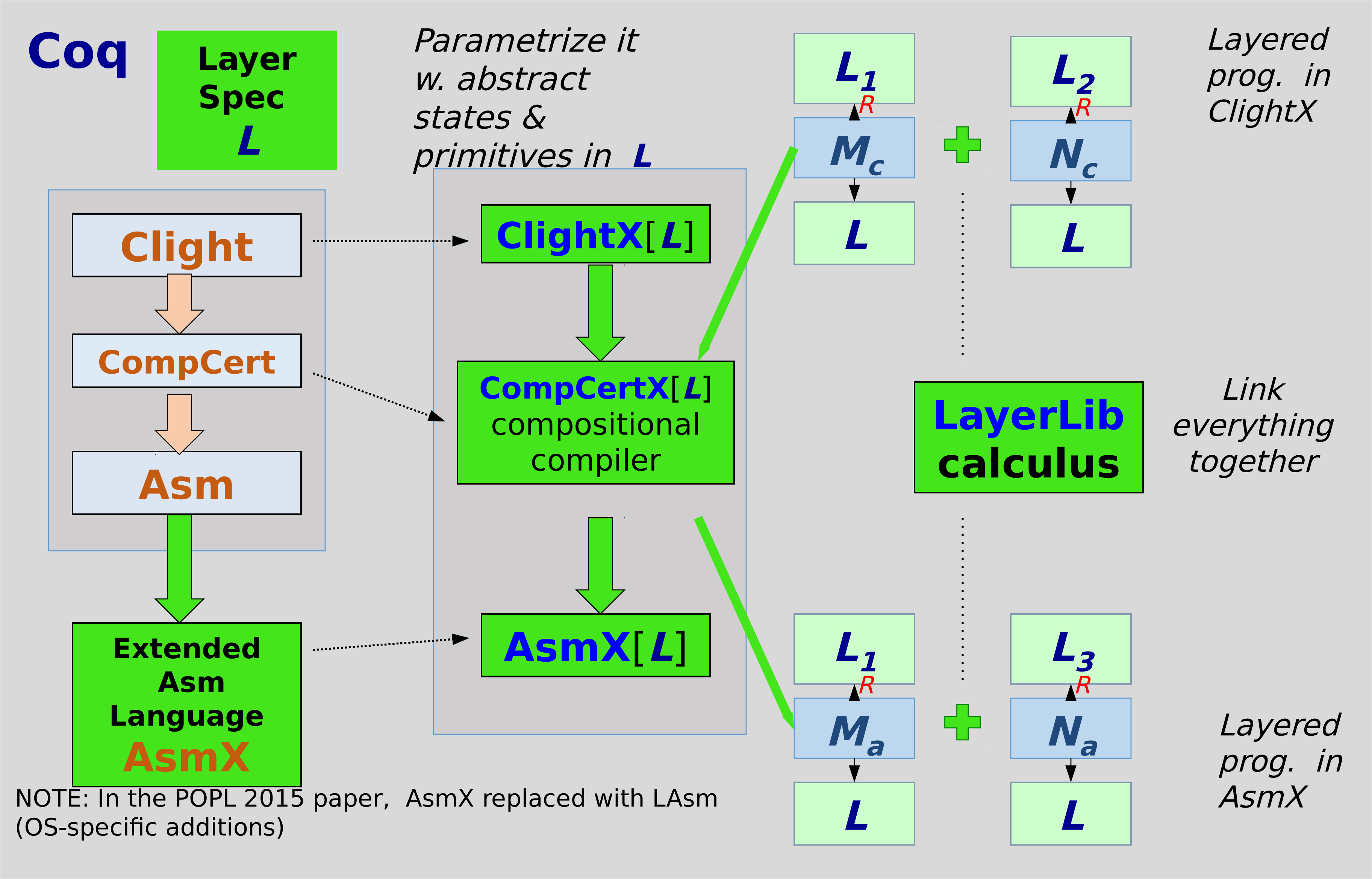
What We Have Done



Coq

Layer Spec L

Parametrize it w. abstract states & primitives in L

Clight

CompCert

Asm

ClightX[L]

CompCertX[L] compositional compiler

AsmX[L]

Extended Asm Language AsmX

$L_1 \xleftarrow{R} M_c \rightarrow L$ + $L_2 \xleftarrow{R} N_c \rightarrow L$

Layered prog. in ClightX

LayerLib calculus

Link everything together

$L_1 \xleftarrow{R} M_a \rightarrow L$ + $L_3 \xleftarrow{R} N_a \rightarrow L$

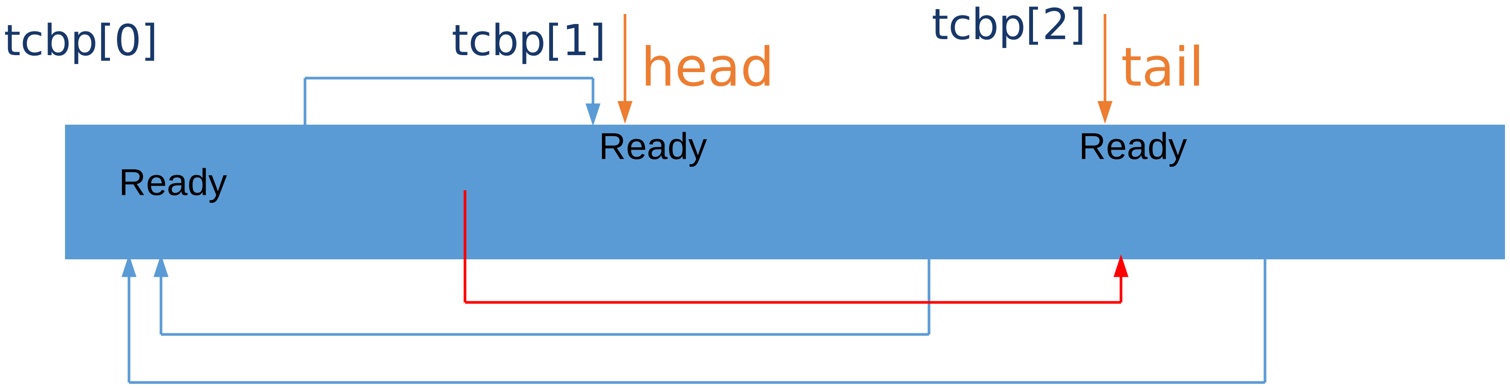
Layered prog. in AsmX

NOTE: In the POPL 2015 paper, AsmX replaced with LAsm (OS-specific additions)

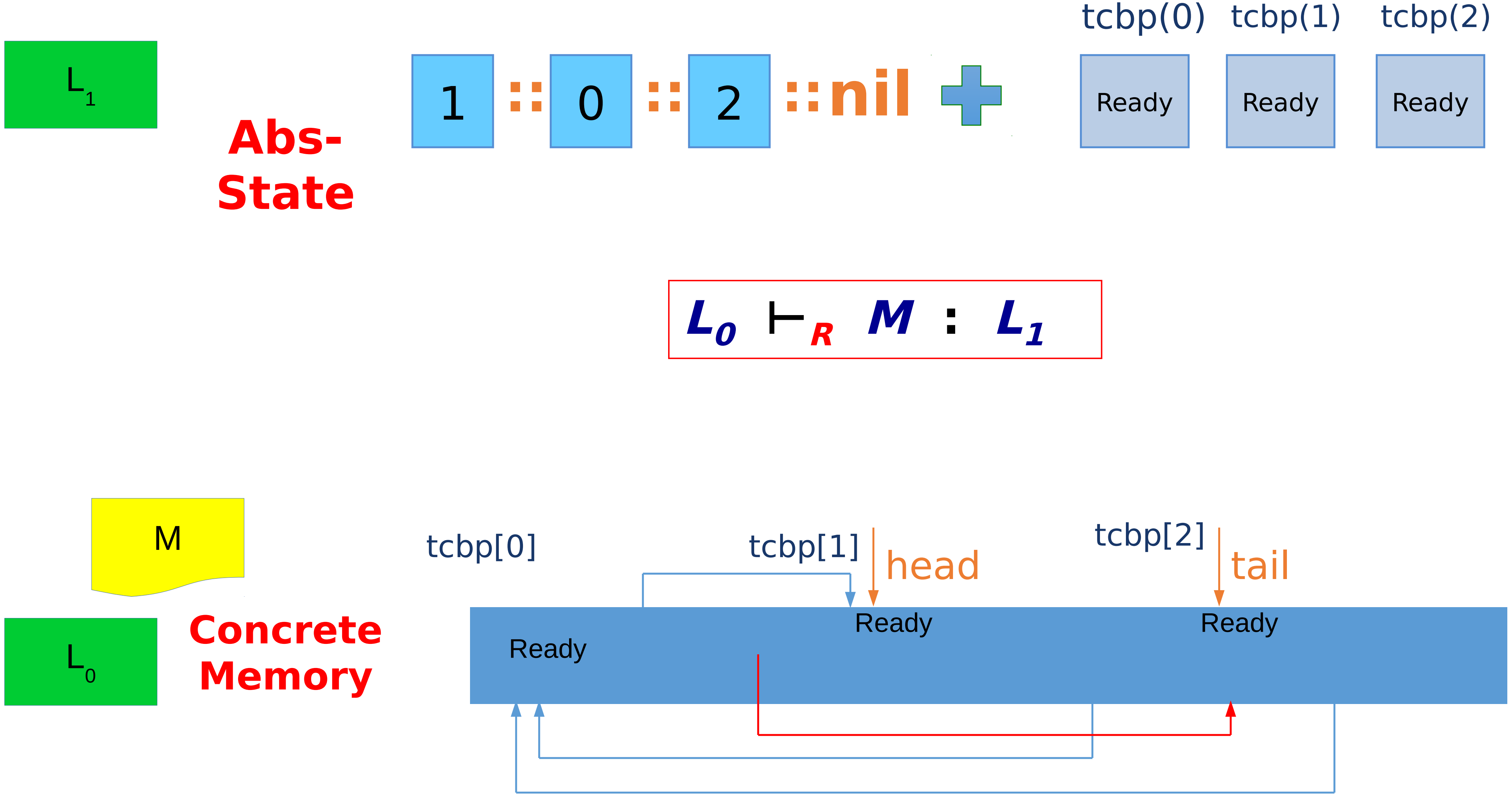
Example: Thread Queues

Abs-State

Concrete Memory



Example: Thread Queues



L_1

Abs-State

1 :: 0 :: 2 :: nil +

tcbp(0) tcbp(1) tcbp(2)

Ready Ready Ready

$$L_0 \vdash_R M : L_1$$

M

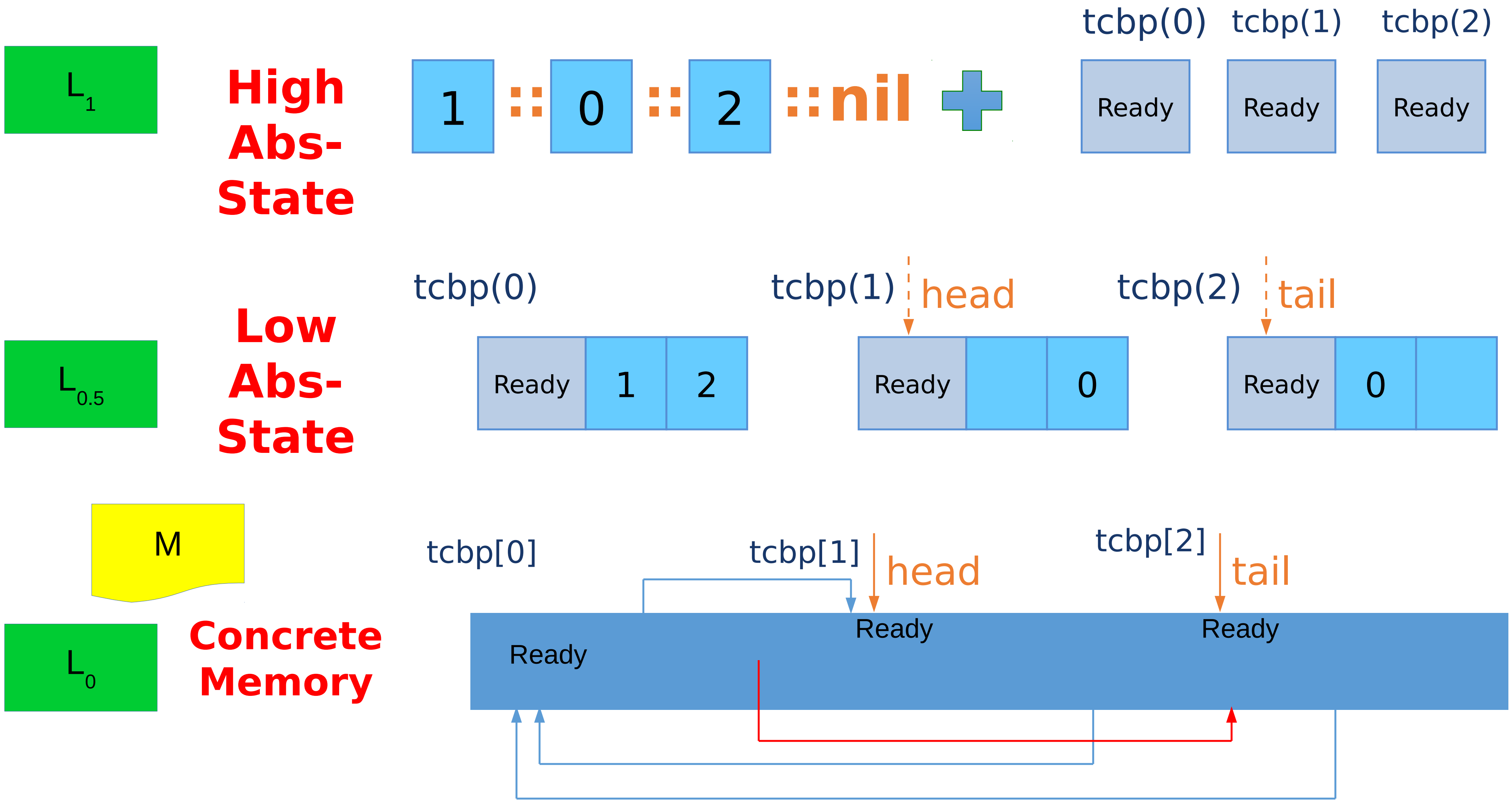
L_0

Concrete Memory

tcbp[0] tcbp[1] head tcbp[2] tail

Ready Ready Ready

Example: Thread Queues



L_1

High Abs-State

1 :: 0 :: 2 ::nil +

tcbp(0) Ready

tcbp(1) Ready

tcbp(2) Ready

$L_{0.5}$

Low Abs-State

tcbp(0) Ready 1 2

tcbp(1) head Ready 0

tcbp(2) tail Ready 0

M

L_0

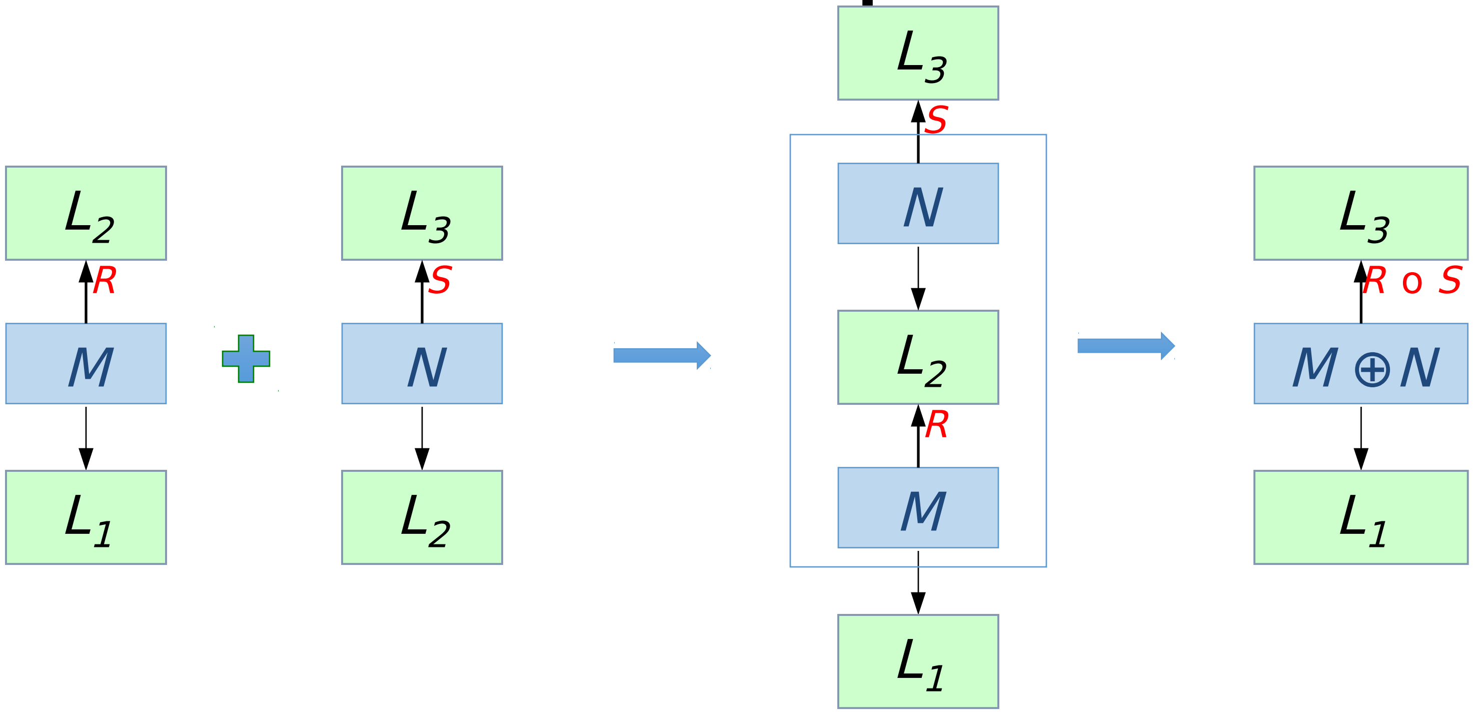
Concrete Memory

tcbp[0] Ready

tcbp[1] head Ready

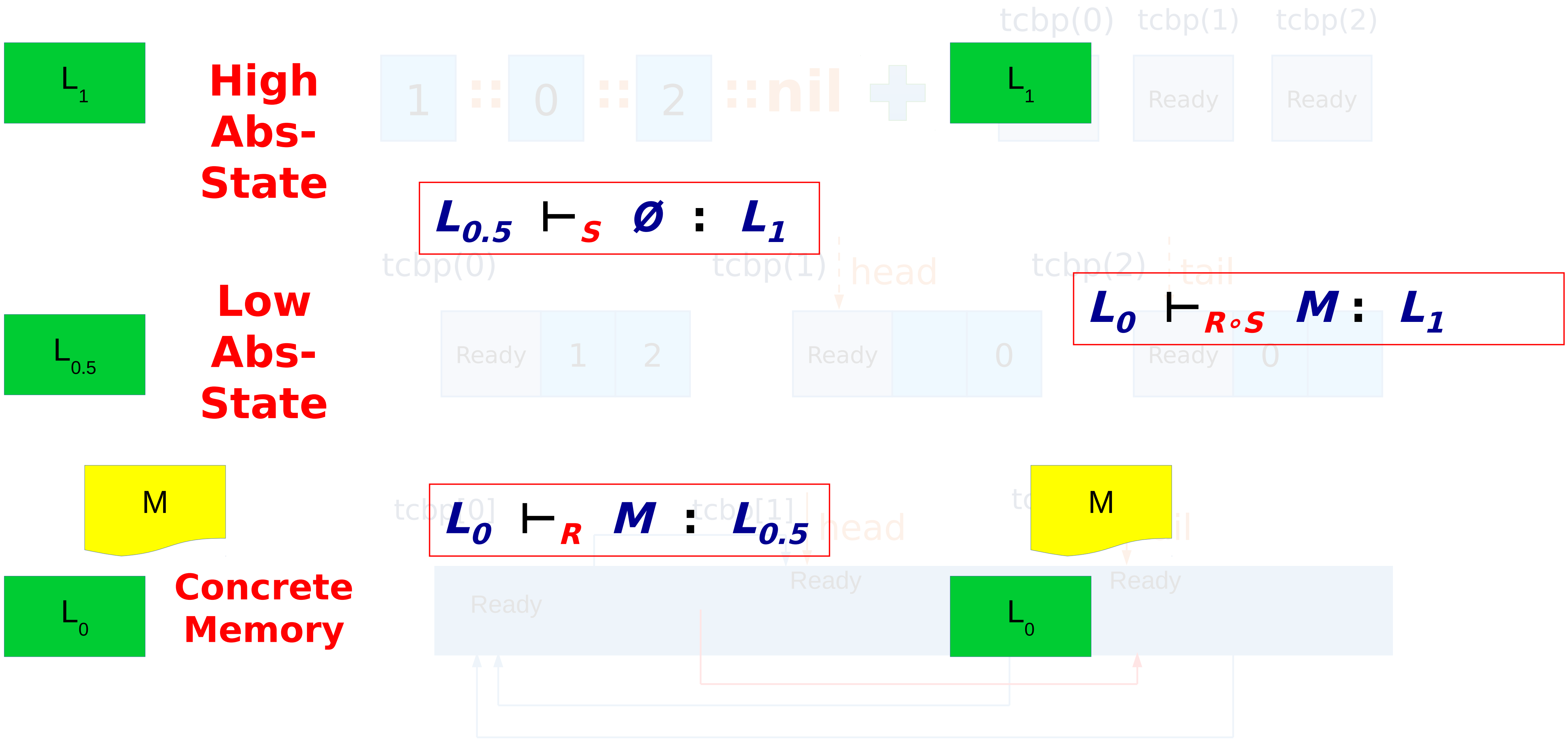
tcbp[2] tail Ready

LayerLib: Vertical Composition



$$\frac{L_1 \vdash_R M : L_2 \qquad L_2 \vdash_S N : L_3}{L_1 \vdash_{R \circ S} M \oplus N : L_3} \textsc{Vcomp}$$

Example: Thread Queues



High Abs-State

$L_{0.5} \vdash_{S} \emptyset : L_1$

Low Abs-State

$L_0 \vdash_{R \circ S} M : L_1$

$L_0 \vdash_{R} M : L_{0.5}$

Concrete Memory

Example: Thread Queues

C Implementation

Low Layer Spec in Coq

High Layer Spec in Coq

M

Example: Thread Queues

C Implementation

```
typedef enum {
   TD_READY, TD_RUN,
   TD_SLEEP, TD_DEAD
}  td_state;
```

Low Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.
```

High Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.
```

Example: Thread Queues

C Implementation

```
typedef enum {
   TD_READY, TD_RUN,
   TD_SLEEP, TD_DEAD
}  td_state;

struct tcb {
   td_state tds;
   struct tcb  *prev,  *next;
};
```

Low Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.


Record tcb := TCBV {
  tds : td_state;
  prev : Z; next : Z
}
```

High Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.

Definition tcb := td_state.
```

Example: Thread Queues

C Implementation

```
typedef enum {
   TD_READY, TD_RUN,
   TD_SLEEP, TD_DEAD
}  td_state;

struct tcb {
   td_state tds;
   struct tcb  *prev,  *next;
};

struct tdq {
  struct tcb  *head,  *tail;
};
```

Low Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.


Record tcb := TCBV {
  tds : td_state;
  prev : Z; next : Z
}

Record tdq := TDQV {
 head: Z; tail: Z
}
```

High Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.

Definition tcb := td_state.





Definition tdq := List Z.
```

Example: Thread Queues

C Implementation

```
typedef enum {
   TD_READY, TD_RUN,
   TD_SLEEP, TD_DEAD
}  td_state;

struct tcb {
   td_state tds;
   struct tcb  *prev,  *next;
};

struct tdq {
  struct tcb  *head,  *tail;
};

struct tcb tcbp[64];
struct tdq tdqp[64];
```

Low Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.


Record tcb := TCBV {
  tds : td_state;
  prev : Z; next : Z
}

Record tdq := TDQV {
 head: Z; tail: Z
}

Record abs:=ABS {
             tcbp :  ZMap.t tcb;
             tdqp : ZMap.t tdq
}
```

High Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.

Definition tcb := td_state.





Definition tdq := list Z.


Record abs := ABS {
             tcbp : ZMap.t tcb;
             tdqp : ZMap.t tdq
}
```

Example: Thread Queues

C Implementation

```
typedef enum {
   TD_READY, TD_RUN,
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}  td_state;

struct tcb {
   td_state tds;
   struct tcb  *prev,  *next;
};

struct tdq {
  struct tcb  *head,  *tail;
};

struct tcb tcbp[64];
struct tdq tdqp[64];

struct tcb * dequeue
       (struct tdq *q)  {
               ……
}
```

Low Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.


Record tcb := TCBV {
  tds : td_state;
  prev : Z; next : Z
}

Record tdq := TDQV {
 head: Z; tail: Z
}

Record abs:=ABS {
             tcbp :  ZMap.t tcb;
             tdqp : ZMap.t tdq
}

Definition dequeue
          (d : abs) (i : Z) :=
………………
```

High Layer Spec in Coq

```
Inductive td_state :=
| TD_READY | TD_RUN
| TD_SLEEP | TD_DEAD.

Definition tcb := td_state.

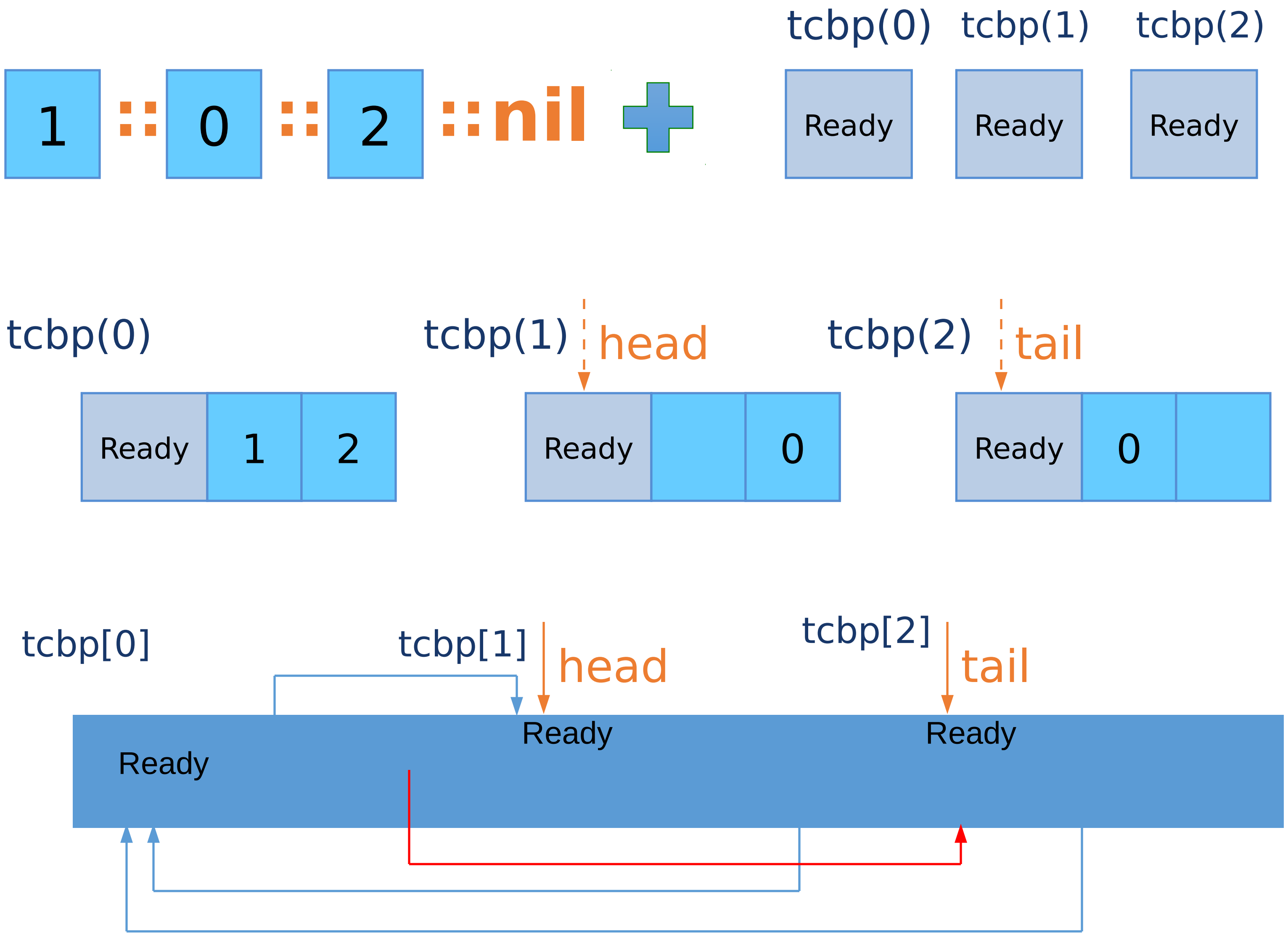



Definition tdq := list Z.


Record abs := ABS {
             tcbp : ZMap.t tcb;
             tdqp : ZMap.t tdq
}

Definition dequeue
       (d : abs) (i : Z) :=
match (d.tdqp i) with
   | h :: q' =>
         Some(set_tdq d i q', h)
   | nil => None
end
```

Example: Dequeue



High Abs-State

1 :: 0 :: 2 ::nil +

tcbp(0) tcbp(1) tcbp(2)

Ready Ready Ready

Low Abs-State

tcbp(0)

Ready 1 2

tcbp(1) head

Ready 0

tcbp(2) tail

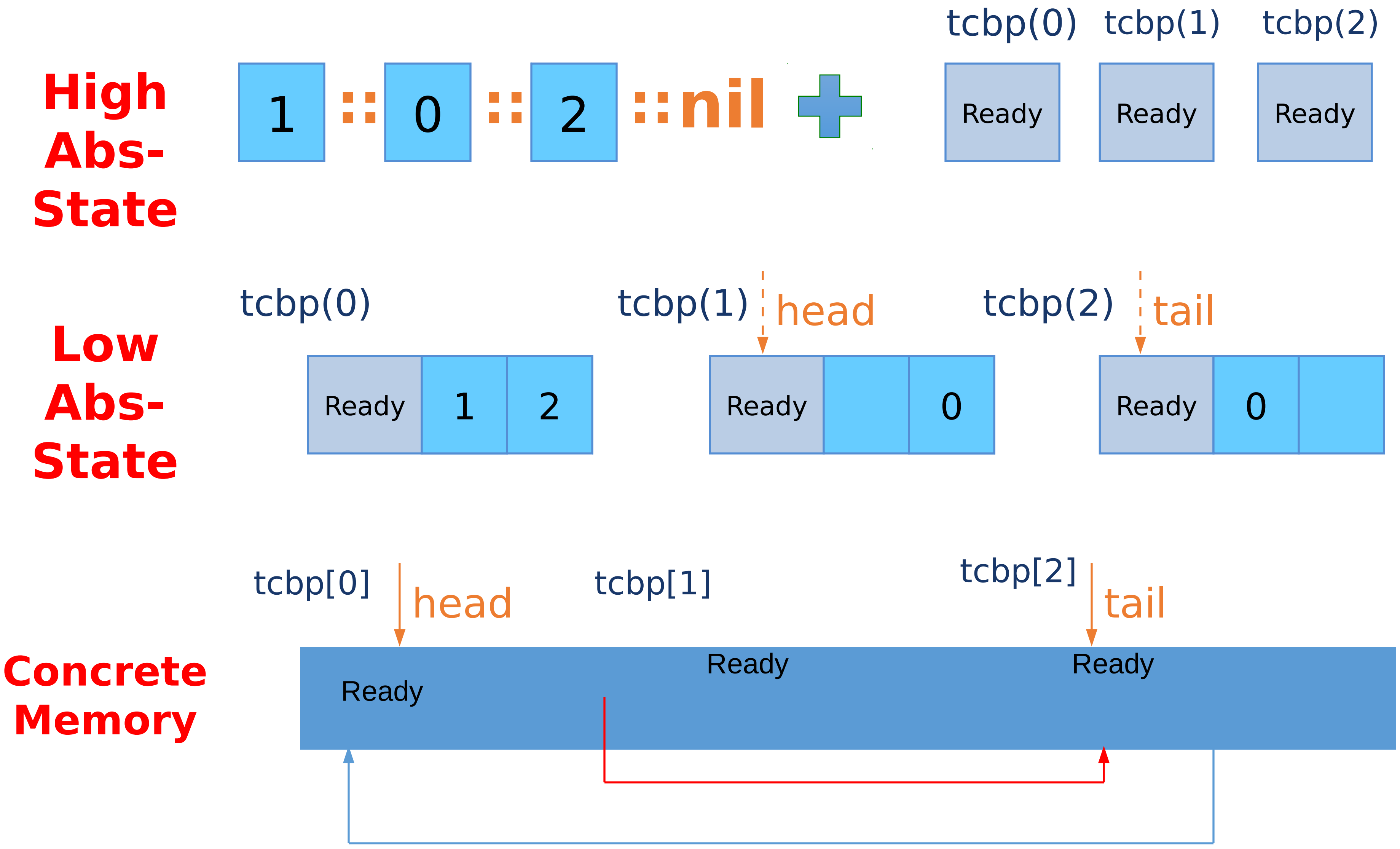
Ready 0

Concrete Memory

tcbp[0] tcbp[1] head tcbp[2] tail

Ready Ready Ready

Example: Dequeue



High Abs-State

1 :: 0 :: 2 ::nil +

tcbp(0) tcbp(1) tcbp(2)

Ready Ready Ready

Low Abs-State

tcbp(0)

Ready 1 2

tcbp(1) head

Ready 0

tcbp(2) tail

Ready 0

Concrete Memory

tcbp[0] head

tcbp[1]

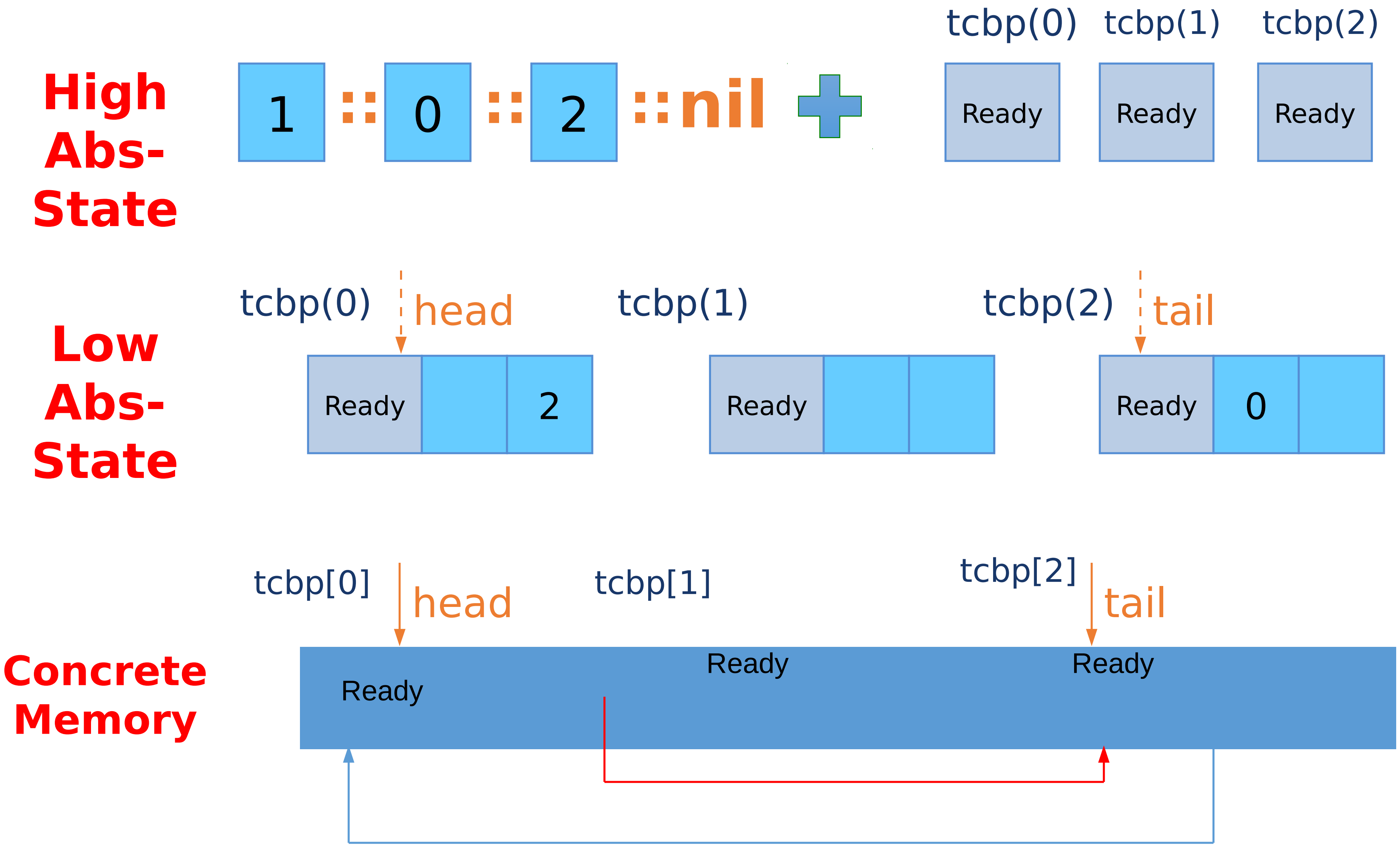
tcbp[2] tail

Ready

Ready

Ready

Example: Dequeue



High Abs-State

1 :: 0 :: 2 ::nil +

tcbp(0) Ready

tcbp(1) Ready

tcbp(2) Ready

Low Abs-State

tcbp(0) head: Ready | | 2

tcbp(1): Ready | |

tcbp(2) tail: Ready | 0 |

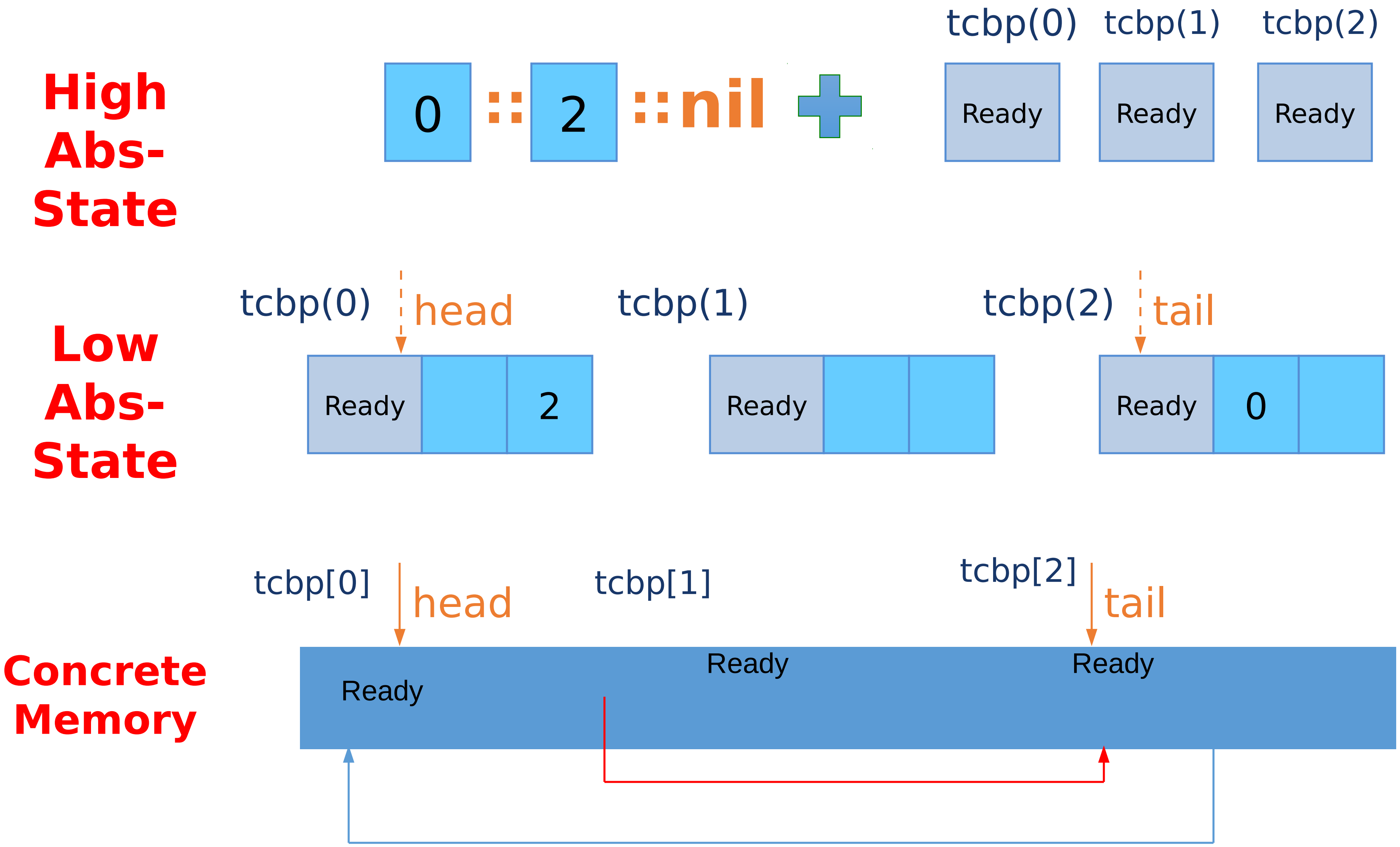
Concrete Memory

tcbp[0] head: Ready

tcbp[1]: Ready

tcbp[2] tail: Ready

Example: Dequeue



Our Contributions

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- We built multiple certified OS kernels in Coq
  - mCertiKOS-hyper consists of 37 layers, took less than one-person-year to develop, and can boot Linux as a guest

From CompCert 2.3 to CompCertX

- Clight to ClightX, Asm to AsmX
  - Parameterize over layer specifications
  - Per-module semantics
- Compilation passes
  - Allow function arguments, etc.
- Summary of changes :
  - 420 lines changed (out of ~120k) due to parameterization
  - 7k new lines due to per-module semantics

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ClightX

- Same syntax as CompCert 2.3 Clight
- Semantics :
  - Parameterized over external function calls
  - Made per-function instead of whole-machine

CompCert Clight: external function calls

```
Inductive step: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

CompCert Clight: external function calls

```
Definition extcall_sem: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

```
Definition external_call (ef: external_function): extcall_sem :=
  match ef with
  | EF_external name sg ⇒ external_functions_sem name sg
  | …
  end
```

```
Inductive step: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

CompCert Clight: external function calls

```
Definition extcall_sem: Type  :=
  forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.

Axiom external_functions_sem: ident → signature → extcall_sem.


Definition external_call (ef: external_function): extcall_sem :=
  match ef with
  | EF_external name sg ⇒ external_functions_sem name sg
  | …
  end



Inductive step: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

ClightX: parameterization over primitives

```
Definition extcall_sem: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

```
Class ExtCallOps := {
  external_call (ef: external_function): extcall_sem
}.
```

```
Inductive step {ec_ops: ExtCallOps}: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

ClightX: parameterization

```
Definition extcall_sem: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

```
Class ExtCallOps := {
  external_call (ef: external_function): extcall_sem
}.
```

Where is the abstract state ?

```
Inductive step {ec_ops: ExtCallOps}: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

ClightX: parameterization

```
Definition extcall_sem: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

```
Class ExtCallOps := {
  external_call (ef: external_function): extcall_sem
}.
```

Here *fits* the abstract state !

```
Inductive step {ec_ops: ExtCallOps}: state → trace → state → Prop :=
| …
|  step_external_function: forall ef targs tres vargs k m vres t m',
      external_call ef ge vargs m t vres m' →
      step (Callstate (External ef targs tres) vargs k m)
         t (Returnstate vres k m')
| …
```

CompCertX: memory model

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
    store:   memory_chunk → mem → block → Z → val → option mem;
    …
}
```

CompCertX: memory model

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
    store:   memory_chunk → mem → block → Z → val → option mem;
    …
}
```

```
Instance compcert_mem: MemoryOps compcert.common.Memory.mem := …
```

CompCertX: memory model

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
    store:   memory_chunk → mem → block → Z → val → option mem;
    …
}

Definition extcall_sem {mem: Type} {mem_ops: MemoryOps mem}: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

CompCertX: memory model

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
     store:   memory_chunk → mem → block → Z → val → option mem;
     …
}

Definition extcall_sem {mem: Type} {mem_ops: MemoryOps mem}: Type  :=
   forall (F V: Type), Genv.t F V → list val → mem → trace → val → mem → Prop.
```

And that's all !
CompCertX itself knows nothing
about the abstract state...

Memory model and abstract state

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
    store:   memory_chunk → mem → block → Z → val → option mem;
    …
}

Class AbstractStateOps (data mwd: Type) := {
    get_abstract_data: mwd → data;
    put_abstract_data: data → mwd → data;
    …
}
```

Memory model and abstract state

```
Class MemoryOps (mem: Type) := {
    load:    memory_chunk → mem → block → Z → option val;
    store:   memory_chunk → mem → block → Z → val → option mem;
    …
}

Class AbstractStateOps (data mwd: Type) := {
    get_abstract_data: mwd → data;
    put_abstract_data: data → mwd → data;
    …
}

Global Instance mem_with_data_mem:
  forall (mem data: Type),
         MemoryOps mem → MemoryOps (mem * data)
:= …

Global Instance mem_with_data_abstract_state:
  forall (mem data: Type),
         AbstractStateOps data (mem * data)
:= …
```

Lenses

CompCert Clight initial and final states

- Whole-machine semantics
- Initial state:
  - Call "main"
  - No arguments
  - Empty memory (except initialized globals)
- Final state:
  - Return an integer
  - Memory is not relevant

```
Inductive initial_state (p: program):
state → Prop := initial_state_intro:
    forall b f m0,
    let ge := Genv.globalenv p in
    Genv.init_mem p = Some m0 →
    Genv.find_symbol ge p.(prog_main) = Some b →
    Genv.find_funct_ptr ge b = Some f →
    type_of_fundef f =
     Tfunction Tnil type_int32s cc_default →
    initial_state p (Callstate f nil Kstop m0).
```

```
Inductive final_state:
  state → int → Prop := final_state_intro:
    forall r m,
    final_state (Returnstate (Vint r) Kstop m) r.
```

Clight vs. ClightX initial and final states

- Whole-machine semantics
- Initial state:
  - Call "main"
  - No arguments
  - Empty memory (except initialized globals)
- Final state:
  - Return an integer
  - Memory is not relevant

- Per-module semantics for a function *i* with arguments *args* and memory *m*
- Initial state :
  - Call the function i
  - With arguments args
  - And the memory m
- Final state
  - Return a value
  - Memory is relevant

ClightX initial and final states

- Per-function semantics for a function *i* with arguments *args* and memory *m*
- Initial state :
  - Call the function i
  - With arguments args
  - And the memory m
- Final state
  - Return a value
  - Memory is relevant

```
Inductive initial_state `{MemoryOps} (p: program)
(i: ident) (m: mem) (sg: signature) (args: list val):

state → Prop := initial_state_intro:
    forall b f targs tres tcc,
    Genv.find_symbol ge i = Some b →
    Genv.find_funct_ptr ge b = Some f →
    type_of_fundef f =
     Tfunction targs tres tcc →
    sg = signature_of_type targs tres tcc →
    initial_state p i m sg args
      (Callstate f args Kstop m).
```

```
Inductive final_state (sg: signature):
  state → val * mem → Prop := final_state_intro:
    forall v m,
    final_state (Returnstate v Kstop m) (v, m).
```

Our Contributions

- We introduce deep specification and present a language-based formalization of certified abstraction layer
- We developed new languages & tools in Coq
  - A formal layer calculus for composing certified layers
  - ClightX for writing certified layers in a C-like language
  - AsmX for writing certified layers in assembly
  - CompCertX that compiles ClightX layers into AsmX layers
- We built multiple certified OS kernels in Coq
  - mCertiKOS-hyper consists of 37 layers, took less than one-person-year to develop, and can boot Linux as a guest

Assembly code

- Low-level stack management
  - Context switching
  - Process creation
- ~200 lines of CertiKOS (out of >5k)

```
kctxt_switch:
        leal    0(%eax,%eax,2), %eax
        leal    KCtxtPool_LOC(,%eax,8), %eax
        movl    %esp, 0(%eax)
        movl    %edi, 4(%eax)
        movl    %esi, 8(%eax)
        movl    %ebx, 12(%eax)
        movl    %ebp, 16(%eax)
        popl    %ecx
        movl    %ecx, 20(%eax)
        leal    0(%edx,%edx,2), %edx
        leal    KCtxtPool_LOC(,%edx,8), %edx
        movl    0(%edx), %esp
        movl    4(%edx), %edi
        movl    8(%edx), %esi
        movl    12(%edx), %ebx
        movl    16(%edx), %ebp
        movl    20(%edx), %ecx
        pushl   %ecx
        xorl    %eax, %eax
        ret
```

AsmX: Layer primitives

- Support for two kinds of primitives:
  - C-style primitives with arguments and calling convention
  - assembly primitives with full register set
    (a la CompCert built-ins)

CompCert x86 Asm external function calls

- External functions + calling convention

```
Inductive external_call'
      (ef: external_function) (ge: Genv.t)
      (vargs: list val) (m1: mem) (t: trace) (vres: list val) (m2: mem) : Prop :=
external_call'_intro: forall v,
    external_call ef ge (decode_longs (sig_args (ef_sig ef)) vargs) m1 t v m2 →
    vres = encode_long (sig_res (ef_sig ef)) v →
    external_call' ef ge vargs m1 t vres m2.
```

```
Inductive step (ge: genv): state -> trace -> state -> Prop :=
| …
|  exec_step_external:
      forall b ef args res rs m t rs' m',
      rs PC = Vptr b Int.zero →
      Genv.find_funct_ptr ge b = Some (External ef) →
      extcall_arguments rs m (ef_sig ef) args →
      external_call' ef ge args m t res m' →
      rs' = (set_regs (loc_external_result (ef_sig ef)) res (rs #PC ← (rs RA) #RA ← Vundef) →
      step ge (State rs m) t (State rs' m')
| …
```

AsmX external function calls

- C-style externals

```
Inductive step {eco: ExtCallOps}                          (ge: genv):
 state -> trace -> state -> Prop :=
| …
|  exec_step_external:
      forall b ef args res rs m t rs' m',
      rs PC = Vptr b Int.zero →
      Genv.find_funct_ptr ge b = Some (External ef) →
      extcall_arguments rs m (ef_sig ef) args →
      external_call' ef ge args m t res m' →
      rs' = (set_regs (loc_external_result (ef_sig ef)) res (rs #PC ← (rs RA) #RA ← Vundef) →
      step ge (State rs m) t (State rs' m')




| …
```

AsmX external function calls

- C-style externals + assembly-style primitives

```
Definition primcall_sem {mem: Type} {mem_ops: MemoryOps mem}: Type  :=
   Asm.genv → regset → mem → trace → regset → mem → Prop.

 Class PrimCallOps := {
   primitive_call (ef: external_function): primcall_sem
 }.

 Inductive step {eco: ExtCallOps} {pco: PrimCallOps}  (ge: genv):
  state -> trace -> state -> Prop :=
 | …
 |  exec_step_external:
      forall b ef args res rs m t rs' m',
      rs PC = Vptr b Int.zero →
      Genv.find_funct_ptr ge b = Some (External ef) →
      extcall_arguments rs m (ef_sig ef) args →
      external_call' ef ge args m t res m'  →
      rs' = (set_regs (loc_external_result (ef_sig ef)) res (rs #PC ← (rs RA) #RA ← Vundef) →
      step ge (State rs m) t (State rs' m')
 | exec_step_primitive:
      forall b ef rs m t rs' m',
          rs PC = Vptr b Int.zero →
          Genv.find_funct_ptr ge b = Some (External ef) →
          primitive_call ef ge rs m t rs' m' →
          step ge (State rs m) t (State rs' m')
 | …
```

AsmX external function calls

- C-style externals + assembly-style primitives

```
Definition primcall_sem {mem: Type} {mem_ops: MemoryOps mem}: Type  :=
   Asm.genv → regset → mem → trace → regset → mem → Prop.

 Class PrimCallOps := {
   primitive_call (ef: external_function): primcall_sem
 }.

 Inductive step {eco: ExtCallOps} {pco: PrimCallOps}  (ge: genv):
  state -> trace -> state -> Prop :=
 | …
 |  exec_step_external:
      forall b ef args res rs m t rs' m',
      rs PC = Vptr b Int.zero →
      Genv.find_funct_ptr ge b = Some (External ef) →
      extcall_arguments rs m (ef_sig ef) args →
      external_call' ef ge args m t res m' →
      rs' = (set_regs (loc_external_result (ef_sig ef)) res (rs #PC ← (rs RA) #RA ← Vundef) →
      step ge (State rs m) t (State rs' m')
 | exec_step_primitive:
      forall b ef rs m t rs' m',
          rs PC = Vptr b Int.zero →
          Genv.find_funct_ptr ge b = Some (External ef) →
          primitive_call ef ge rs m t rs' m' →
          step ge (State rs m) t (State rs' m')
 | …
```

Keep both rules
to avoid distinguishing between
C layers and assembly layers

CompCert Asm initial and final states

- CompCert x86 Asm Whole-Program Semantics
- Initial state :
  - Call main
  - Empty memory (except initialized globals)
  - Empty register set
- Final state :
  - Return an integer
  - Memory and register sets are not relevant

```
Inductive initial_state (p: program): state -> Prop :=
  | initial_state_intro: forall m0,
      Genv.init_mem p = Some m0 →
      let ge := Genv.globalenv p in
      let rs0 :=
        (Pregmap.init Vundef)
        # PC <- (symbol_offset ge p.(prog_main) Int.zero)
        # RA <- Vzero
        # ESP <- Vzero in
      initial_state p (State rs0 m0).

Inductive final_state: state -> int -> Prop :=
  | final_state_intro: forall rs m r,
      rs#PC = Vzero →
      rs#EAX = Vint r →
      final_state (State rs m) r.
```

Asm vs. AsmX initial and final states

- CompCert x86 Asm Whole-Program Semantics
- Initial state :
  - Call main
  - Empty memory (except initialized globals)
  - Empty register set
- Final state :
  - Return an integer
  - Memory and register sets are not relevant

- AsmX per-module semantics for function *i* with register set *rs* and memory *m*
  - Initial state
    - Call function *i*
    - With memory *m*
    - And register set *rs*
  - Final state
    - Return a list of 32-bit values
    - Memory and register sets are relevant
- Function semantics can use :
  - C-style pattern with arguments and calling convention for CompCertX
  - Assembly-style pattern with no return values for the layer language
  - Whole memory and register set are relevant in both cases

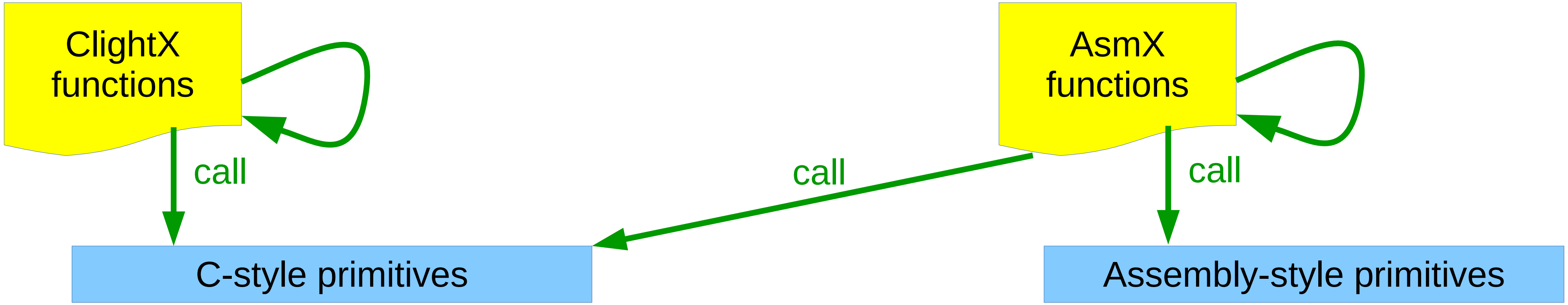
AsmX initial and final states (C-style pattern)

- AsmX per-module semantics for function *i* with arguments *args*, register set *rs* and memory *m*
  - Initial state
    - Call function *i*
    - With arguments *args*
    - With memory *m*
    - And register set *rs*
  - Final state
    - Return a list of 32-bit values
    - Memory and register sets are relevant
  - Embed the C calling convention

```
Inductive initial_state (rs: regset) (p: Asm.program)
(i: ident) (sg: signature) (args: list val) (m: mem):
state -> Prop :=
| initial_state'_intro:  forall
    b
    (Hb: Genv.find_symbol (Genv.globalenv p) i = Some b)
    (Hpc: rs PC = Vptr b Int.zero)
    (Hargs: extcall_arguments rs m sg args),
  initial_state rs p i sg args m (State lm m).

Inductive final_state (rs0: regset) (sg: signature) : state ->
(list val * mem) -> Prop :=
  | final_state_intro:
      forall rs,
        (rs0 # RA) = (rs # PC) →
        (rs0 # ESP) = (rs # ESP) →
        forall v,
          v = List.map rs (loc_external_result sg) →
          forall
            (CALLEE_SAVE:
              forall r,
              ~ In r destroyed_at_call →
              Val.lessdef (rs0 (preg_of r)) (rs (preg_of r))),
          forall m_,
            final_state rs0 sg (State rs m_) (v, m_).
```

Functions and primitives



ClightX functions

AsmX functions

call

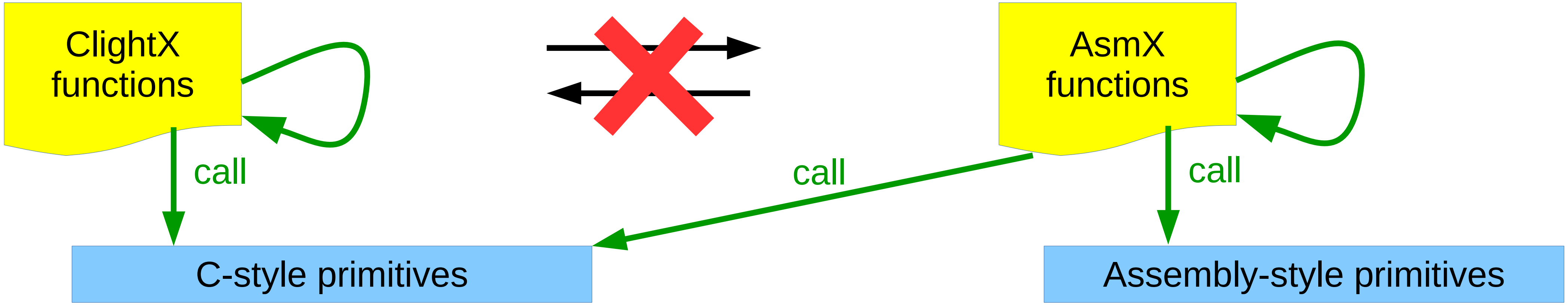
call

call

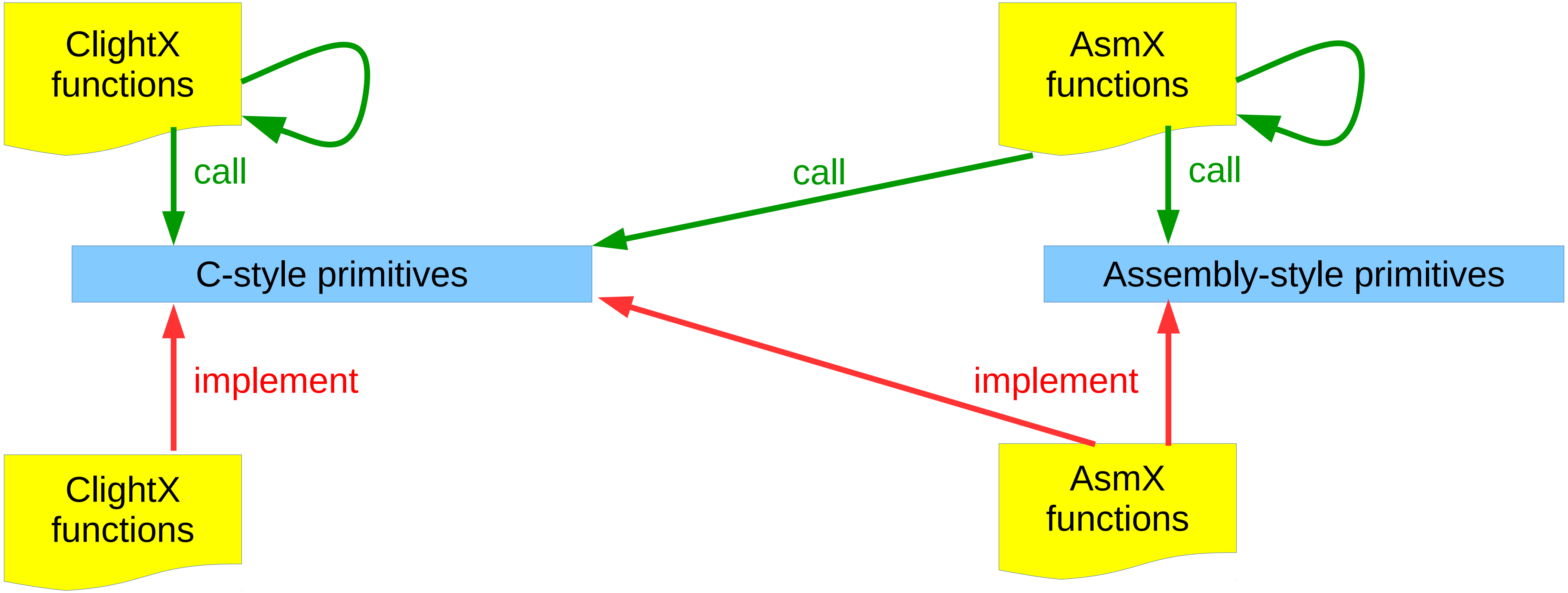
C-style primitives

Assembly-style primitives

Functions and primitives



Functions and primitives



ClightX functions

call

C-style primitives

implement

ClightX functions

AsmX functions

call

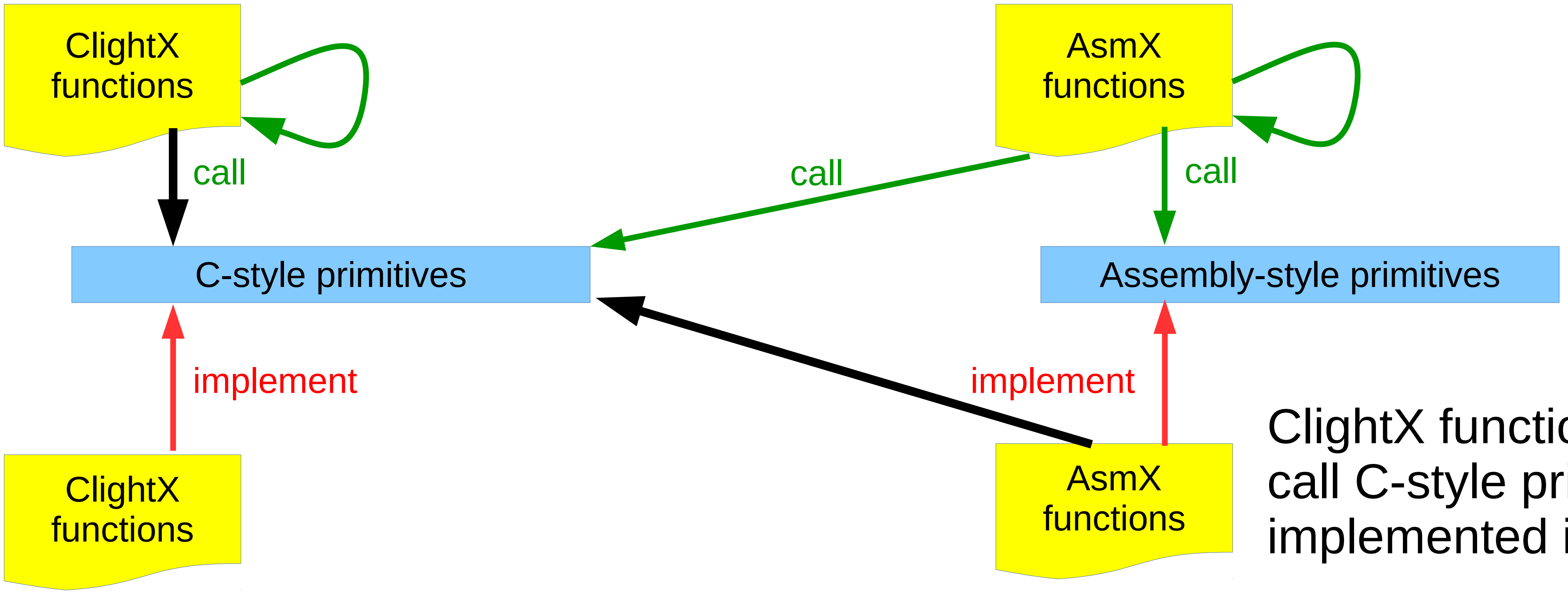
call

Assembly-style primitives

implement

AsmX functions

Functions and primitives



ClightX functions

call

AsmX functions

call

call

C-style primitives

Assembly-style primitives

implement

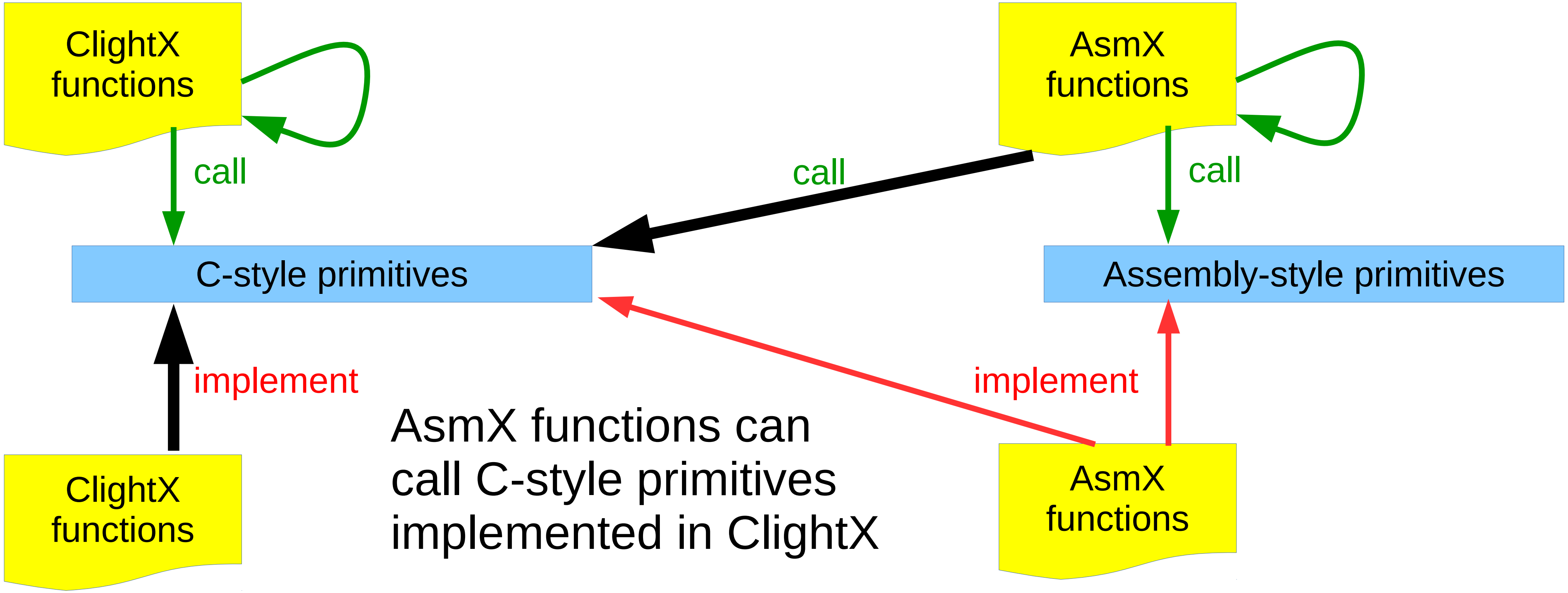
implement

ClightX functions

AsmX functions

ClightX functions can
call C-style primitives
implemented in AsmX

Functions and primitives



AsmX functions can
call C-style primitives
implemented in ClightX

POPL 2015 Mumbai, India January 12-18

Our Contributions

- We introduce deep specification and present a language-based formalization of certified abstraction layer
- We developed new languages & tools in Coq
  - A formal layer calculus for composing/linking certified layers
  - ClightX for writing certified layers in a C-like language
  - AsmX for writing certified layers in assembly
  - CompCertX that compiles ClightX layers into AsmX layers
- We built multiple certified OS kernels in Coq
  - mCertiKOS-hyper consists of 37 layers, took less than one-person-year to develop, and can boot Linux as a guest

Programming & Compiling Layers

ClightX

$$L \vdash_R M_c : L_1 \rightarrow L_1 \leq_R [\![M_c]\!]_{\text{ClightX}} (L)$$

Programming & Compiling Layers

ClightX

$$L \vdash_{R} M_c : L_1$$

$$L_1 \leq_{R} [\![\; M_c \;]\!]_{\text{ClightX}} (L)$$

CompCertX correctness theorem (where *minj* is a memory injection)

$$[\![\; M_c \;]\!]_{\text{ClightX}} (L) \leq_{minj} [\![\; \text{CompCertX}[L](M_c) \;]\!]_{\text{AsmX}} (L)$$

Programming & Compiling Layers

ClightX $L \vdash_{R} M_c : L_1$ → $L_1 \le_{R} [\![M_c]\!]_{\text{ClightX}}(L)$

↓

CompCertX correctness theorem (where *minj* is a memory injection)

$$[\![M_c]\!]_{\text{ClightX}}(L) \le_{minj} [\![\text{CompCertX[L]}(M_c)]\!]_{\text{AsmX}}(L)$$

↓

$$L_1 \le_{R \circ minj} [\![\text{CompCertX[L]}(M_c)]\!]_{\text{AsmX}}(L)$$

Programming & Compiling Layers

ClightX $L \vdash_R M_c : L_1$ → $L_1 \le_R \llbracket M_c \rrbracket_{\text{ClightX}}(L)$

↓

CompCertX correctness theorem (**where** ***minj*** **is a memory injection**)

$$\llbracket M_c \rrbracket_{\text{ClightX}}(L) \le_{minj} \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

↓

$$L_1 \le_{R \circ minj} \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

↓

R must absorb such memory injection: $R \circ minj = R$ *then we have:*

$$L_1 \le_R \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

Programming & Compiling Layers

ClightX $L \vdash_{R} M_c : L_1$ → $L_1 \leq_{R} \llbracket M_c \rrbracket_{\text{ClightX}}(L)$

CompCertX correctness theorem (where *minj* is a memory injection)

$$\llbracket M_c \rrbracket_{\text{ClightX}}(L) \leq_{minj} \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

$$L_1 \leq_{R \circ minj} \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

R must absorb such memory injection: $R \circ minj = R$ *then we have:*

$$L_1 \leq_{R} \llbracket \text{CompCertX[L]}(M_c) \rrbracket_{\text{AsmX}}(L)$$

Let $M_a = \text{CompCertX[L]}(M_c)$ then $L \vdash_{R} M_a : L_1$ **AsmX**

Programming & Compiling Layers

ClightX $L \vdash_R M_c : L_1$ → $L_1 \leq_R [\![\; M_c \;]\!]_{\text{ClightX}}(L)$

↓

CompCertX correctness theorem (where *minj* is a memory injection)

$$[\![\; M_c \;]\!]_{\text{ClightX}}(L) \leq_{minj} [\![\; \text{CompCertX[L]}(M_c) \;]\!]_{\text{AsmX}}(L)$$

↓

$$L_1 \leq_{R \circ minj} [\![\; \text{CompCertX[L]}(M_c) \;]\!]_{\text{AsmX}}(L)$$

↓

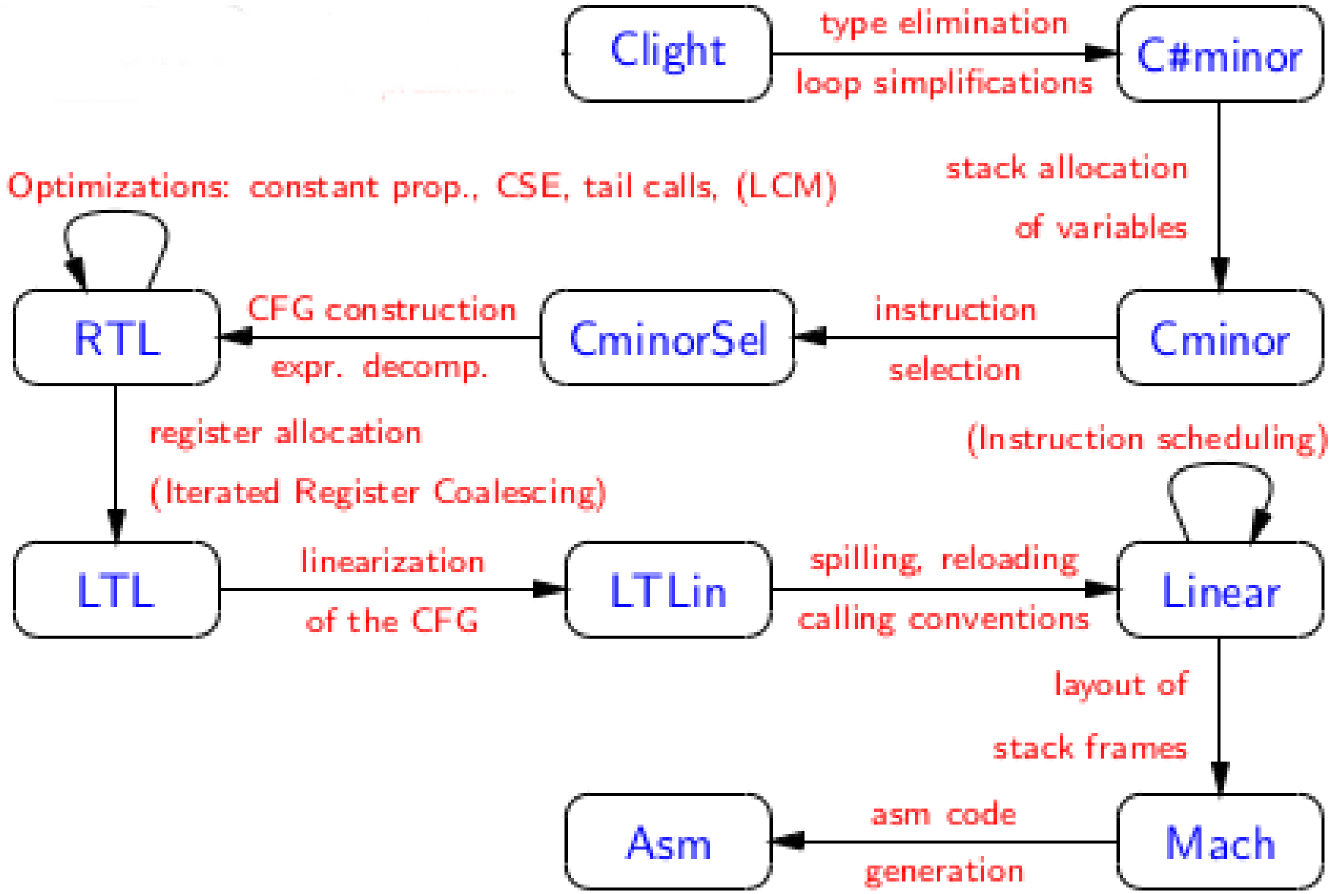
R must absorb such memory injection: $R \circ minj = R$ *then we have:*

$$L_1 \leq_R [\![\; \text{CompCertX[L]}(M_c) \;]\!]_{\text{AsmX}}(L)$$

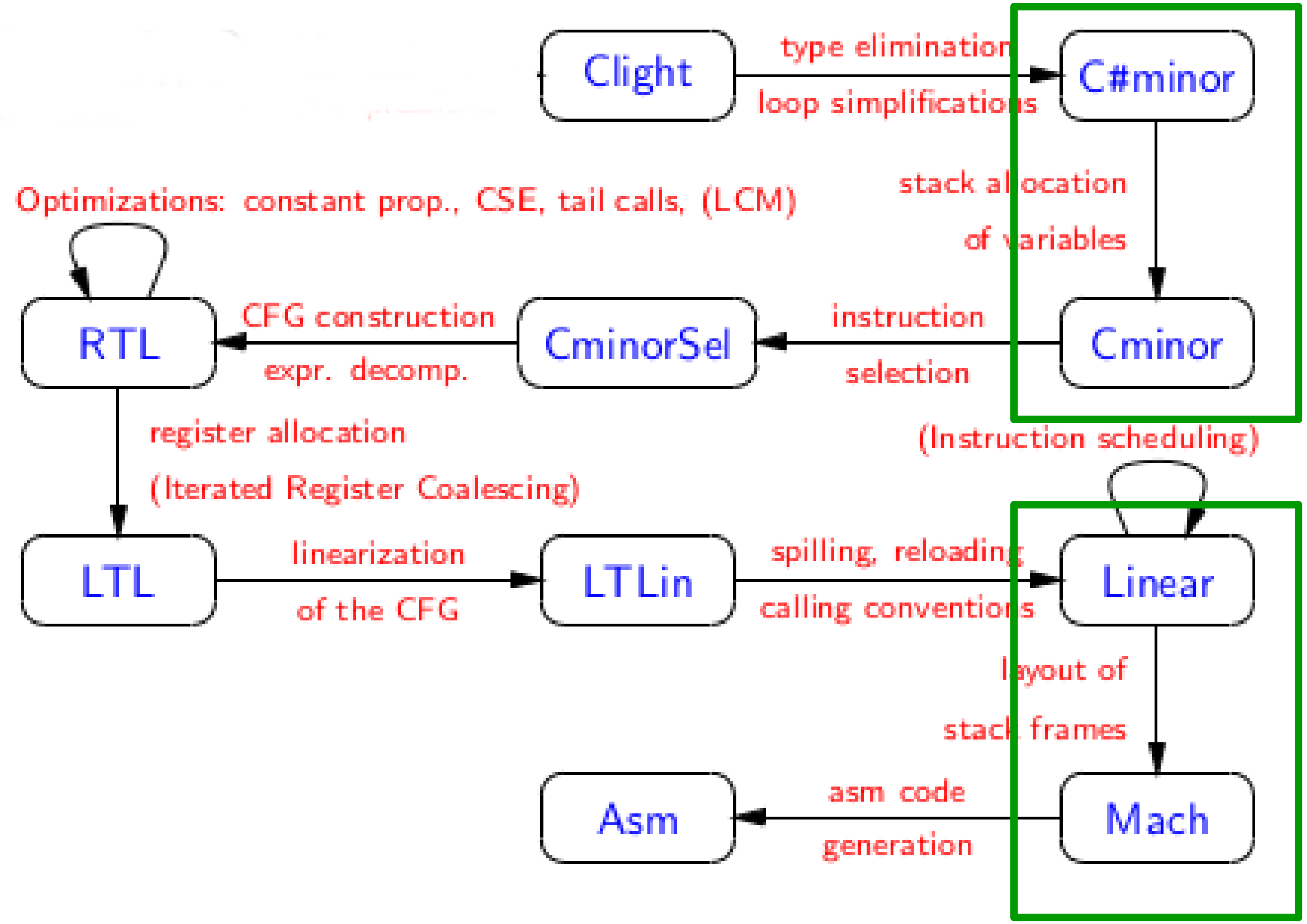
↓

Let $M_a = \text{CompCertX[L]}(M_c)$ then $L \vdash_R M_a : L_1$ **AsmX**

Reminder: CompCert compilation passes



Reminder: CompCert compilation passes



Memory injections

Assembly layer refinement proof

$$\boxed{L_1 \vdash_R M : L_2}$$

$$\begin{tikzcd}
\text{Assembly} & s2 \arrow[rr, "L_2(f)"] \arrow[d, dash, "R"'] & & s2' \arrow[d, dash, dotted, "R"] & \text{Assembly} \\
\text{Assembly} & s1 \arrow[rr, dotted, "\text{AsmX}", "⟦ M ⟧(L_1)(f)"'] & & s1' & \text{Assembly}
\end{tikzcd}$$

Layer refinement proof

$\boxed{L_1 \vdash_R M : L_2}$

$$\begin{tikzcd}
\text{Assembly} & s2 \arrow[r, "L_2(\mathbf{f})"] \arrow[d, dash, "R"'] & s2' \arrow[d, dash, dotted, "R"] & \text{Assembly} \\
\text{Assembly} & s1 \arrow[r, dotted, "{[\![M_c]\!] (L_1)(\mathbf{f})}"'] & s1'C &
\end{tikzcd}$$

ClightX ?

~~AsmX~~

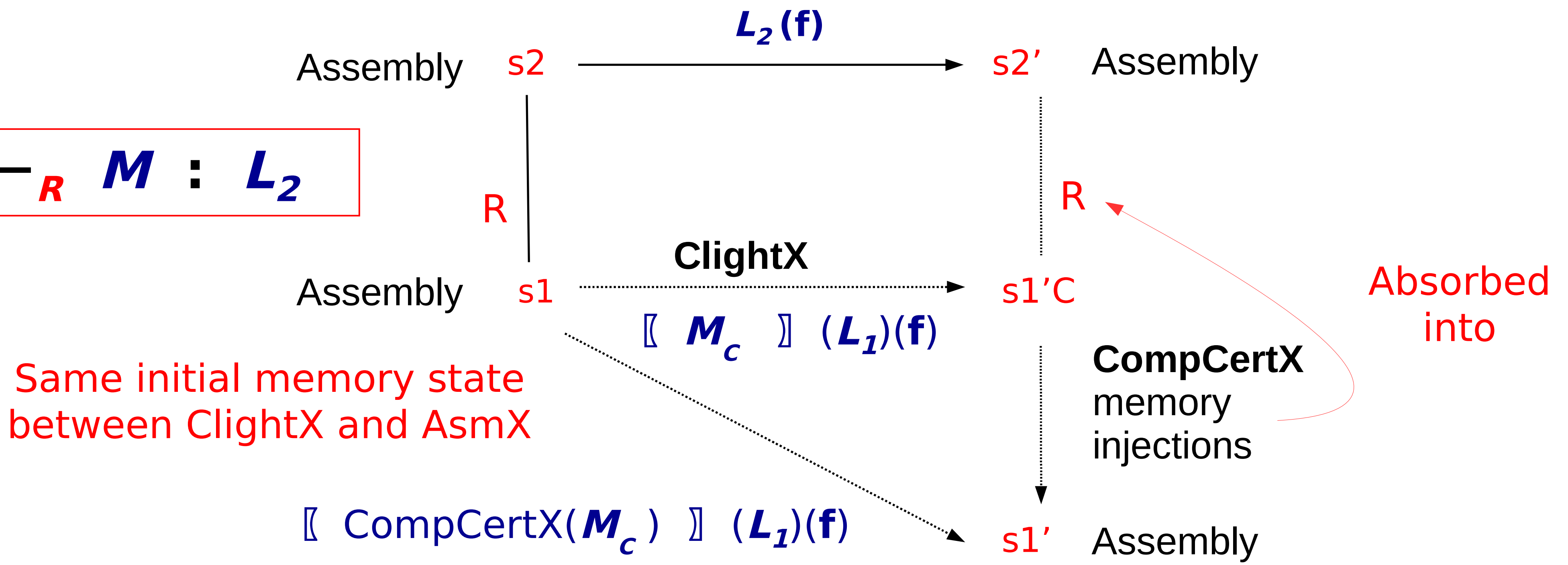
Layer refinement proof with CompCertX

$$\boxed{L_1 \vdash_R M : L_2}$$

$$\begin{tikzcd}
\text{Assembly} & s2 \arrow[rr, "L_2(\mathbf{f})"] \arrow[d, dash, "R"'] & & s2' \arrow[d, dotted, dash, "R"] & \text{Assembly} \\
? & s1' \arrow[rr, dotted, "\textbf{ClightX}", "\llbracket M_c \rrbracket (L_1)(\mathbf{f})"'] \arrow[d, dotted, "?"'] & & s1'C \arrow[d, dotted, "\textbf{CompCertX}\ \text{memory injections}"] & \\
\text{Assembly} & s1'? \arrow[rr, dotted, "\text{AsmX}", "\llbracket \text{CompCertX}(M_c) \rrbracket (L_1)(\mathbf{f})"'] & & s1' & \text{Assembly}
\end{tikzcd}$$

Layer refinement proof with CompCertX

$$\boxed{L_1 \vdash_R M : L_2}$$



$L_2(\mathbf{f})$

Assembly s2 → s2' Assembly

R

R

Assembly s1 → s1'C

ClightX

$⟦ M_c ⟧ (L_1)(\mathbf{f})$

CompCertX memory injections

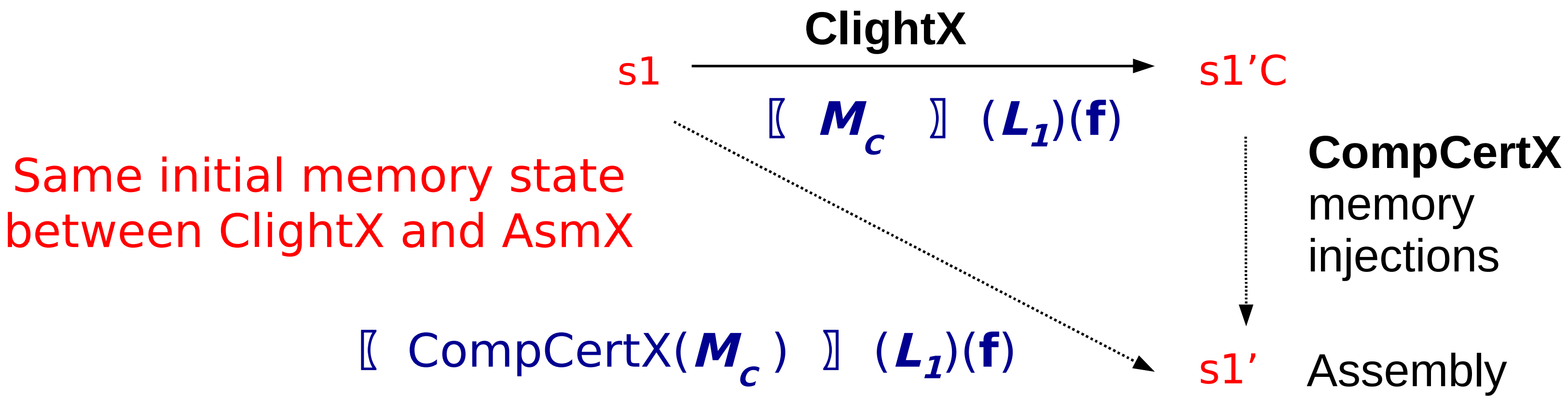
Absorbed into

Same initial memory state between ClightX and AsmX

$⟦ \text{CompCertX}(M_c) ⟧ (L_1)(\mathbf{f})$

s1' Assembly

CompCertX correctness statement



s1

ClightX

s1'C

$⟦ \boldsymbol{M_c} ⟧ (\boldsymbol{L_1})(\mathbf{f})$

Same initial memory state
between ClightX and AsmX

CompCertX
memory
injections

$⟦ \text{CompCertX}(\boldsymbol{M_c}) ⟧ (\boldsymbol{L_1})(\mathbf{f})$

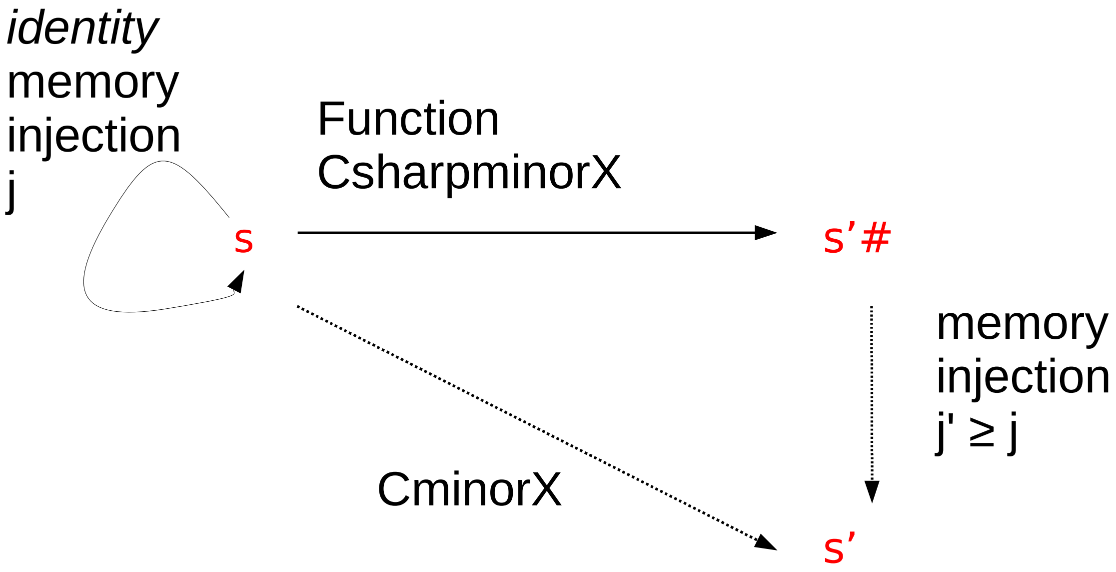
s1'

Assembly

Example: CsharpminorX to CminorX correctness proof

$$\begin{tikzcd}
s\# \arrow[r, "\text{One single step CsharpminorX}"] \arrow[d, "\text{memory injection } j"'] & s'\# \arrow[d, dotted, "\text{memory injection } j' \geq j"] \\
s \arrow[r, dotted, "\text{CminorX}"] & s'
\end{tikzcd}$$

Example: CsharpminorX to CminorX correctness proof



identity memory injection j

Function CsharpminorX

s

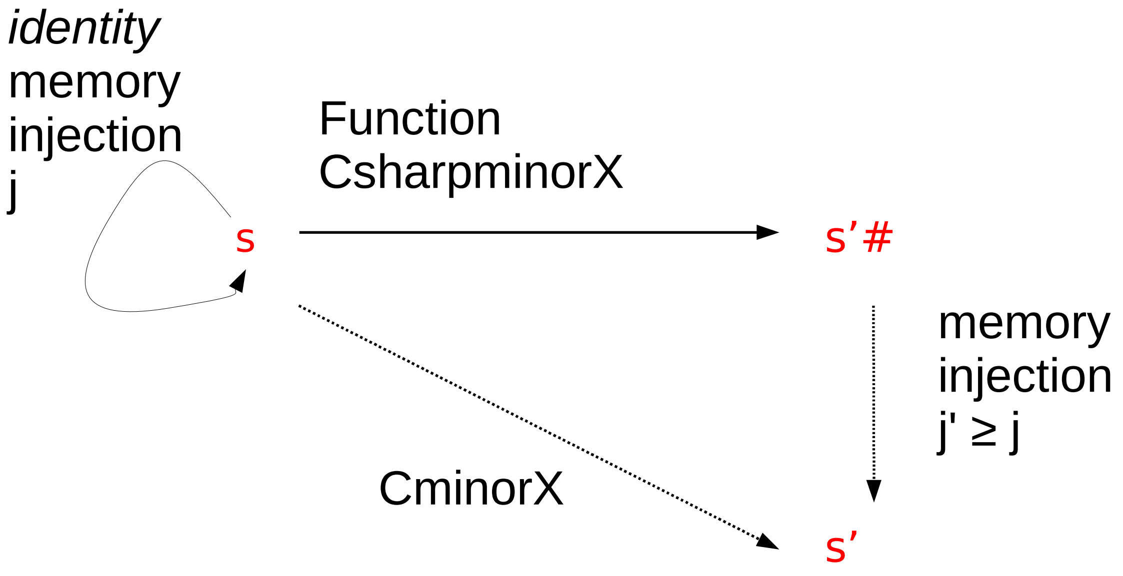
s'#

memory injection j' ≥ j

CminorX

s'

Example: CsharpminorX to CminorX correctness proof



identity
memory
injection
j

s

Function
CsharpminorX

s′#

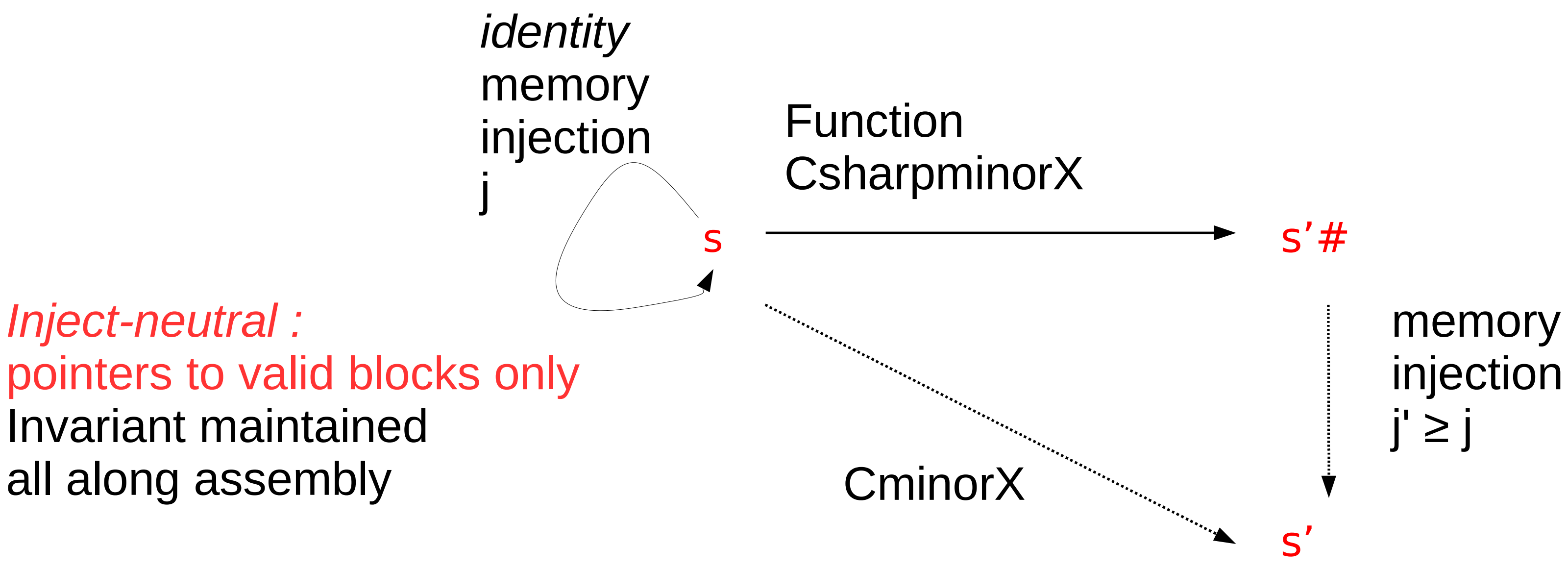
memory
injection
j' ≥ j

CminorX

s′

Wrap final state
into ∃ j' ≥ j

Example: CsharpminorX to CminorX correctness proof



identity
memory
injection
j

s

Function
CsharpminorX

s’#

Inject-neutral :
pointers to valid blocks only
Invariant maintained
all along assembly

memory
injection
j' ≥ j

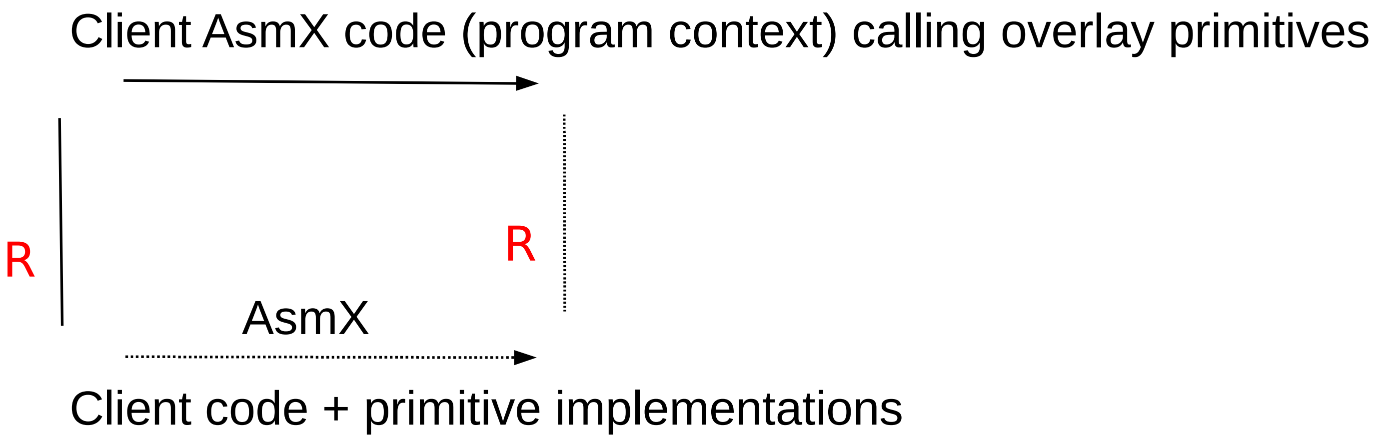
CminorX

s’

Requirements

- C-style layer primitives must abide by CompCert external function requirements :
  - Stability by memory injection, extension, etc.
  - Must preserve *inject-neutral* (no pointers to invalid blocks created)
- Also needed for assembly-style primitives
  - Layer refinement relation also includes a memory injection
  - Accumulates all memory injections due to calls to code compiled by CompCertX

Layer refinement and memory injections

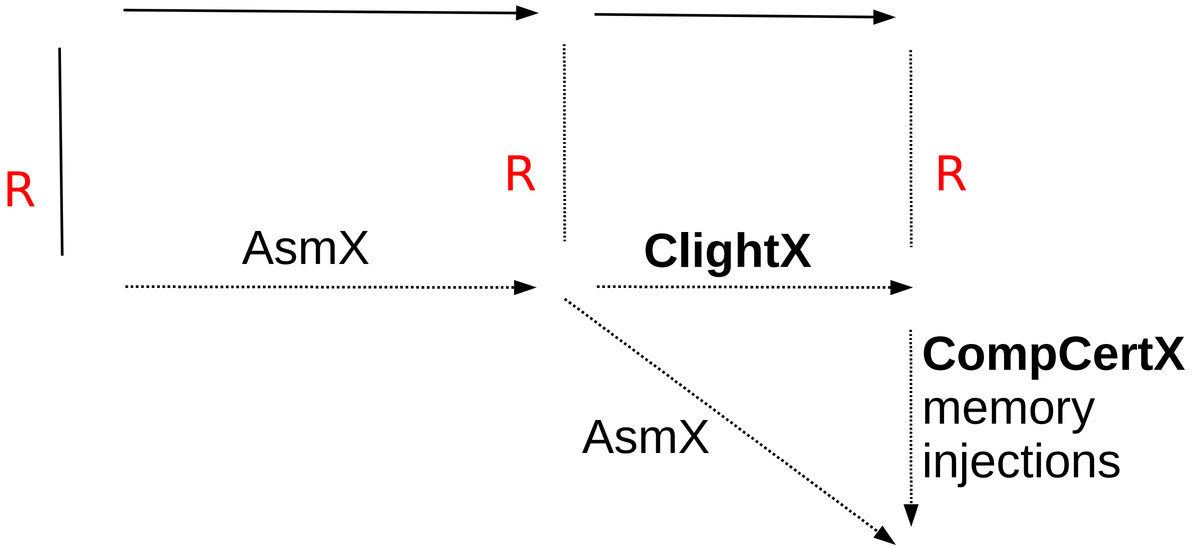


Client AsmX code (program context) calling overlay primitives

Client code + primitive implementations

Layer refinement and memory injections

Client AsmX code (program context) calling overlay primitives



R

R

R

AsmX

ClightX

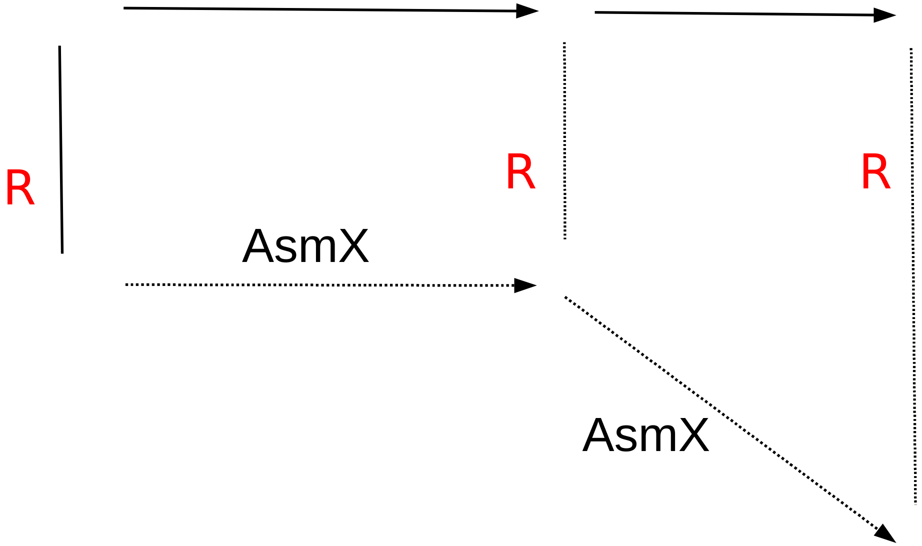
CompCertX
memory
injections

AsmX

Client code + primitive implementations

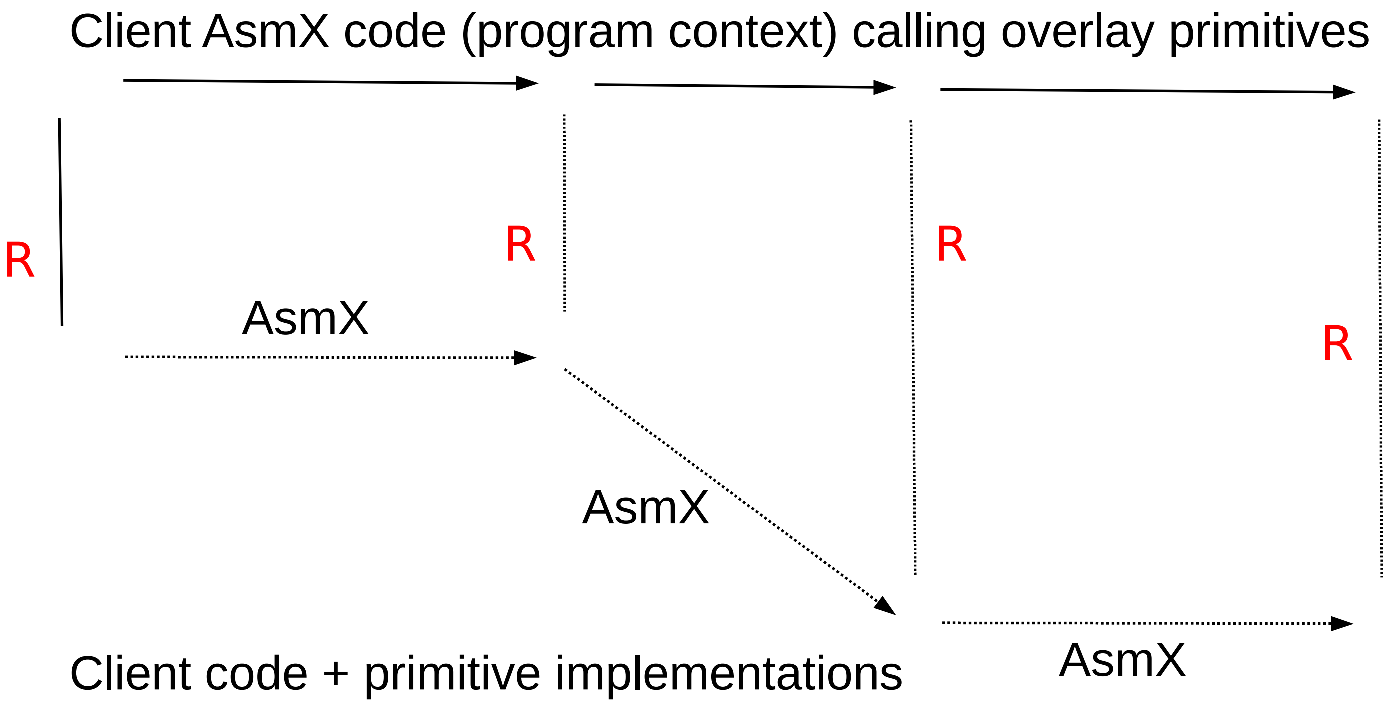
Layer refinement and memory injections

Client AsmX code (program context) calling overlay primitives



Client code + primitive implementations

Layer refinement and memory injections



Client AsmX code (program context) calling overlay primitives

R

R

R

AsmX

R

AsmX

Client code + primitive implementations

AsmX

Layer refinement and memory injections

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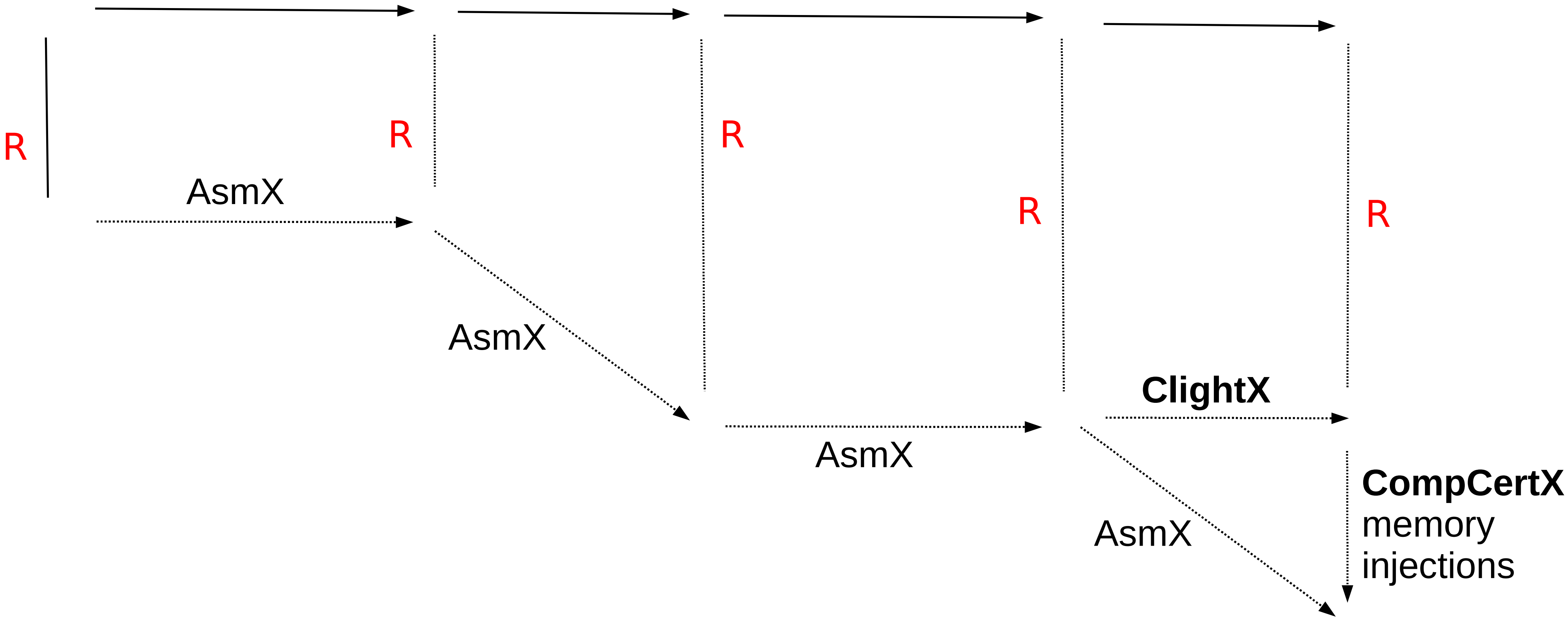
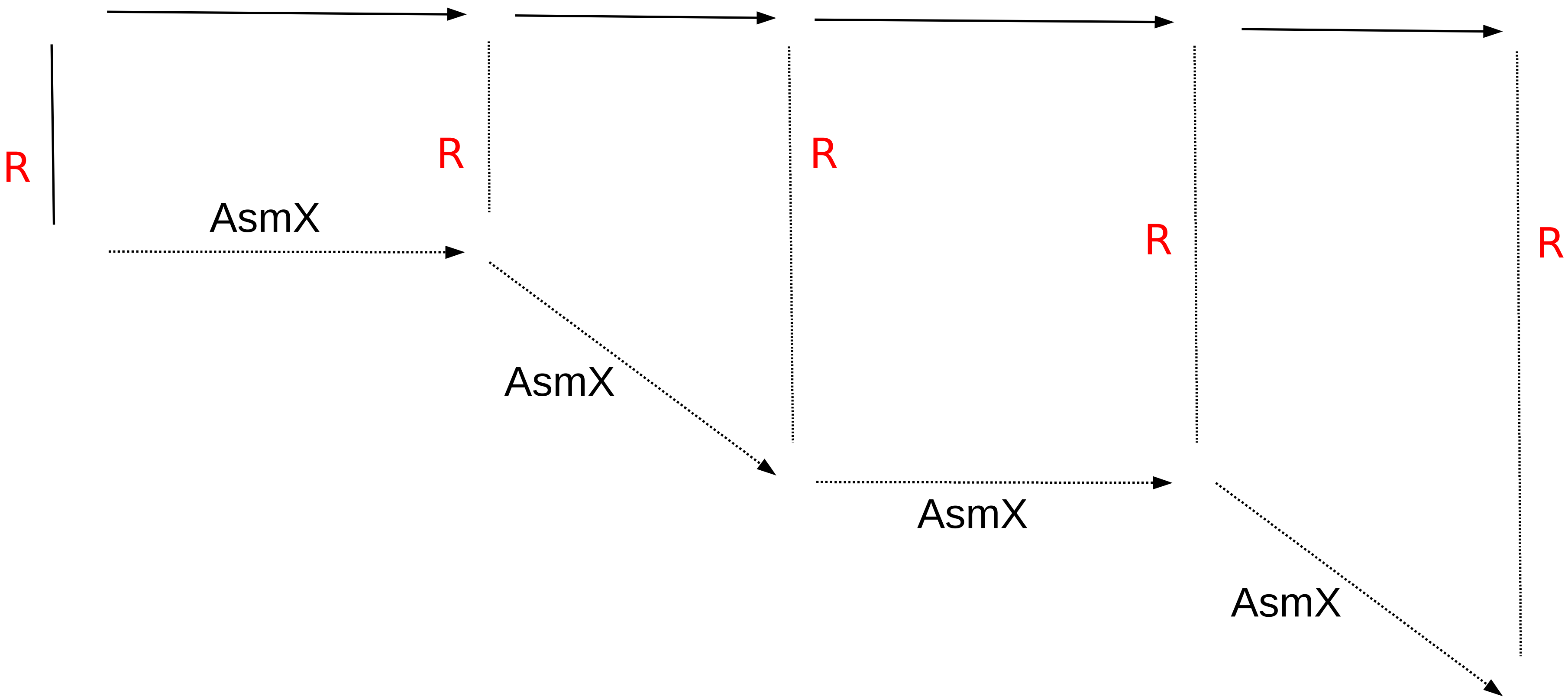


Client code + primitive implementations

Layer refinement and memory injections

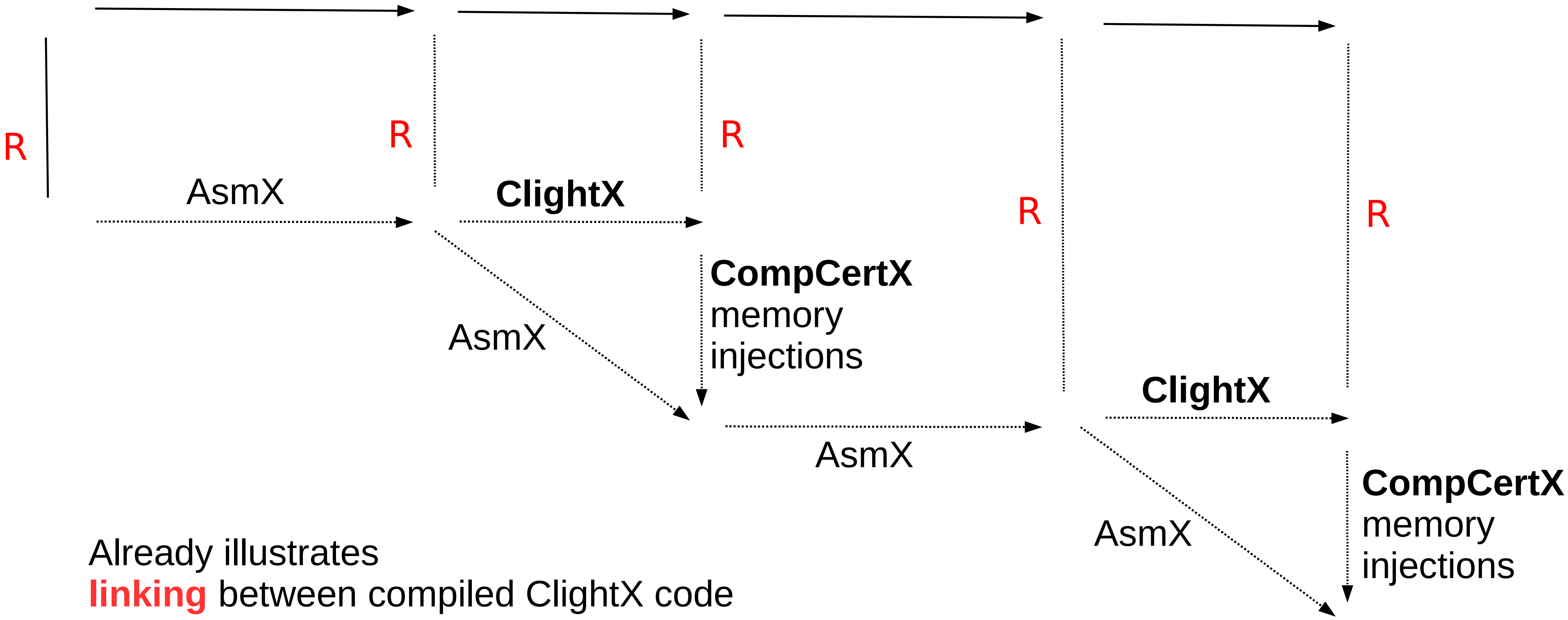
Client AsmX code (program context) calling overlay primitives



Client code + primitive implementations

Layer refinement and memory injections

Client AsmX code (program context) calling overlay primitives



R

R

AsmX

R

ClightX

CompCertX
memory
injections

AsmX

AsmX

R

R

ClightX

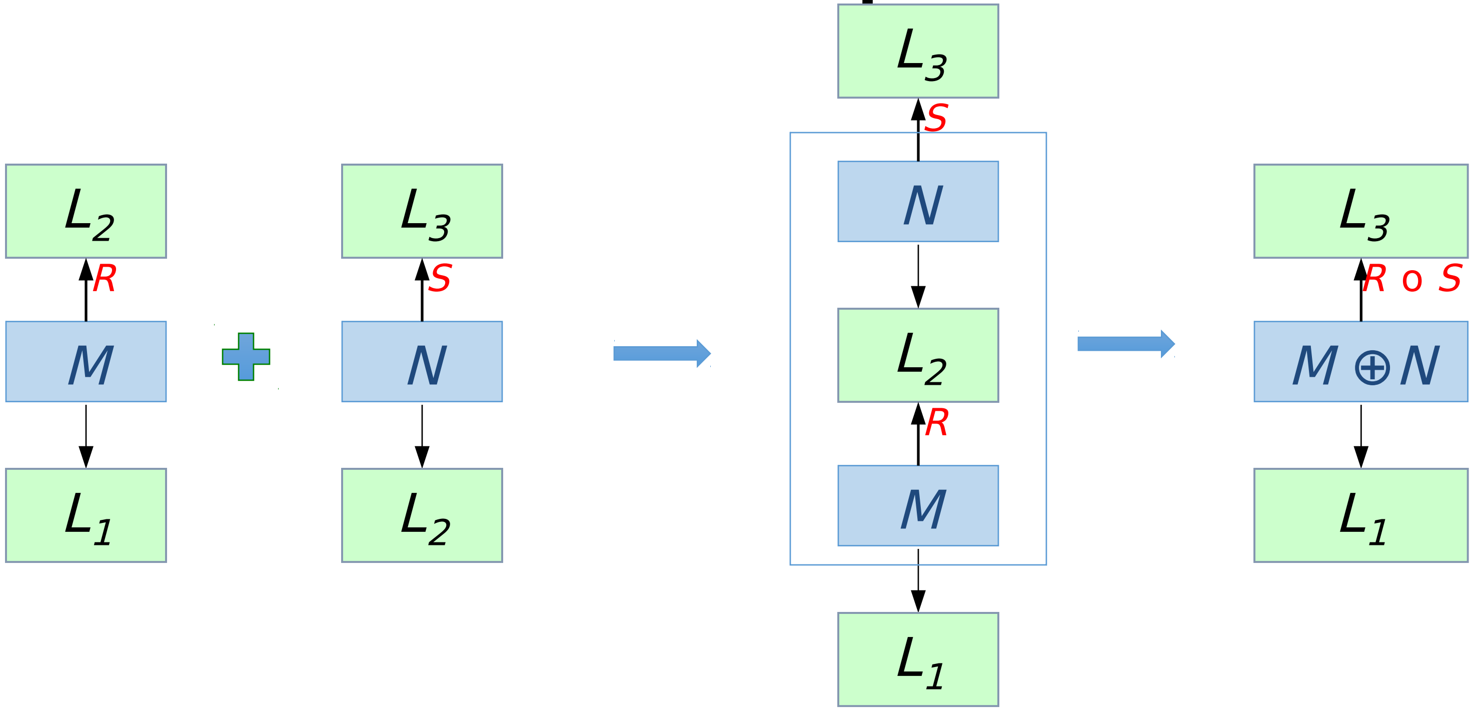
CompCertX
memory
injections

AsmX

Already illustrates
linking between compiled ClightX code
and AsmX program context

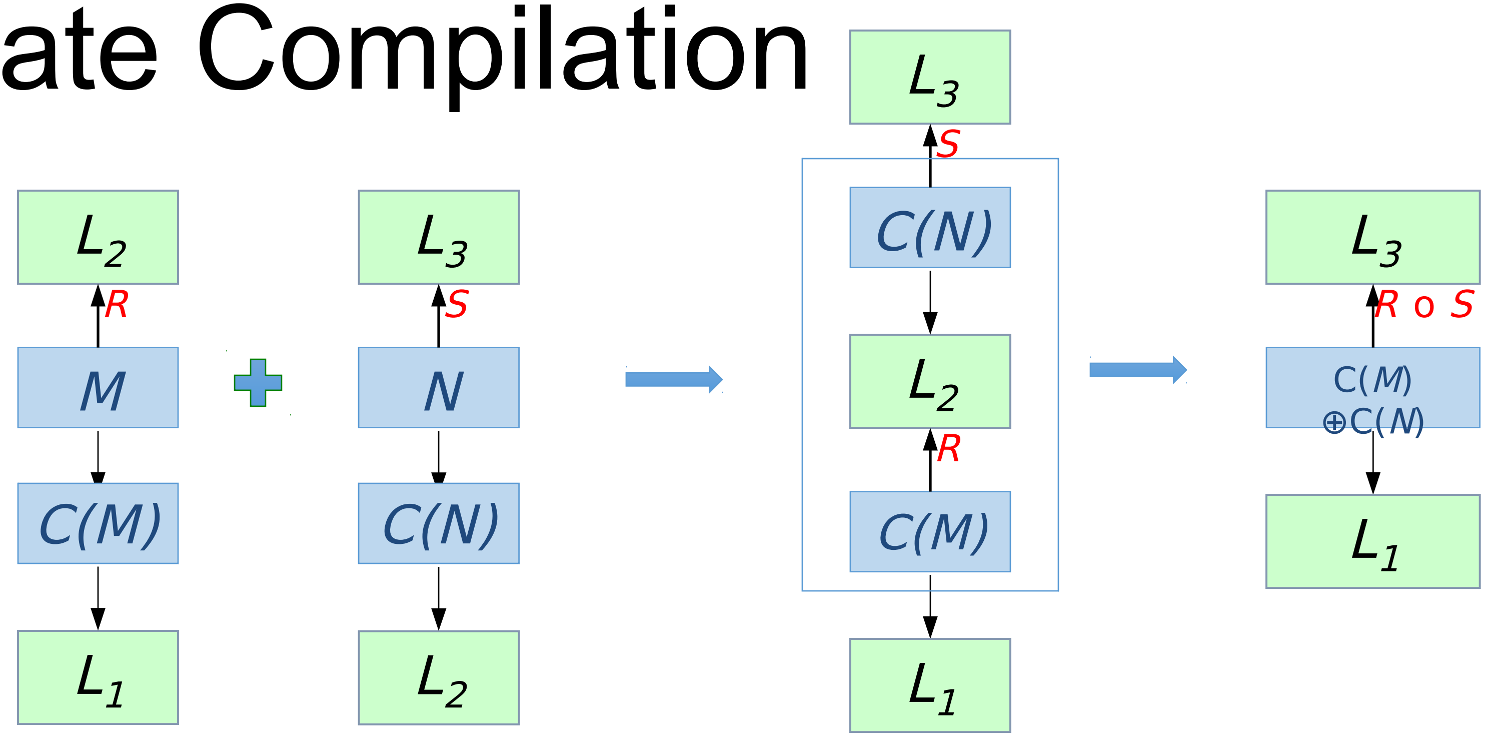
Client code + primitive implementations

LayerLib: Vertical Composition



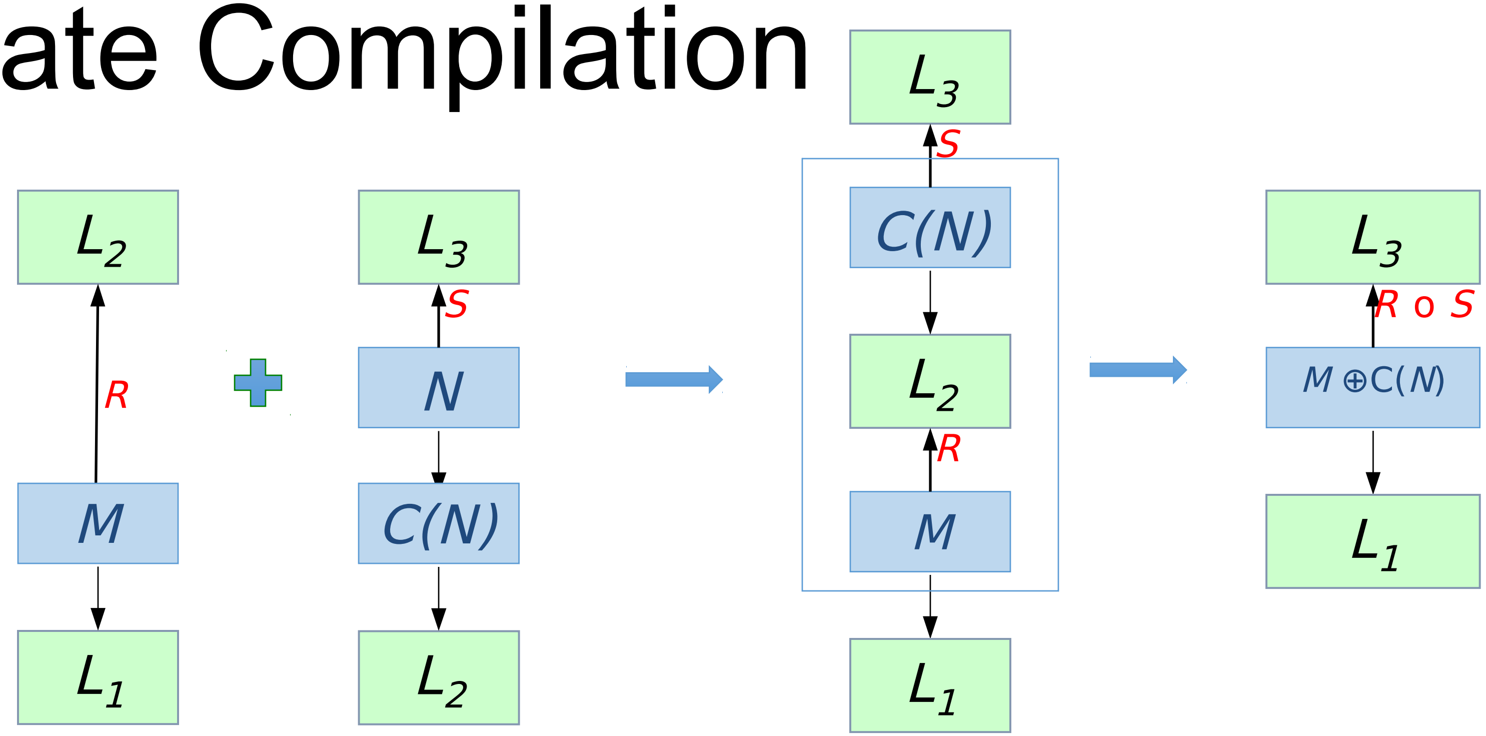
$$\frac{L_1 \vdash_R M : L_2 \qquad\qquad L_2 \vdash_S N : L_3}{L_1 \vdash_{R \circ S} M \oplus N : L_3}\ \textsc{Vcomp}$$

LayerLib: Vertical Composition and Separate Compilation



LayerLib: Vertical Composition and Separate Compilation

ClightX code N
« calls »
AsmX code M
through L2
primitives



LayerLib: Vertical Composition and Separate Compilation

AsmX code N
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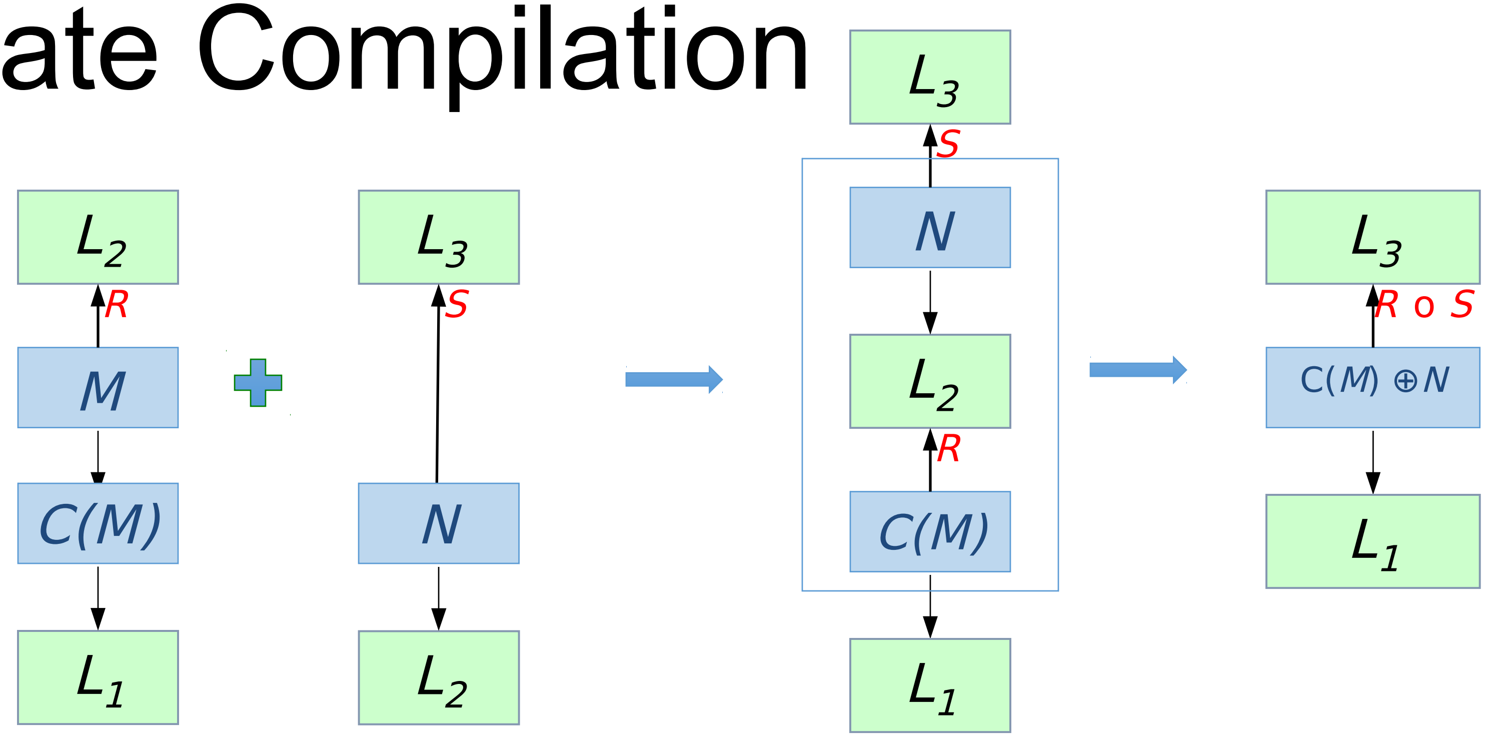
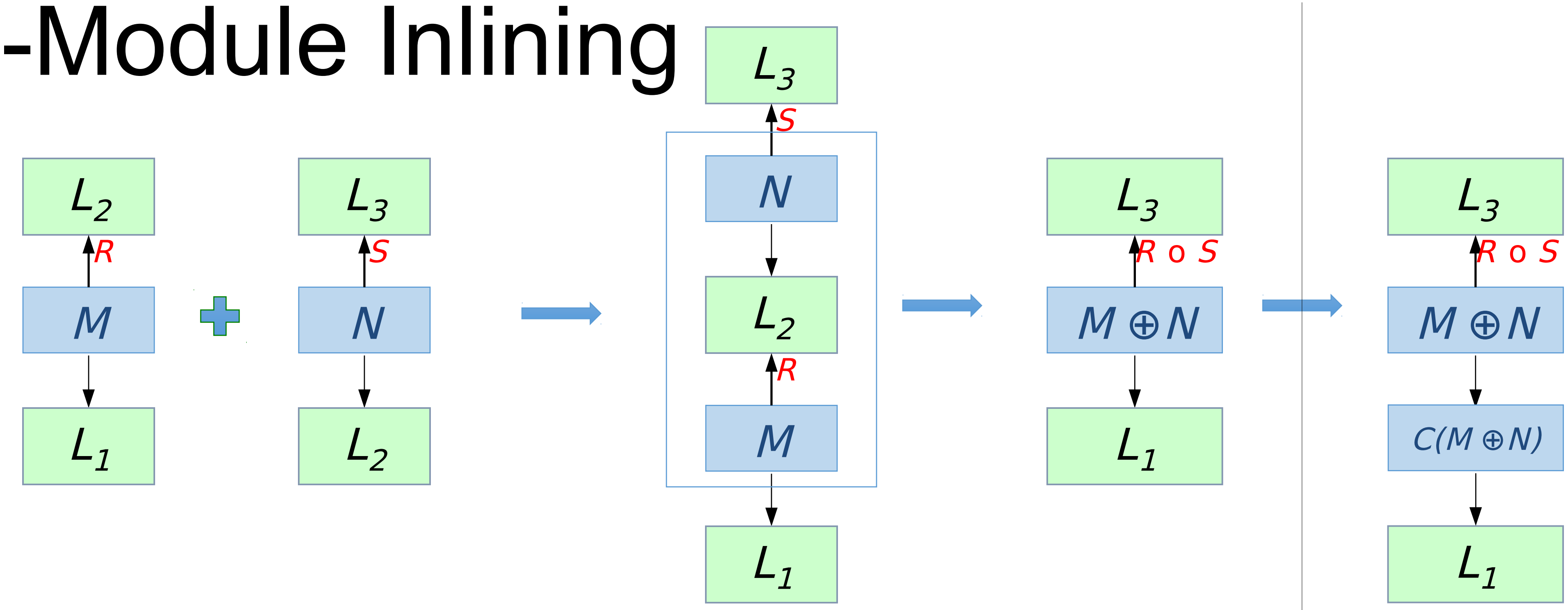


LayerLib: Vertical Composition and Cross-Module Inlining

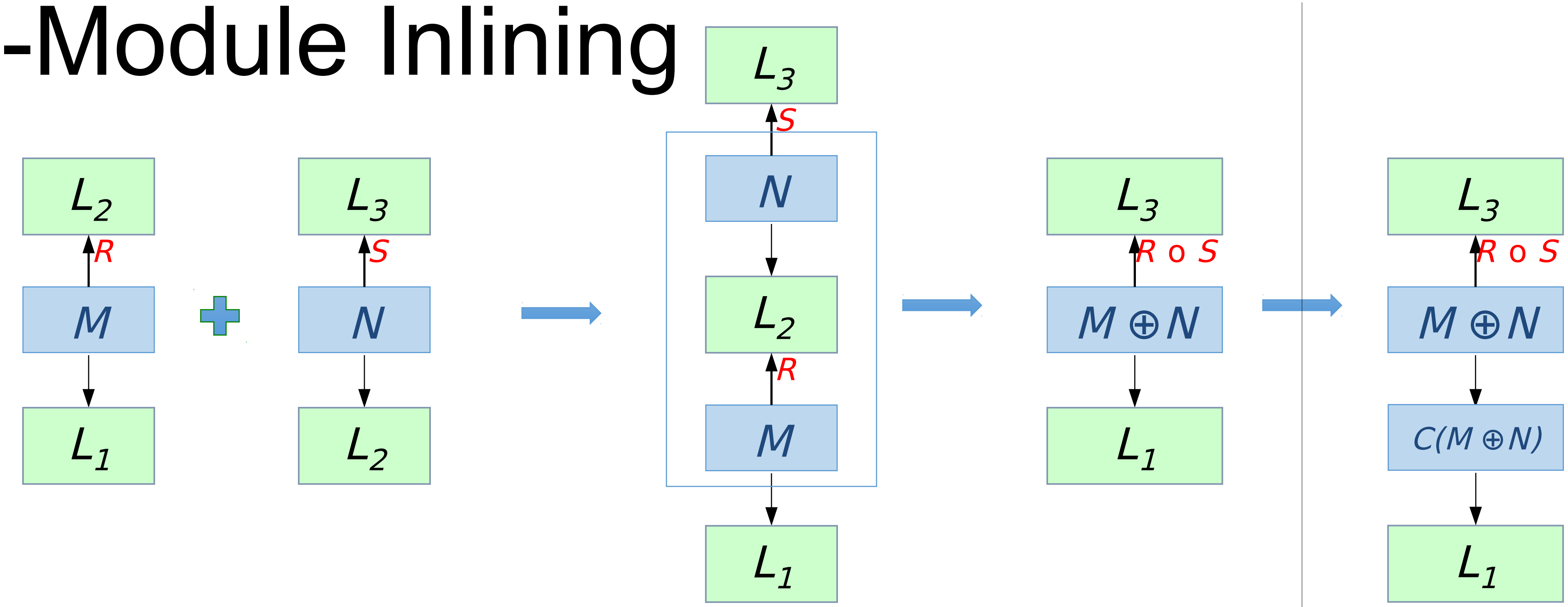


This is work in progress.

C layer refinement

Assembly layer refinement

LayerLib: Vertical Composition and Cross-Module Inlining



Useful if :
- N concretizes high-level data into **low-level data**
- M concretizes low-level data into memory

C layer refinement

Assembly layer refinement

Example : Page maps

MPTOP

idpde_init : Initialize the kernel page map to identity page map

idpde_init.c

Abstract state

MPTIntro

set_IDPTE : Access (get/set) the page map

---

set_IDPTE.c

MALT

Concrete in-memory representation

Example: Page Tables

MPTOP

idpde_init.c

MPTIntro

set_IDPTE

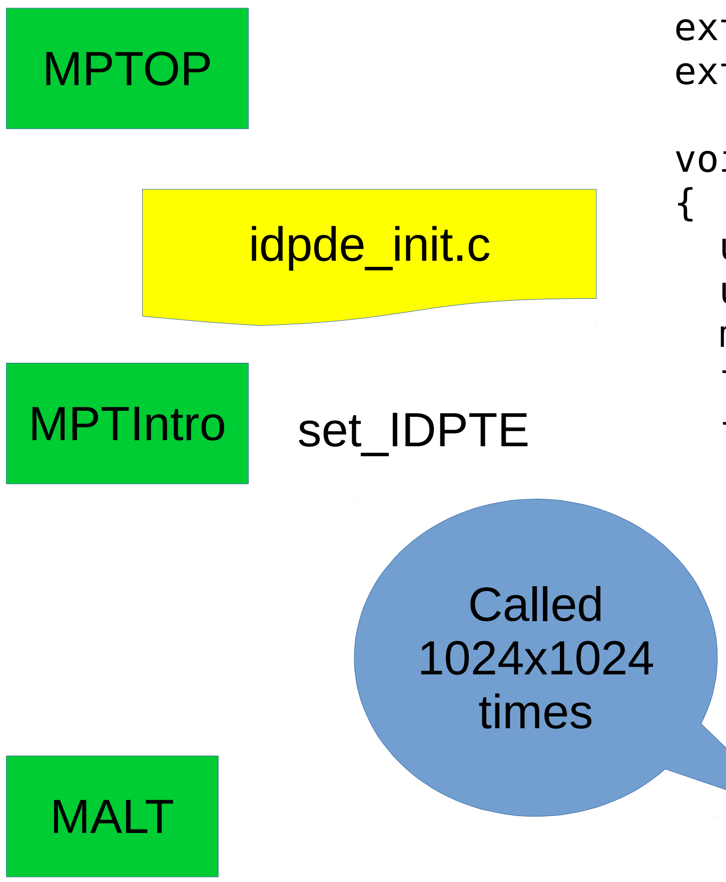
MALT

```
#define PT_PERM_PTKF 3
#define PT_PERM_PTKT 259

extern void mem_init(unsigned int);
extern void set_IDPTE(unsigned int, unsigned int, unsigned int);

void idpde_init(unsigned int mbi_adr)
{
  unsigned int i, j;
  unsigned int perm;
  mem_init(mbi_adr);
  for(i = 0; i < 1024; i ++)
  {
    if (i < 256)
      perm = PT_PERM_PTKT;
    else if (i >= 960)
      perm = PT_PERM_PTKT;
    else
      perm = PT_PERM_PTKF;
    for(j = 0; j < 1024; j ++)
    {
      set_IDPTE(i, j, perm);
    }
  }
}
```

Example: Page Tables


MPTOP

idpde_init.c

MPTIntro

set_IDPTE

Called 1024x1024 times

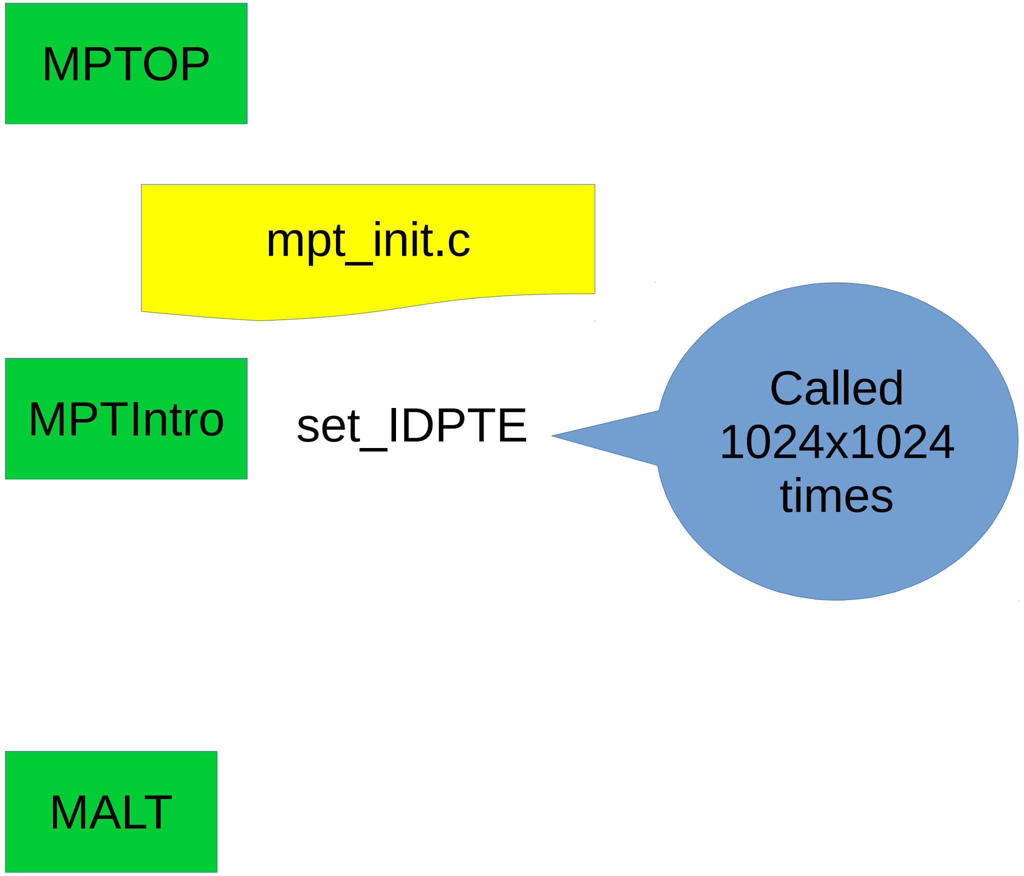
MALT

```
#define PT_PERM_PTKF 3
#define PT_PERM_PTKT 259

extern void mem_init(unsigned int);
extern void set_IDPTE(unsigned int, unsigned int, unsigned int);

void idpde_init(unsigned int mbi_adr)
{
  unsigned int i, j;
  unsigned int perm;
  mem_init(mbi_adr);
  for(i = 0; i < 1024; i ++)
  {
    if (i < 256)
      perm = PT_PERM_PTKT;
    else if (i >= 960)
      perm = PT_PERM_PTKT;
    else
      perm = PT_PERM_PTKF;
    for(j = 0; j < 1024; j ++)
    {
      set_IDPTE(i, j, perm);
    }
  }
}
```

Example: Page Tables



MPTOP

mpt_init.c

MPTIntro

set_IDPTE

Called 1024x1024 times

MALT

Example: Page Tables

MPTOP

MPTIntro

set_IDPTE

Called 1024x1024 times

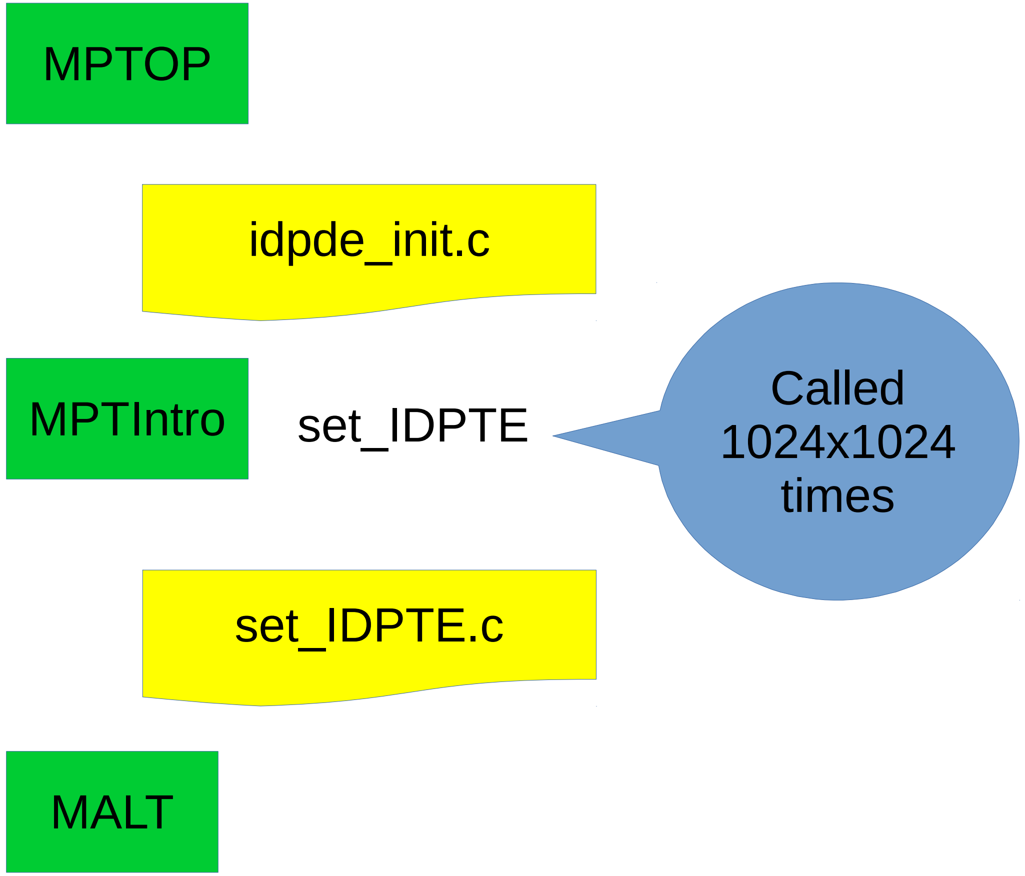
set_IDPTE.c

MALT

```
extern unsigned int IDPMap_LOC[1024][1024];

     void set_IDPTE
     (unsigned int pde_index,
      unsigned int vadr, unsigned int perm)
     {
         IDPMap_LOC[pde_index][vadr] =
         (pde_index * 1024 + vadr) * 4096 + perm;
     }
```

Example: Page Tables



MPTOP

idpde_init.c

MPTIntro

set_IDPTE

Called 1024x1024 times

set_IDPTE.c

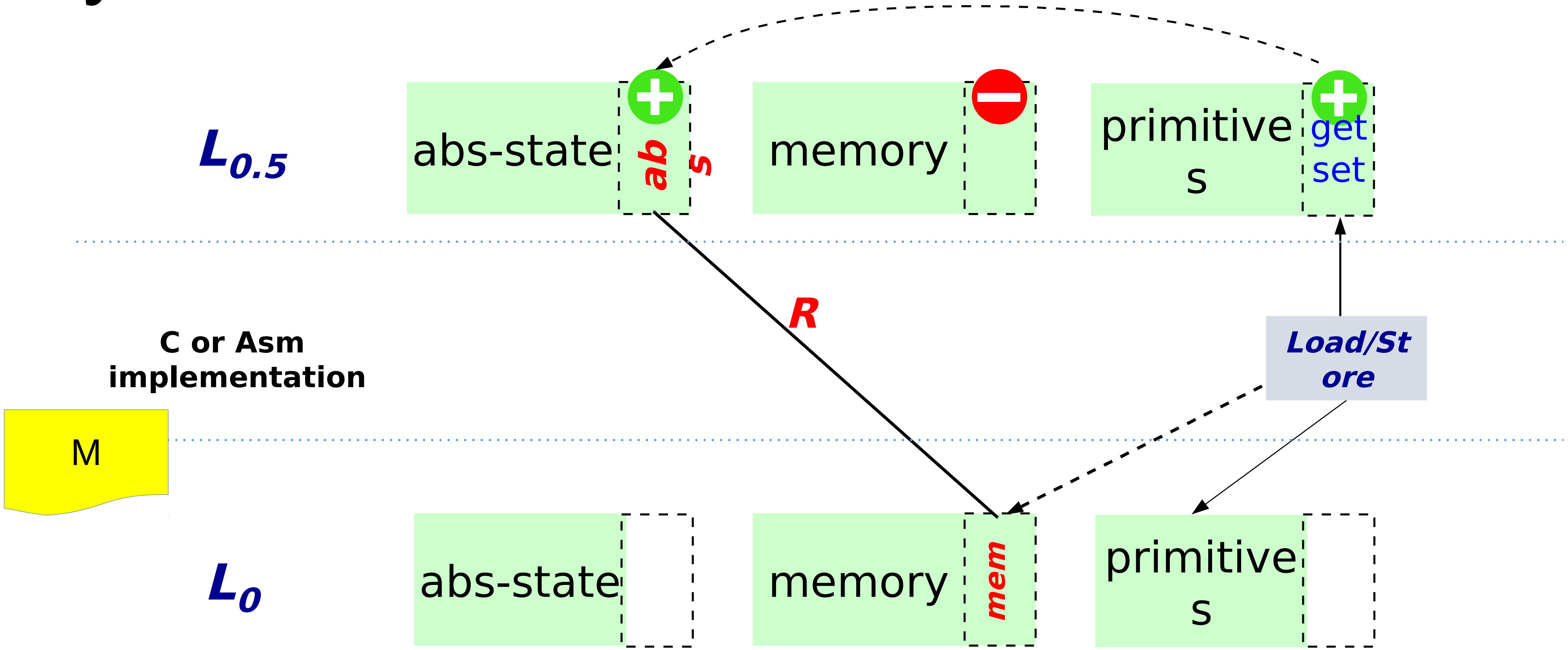
MALT

```
extern unsigned int IDPMap_LOC[1024][1024];

     void set_IDPTE
     (unsigned int pde_index,
      unsigned int vadr, unsigned int perm)
     {
         IDPMap_LOC[pde_index][vadr] =
         (pde_index * 1024 + vadr) * 4096 + perm;
     }
```

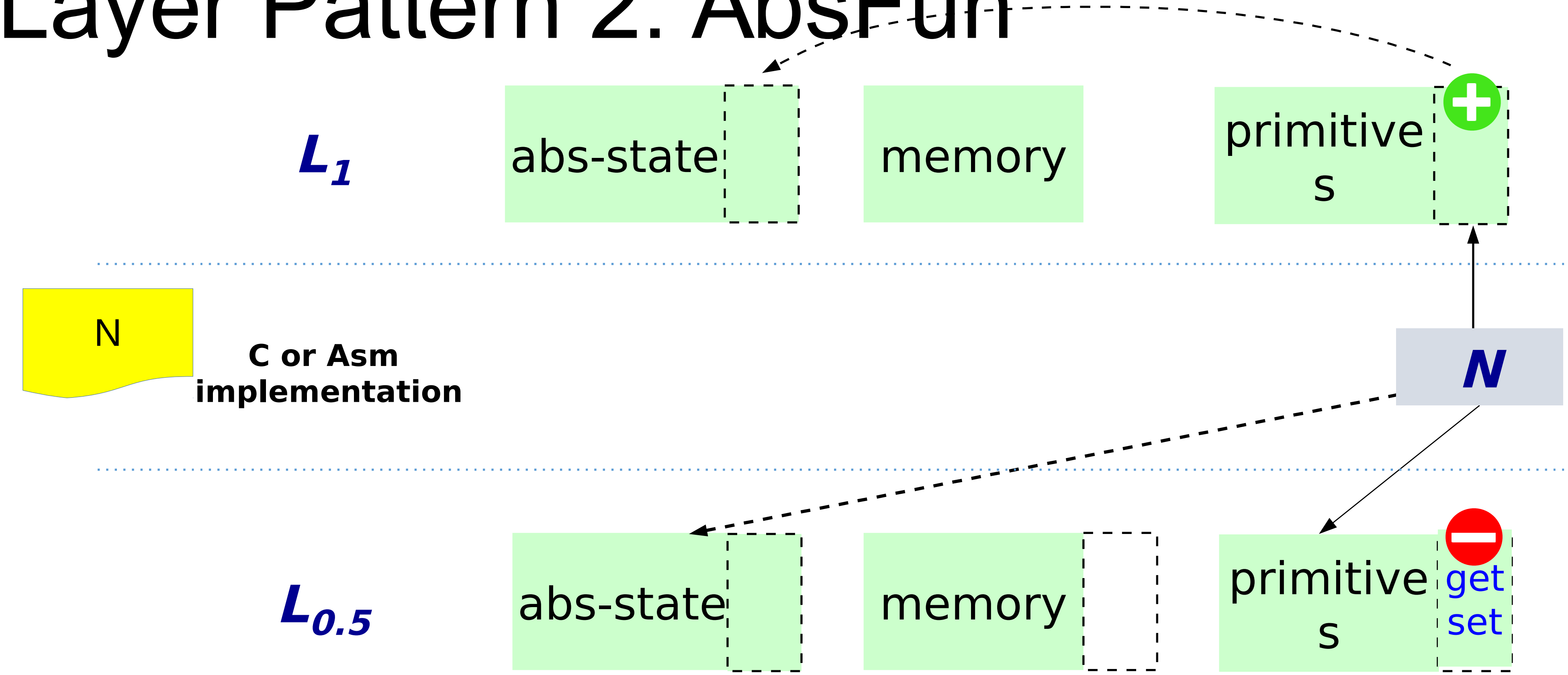
This function should be inlined in idpde_init.**s** !

Layer Pattern 1: Getter/Setter



Hide concrete memory; replace it with Abstract State
Only the getter and setter primitives can access memory

Layer Pattern 2: AbsFun



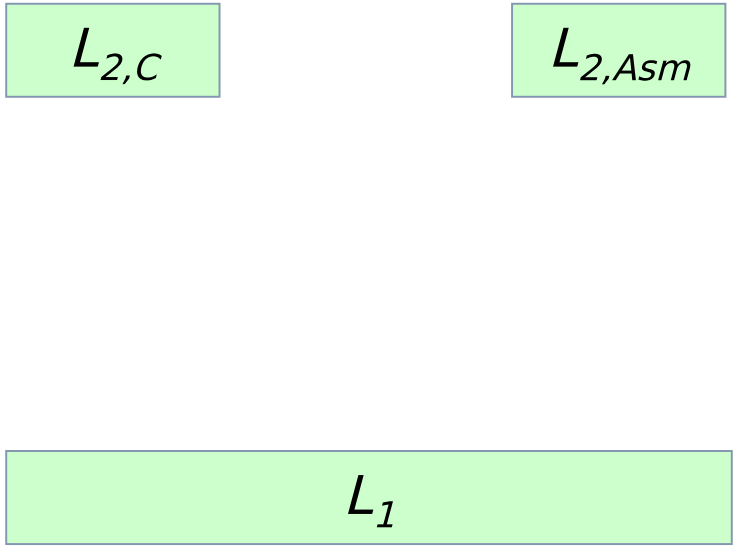
Memory does not change
New implementation code does not access memory directly!

Refinement proof : general pattern

L_2

L_1

Refinement proof : general pattern



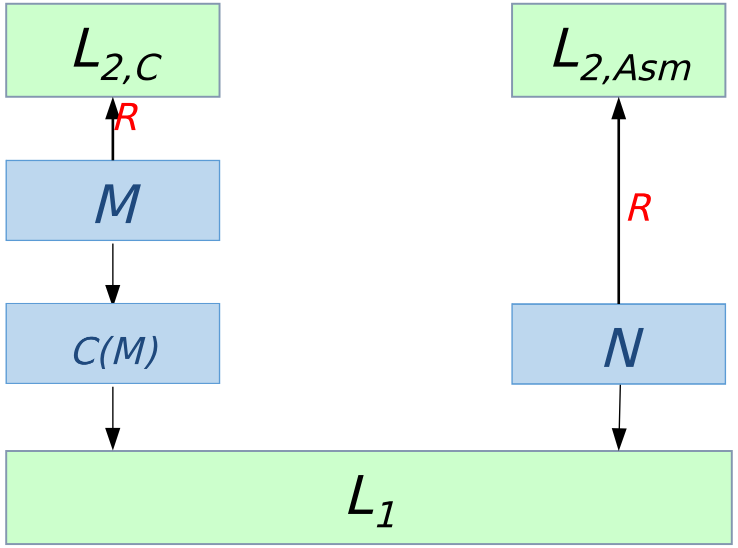
$L_{2,C}$

$L_{2,Asm}$

Same abstract state

L_1

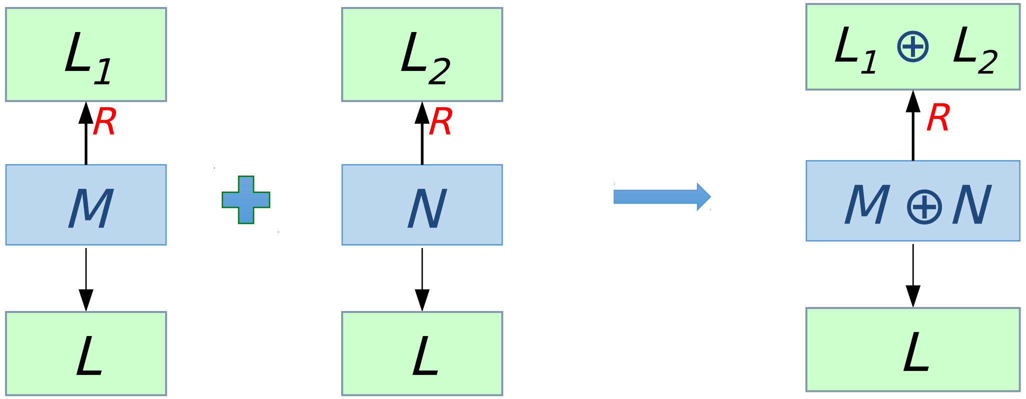
Refinement proof : general pattern



Same abstract state

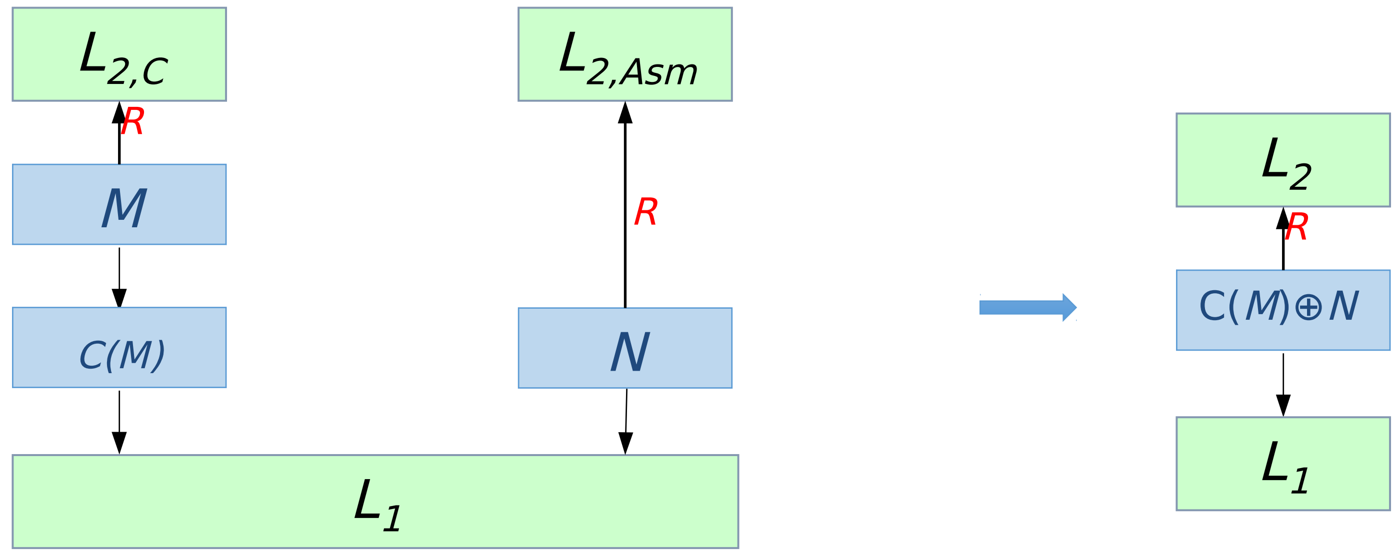
Same refinement relation

LayerLib: Horizontal Composition



- L_1 and L_2 must have the same abstract state

Refinement proof : general pattern



$L_{2,C}$

R

M

$C(M)$

$L_{2,Asm}$

R

N

L_1

L_2

R

$C(M) \oplus N$

L_1

Current limitations

- Non-global caller memory blocks are read-only
  - Due to CompCert assumption in Linear-to-Mach
  - Function call arguments must be protected
  - No arguments to top-most callee
  - 2 solutions (in progress) : copy arguments ? Use permissions ?

Limitations

- CompCertX supports no callbacks
  - Functions can only call :
    - Functions of the same module
    - Primitives of the immediate layer below
    - Lower-layer primitives must be explicitly exposed in the immediate layer
      - passed through explicitly in refinement proofs
  - Enough for CertiKOS
    - Proof by example : callbacks are not needed
    - Avoid breaches of abstraction

POPL 2015 Mumbai, India January 12-18

Our Contributions

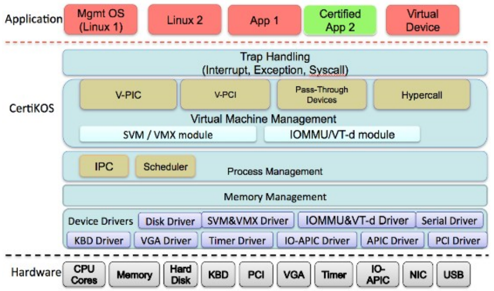
Artifact Evaluated AEC POPL Consistent Complete Well Documented Easy to Reuse

- We introduce deep specification and present a language-based formalization of certified abstraction layer

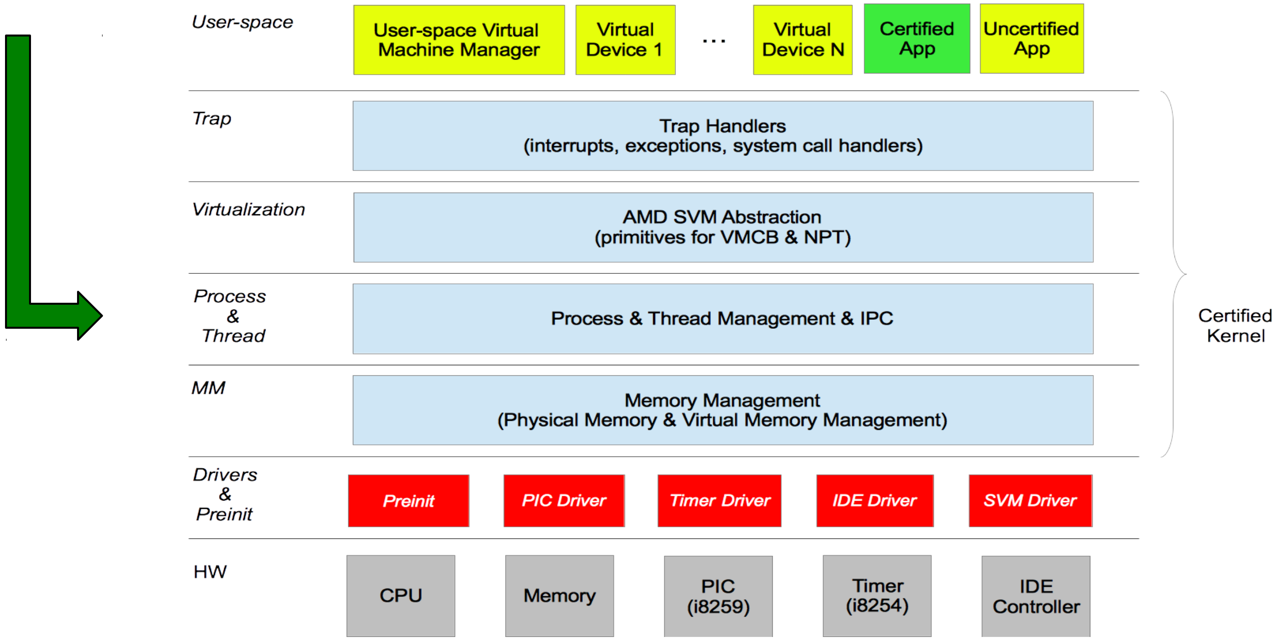
- We developed new languages & tools in Coq
  - A formal layer calculus for composing certified layers
  - ClightX for writing certified layers in a C-like language
  - AsmX for writing certified layers in assembly
  - CompCertX that compiles ClightX layers into AsmX layers

- We built multiple certified OS kernels in Coq
  - mCertiKOS-hyper consists of 37 layers, took less than one-person-year to develop, and can boot Linux as a guest

Case Study: mCertiKOS



Single-core version of CertiKOS (developed under DARPA CRASH & HACMS programs), 3 kloc, can boot Linux



User-space
User-space Virtual Machine Manager
Virtual Device 1
…
Virtual Device N
Certified App
Uncertified App

Trap
Trap Handlers
(interrupts, exceptions, system call handlers)

Virtualization
AMD SVM Abstraction
(primitives for VMCB & NPT)

Process & Thread
Process & Thread Management & IPC

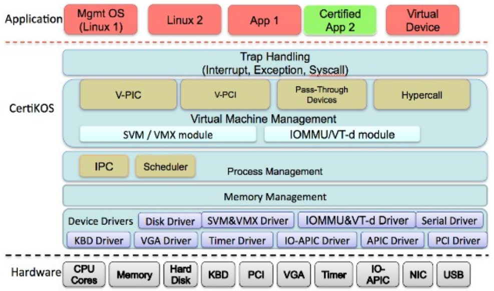
MM
Memory Management
(Physical Memory & Virtual Memory Management)

Certified Kernel

Drivers & Preinit
Preinit
PIC Driver
Timer Driver
IDE Driver
SVM Driver

HW
CPU
Memory
PIC (i8259)
Timer (i8254)
IDE Controller

Case Study: mCertiKOS



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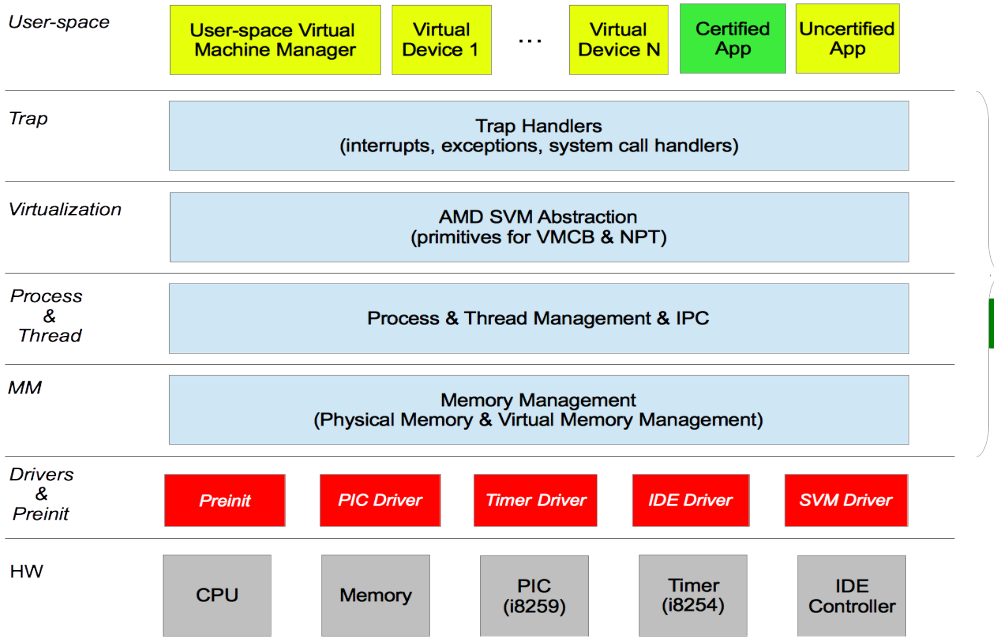
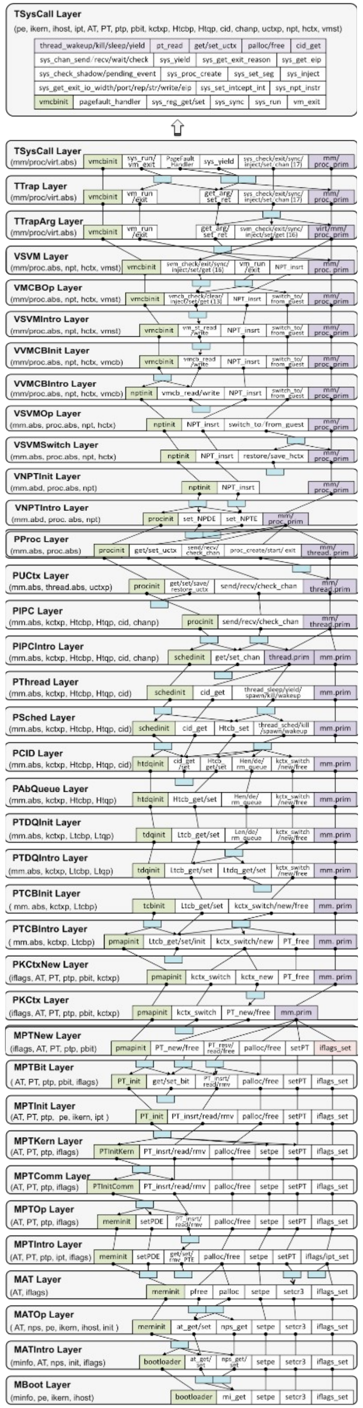
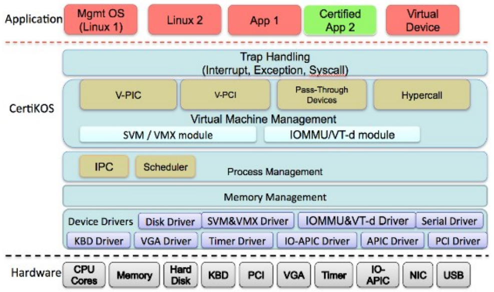


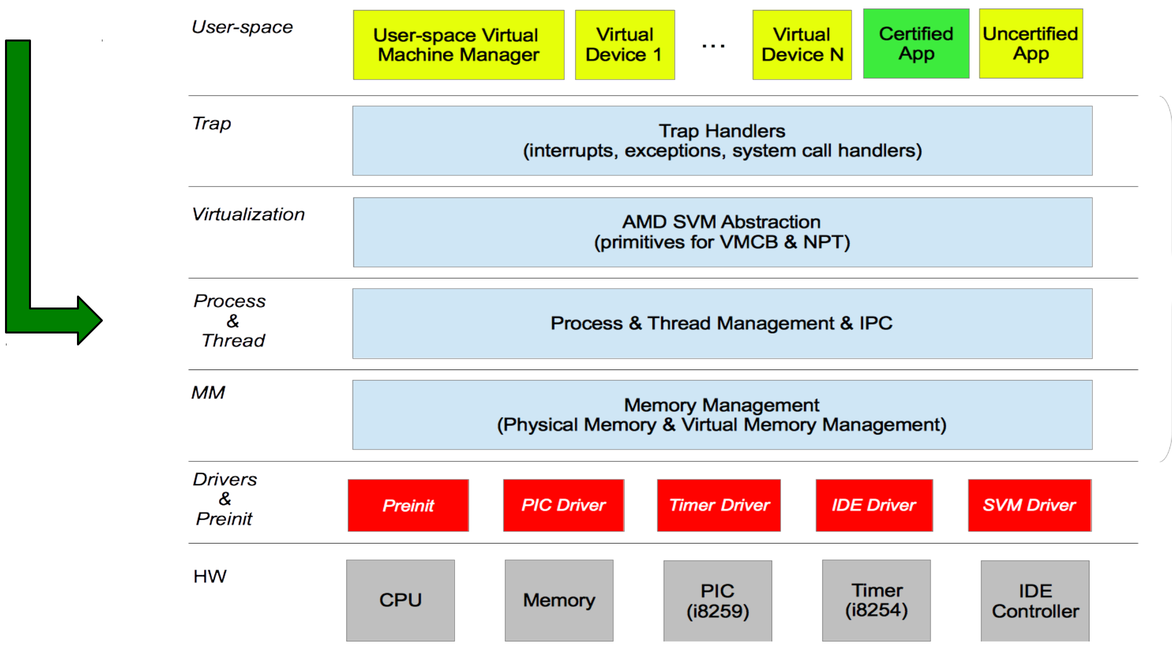


Case Study: mCertiKOS



Single-core version of CertiKOS (developed under DARPA CRASH & HACMS programs), 3 kloc, can boot Linux

Aggressive use of abstraction over deep specs (37 layers in ClightX & AsmX)



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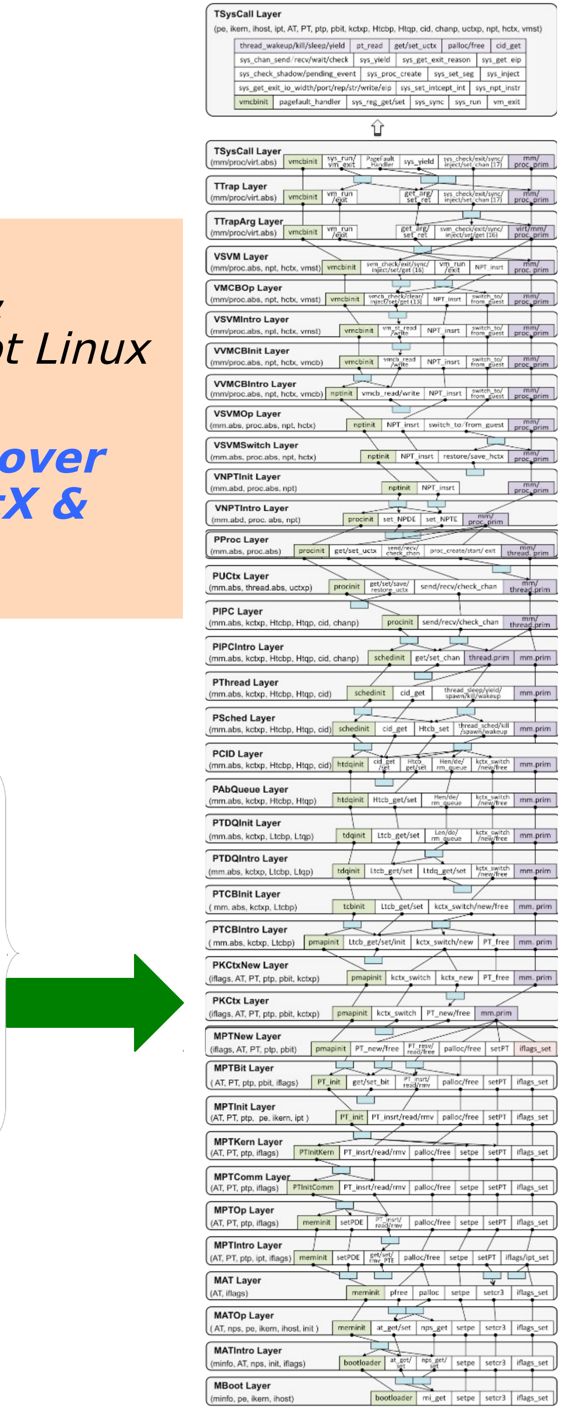
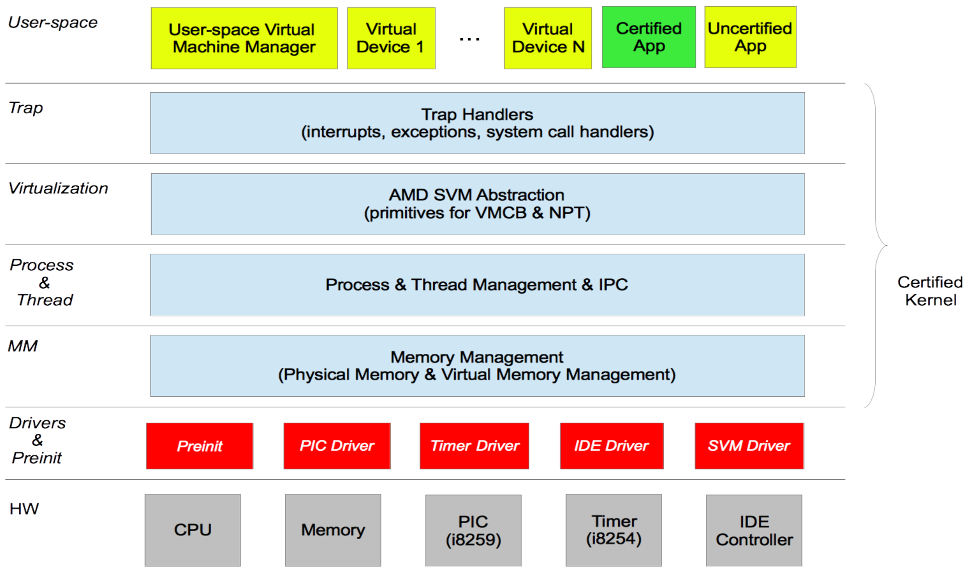
Drivers & Preinit: ***Preinit*** | ***PIC Driver*** | ***Timer Driver*** | ***IDE Driver*** | ***SVM Driver***

HW: CPU | Memory | PIC (i8259) | Timer (i8254) | IDE Controller



Decomposing mCertiKOS



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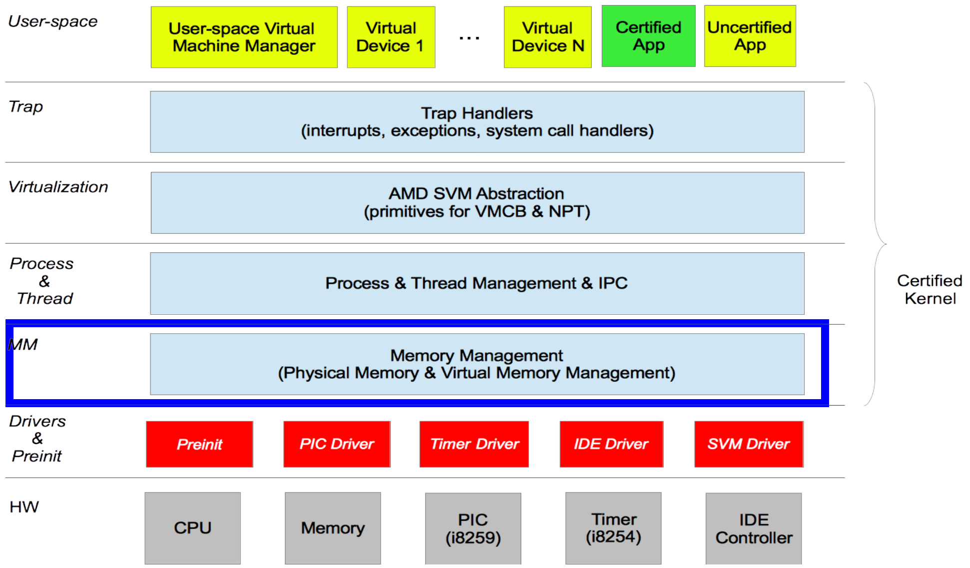
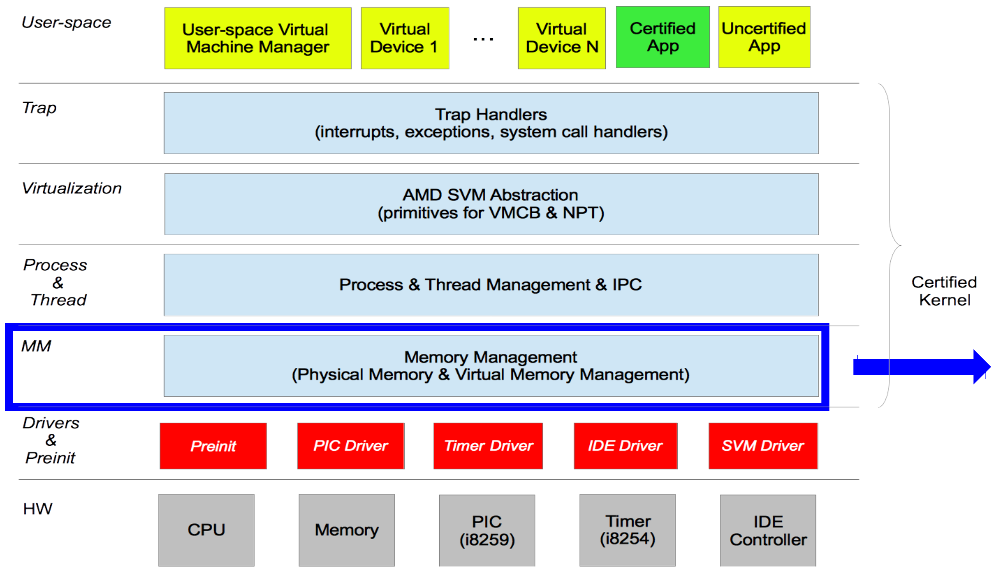
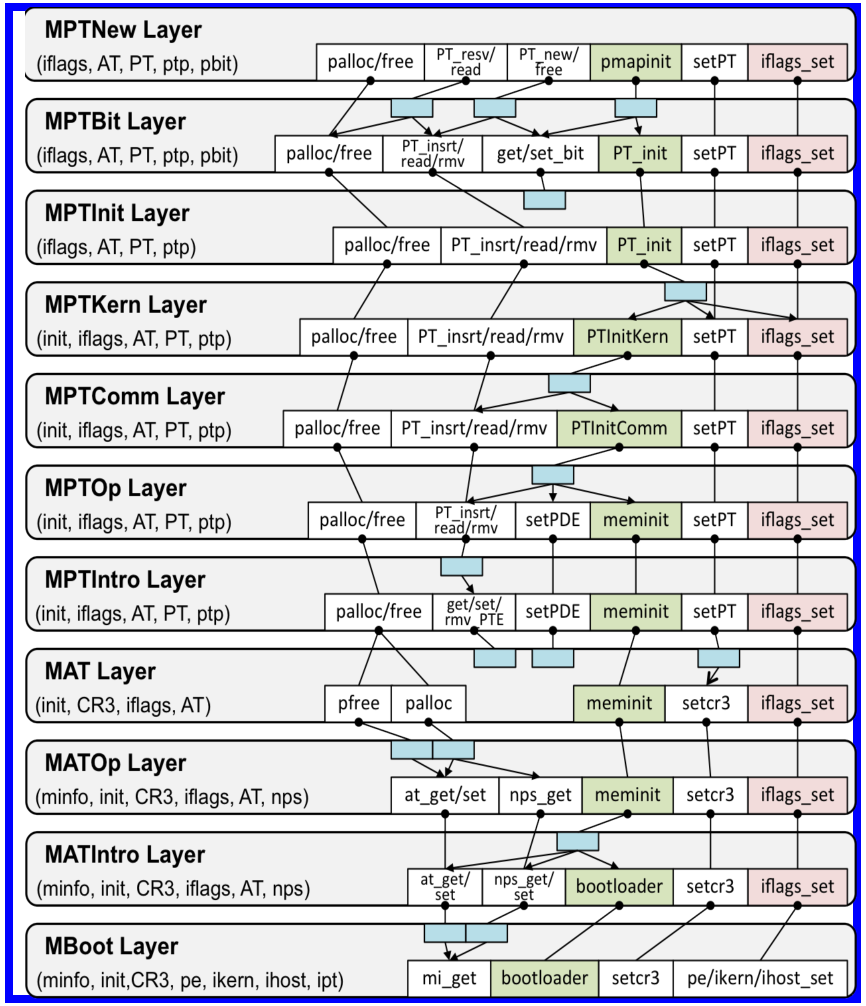


Physical Memory and Virtual Memory Management (11 Layers)

Based on the abstract machine provided by boot loader

Decomposing mCertiKOS





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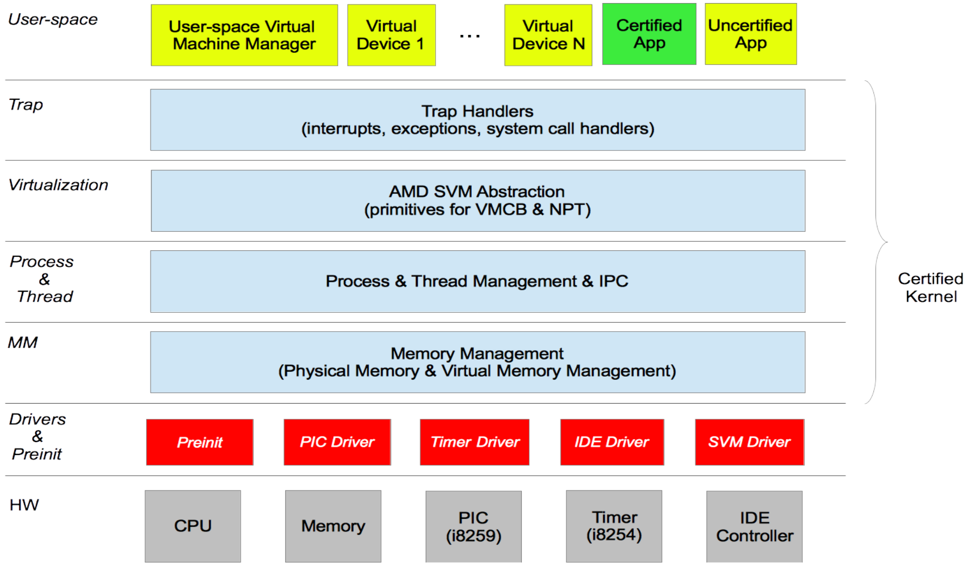
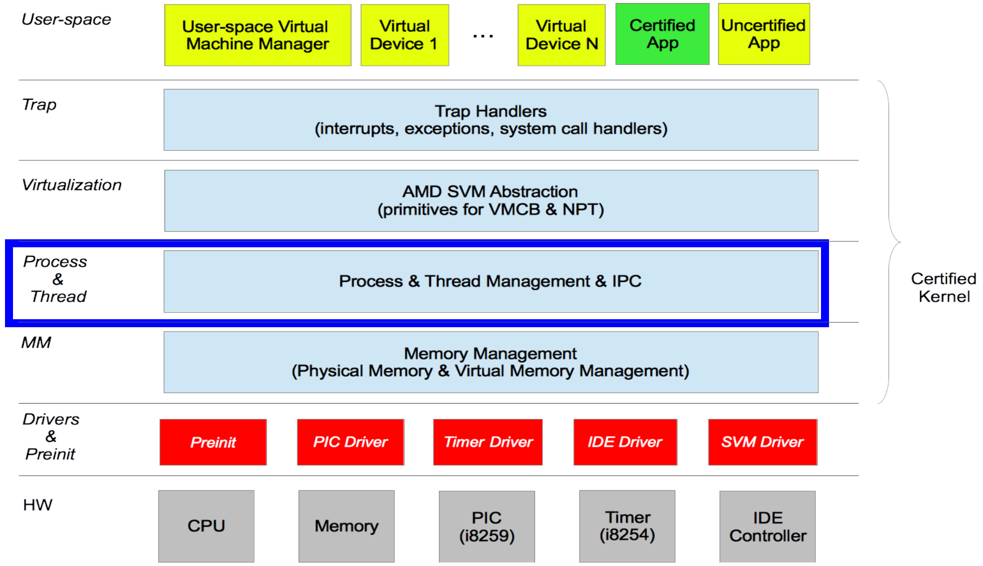
Based on the abstract machine provided by boot loader

Decomposing mCertiKOS (cont’d)

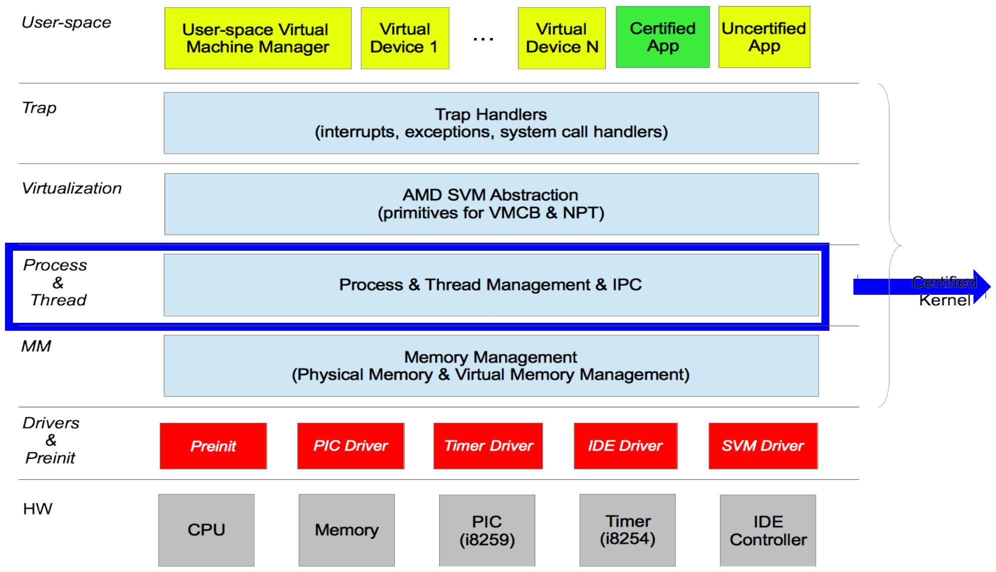


Decomposing mCertiKOS (cont'd)



Thread and Process Management (14 Layers)

Decomposing mCertiKOS (cont'd)



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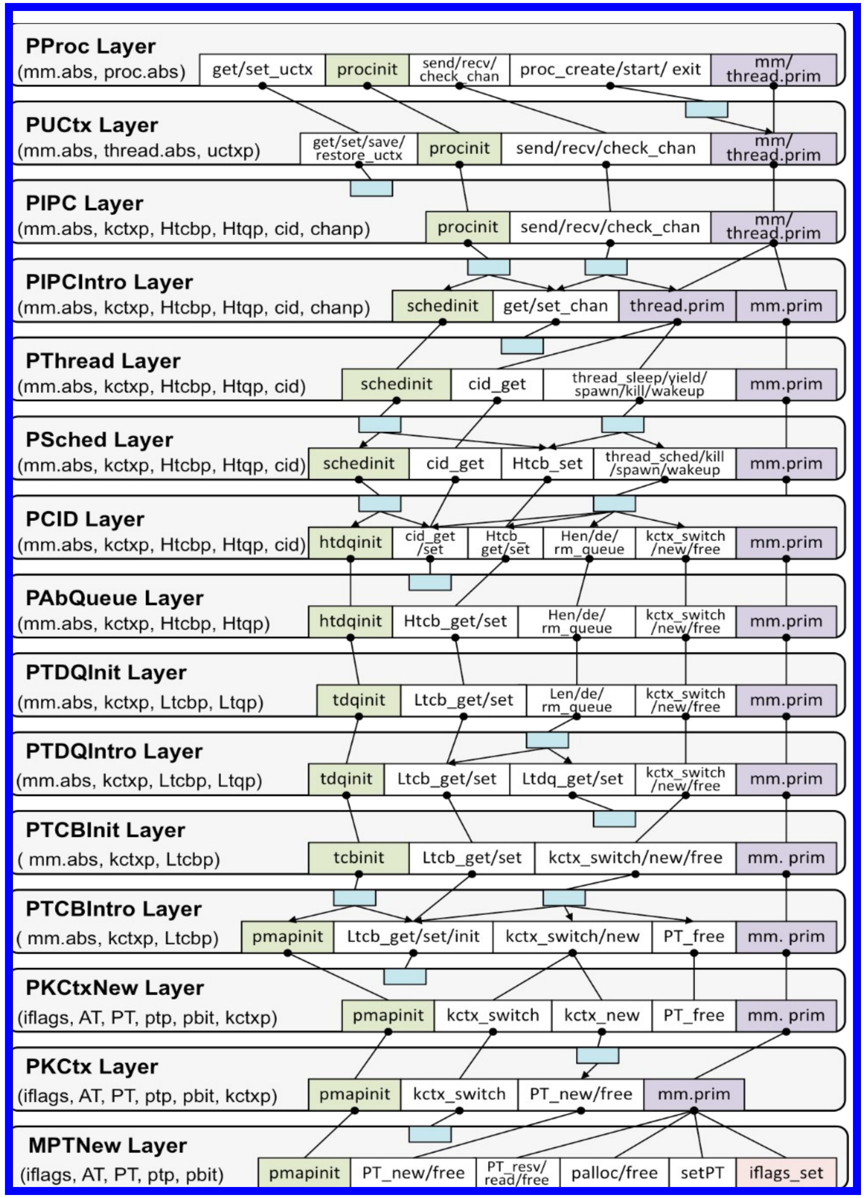


PProc Layer
(mm.abs, proc.abs)
get/set_uctx | procinit | send/recv/ check_chan | proc_create/start/ exit | mm/ thread.prim

PUCtx Layer
(mm.abs, thread.abs, uctxp)
get/set/save/ restore_uctx | procinit | send/recv/check_chan | mm/ thread.prim

PIPC Layer
(mm.abs, kctxp, Htcbp, Htqp, cid, chanp)
procinit | send/recv/check_chan | mm/ thread.prim

PIPCIntro Layer
(mm.abs, kctxp, Htcbp, Htqp, cid, chanp)
schedinit | get/set_chan | thread.prim | mm.prim

PThread Layer
(mm.abs, kctxp, Htcbp, Htqp, cid)
schedinit | cid_get | thread_sleep/yield/ spawn/kill/wakeup | mm.prim

PSched Layer
(mm.abs, kctxp, Htcbp, Htqp, cid)
schedinit | cid_get | Htcb_set | thread_sched/kill /spawn/wakeup | mm.prim

PCID Layer
(mm.abs, kctxp, Htcbp, Htqp, cid)
htdqinit | cid_get /set | Htcb_ get/set | Hen/de/ rm_queue | kctx_switch /new/free | mm.prim

PAbQueue Layer
(mm.abs, kctxp, Htcbp, Htqp)
htdqinit | Htcb_get/set | Hen/de/ rm_queue | kctx_switch /new/free | mm.prim

PTDQInit Layer
(mm.abs, kctxp, Ltcbp, Ltqp)
tdqinit | Ltcb_get/set | Len/de/ rm_queue | kctx_switch /new/free | mm.prim

PTDQIntro Layer
(mm.abs, kctxp, Ltcbp, Ltqp)
tdqinit | Ltcb_get/set | Ltdq_get/set | kctx_switch /new/free | mm.prim

PTCBInit Layer
(mm.abs, kctxp, Ltcbp)
tcbinit | Ltcb_get/set | kctx_switch/new/free | mm. prim

PTCBIntro Layer
(mm.abs, kctxp, Ltcbp)
pmapinit | Ltcb_get/set/init | kctx_switch/new | PT_free | mm. prim

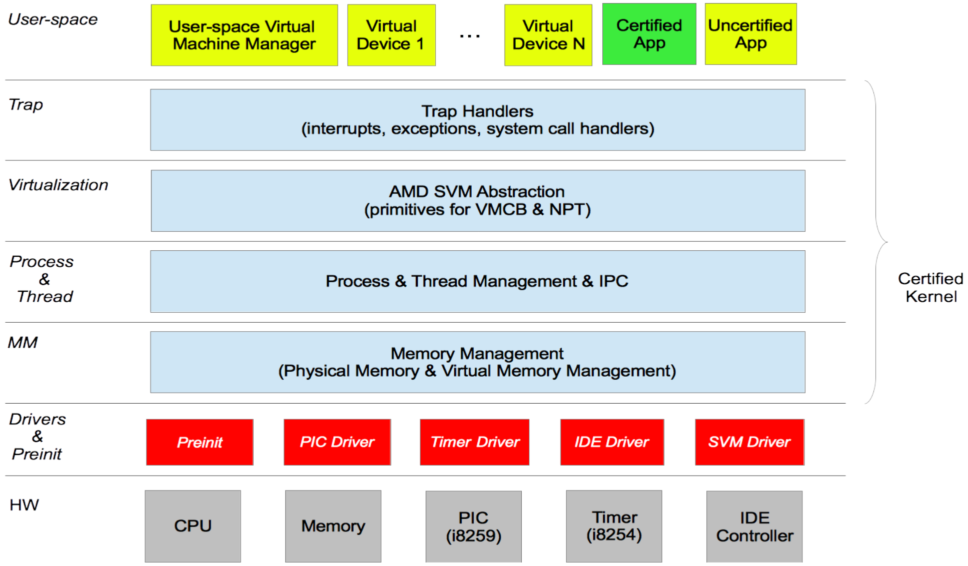
PKCtxNew Layer
(iflags, AT, PT, ptp, pbit, kctxp)
pmapinit | kctx_switch | kctx_new | PT_free | mm. prim

PKCtx Layer
(iflags, AT, PT, ptp, pbit, kctxp)
pmapinit | kctx_switch | PT_new/free | mm.prim

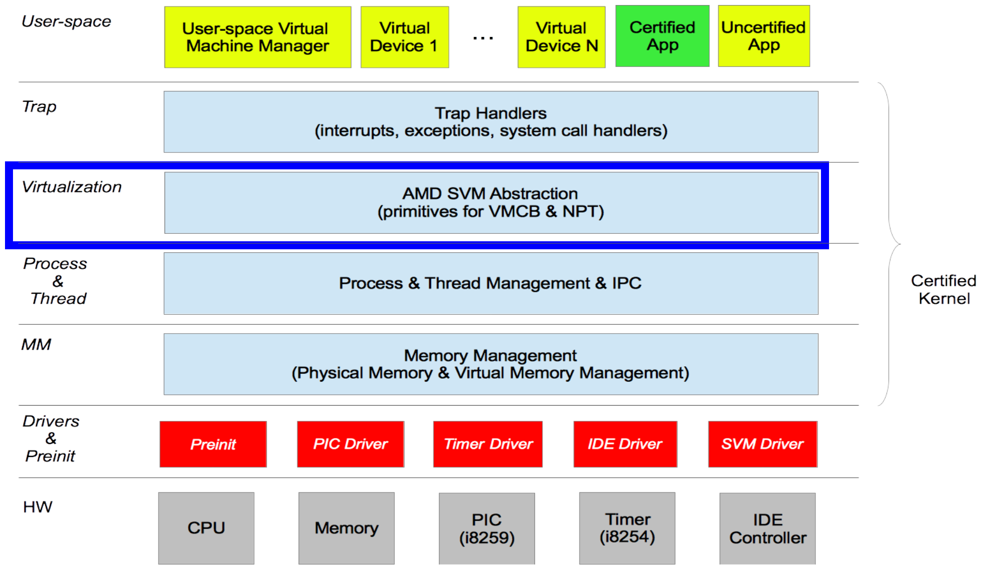
MPTNew Layer
(iflags, AT, PT, ptp, pbit)
pmapinit | PT_new/free | PT_resv/ read/free | palloc/free | setPT | iflags_set

Thread and Process Management (14 Layers)

Decomposing mCertiKOS (cont’d)

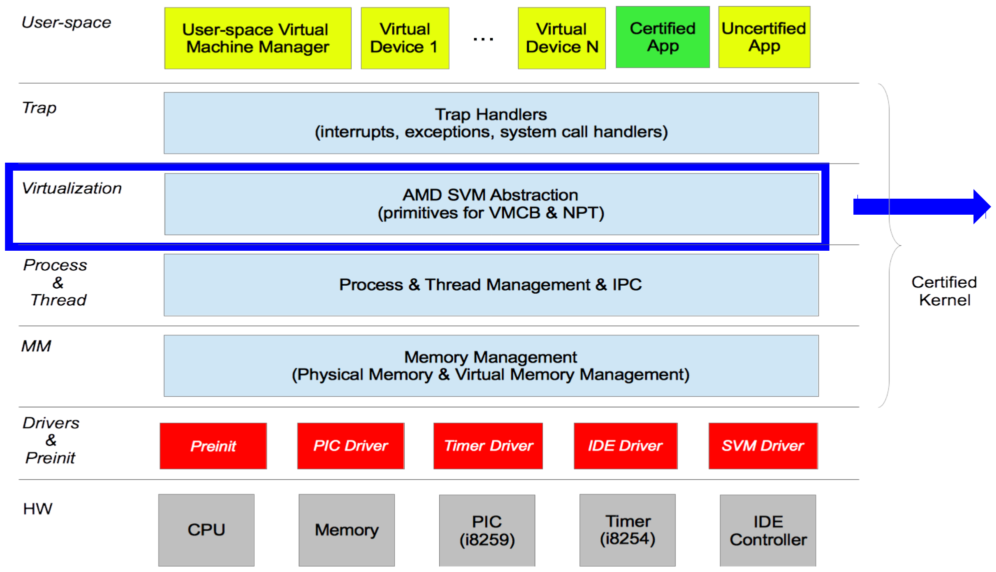


Decomposing mCertiKOS (cont’d)



Virtualization Support (9 Layers)

Decomposing mCertiKOS (cont’d)



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AMD SVM Abstraction
(primitives for VMCB & NPT)

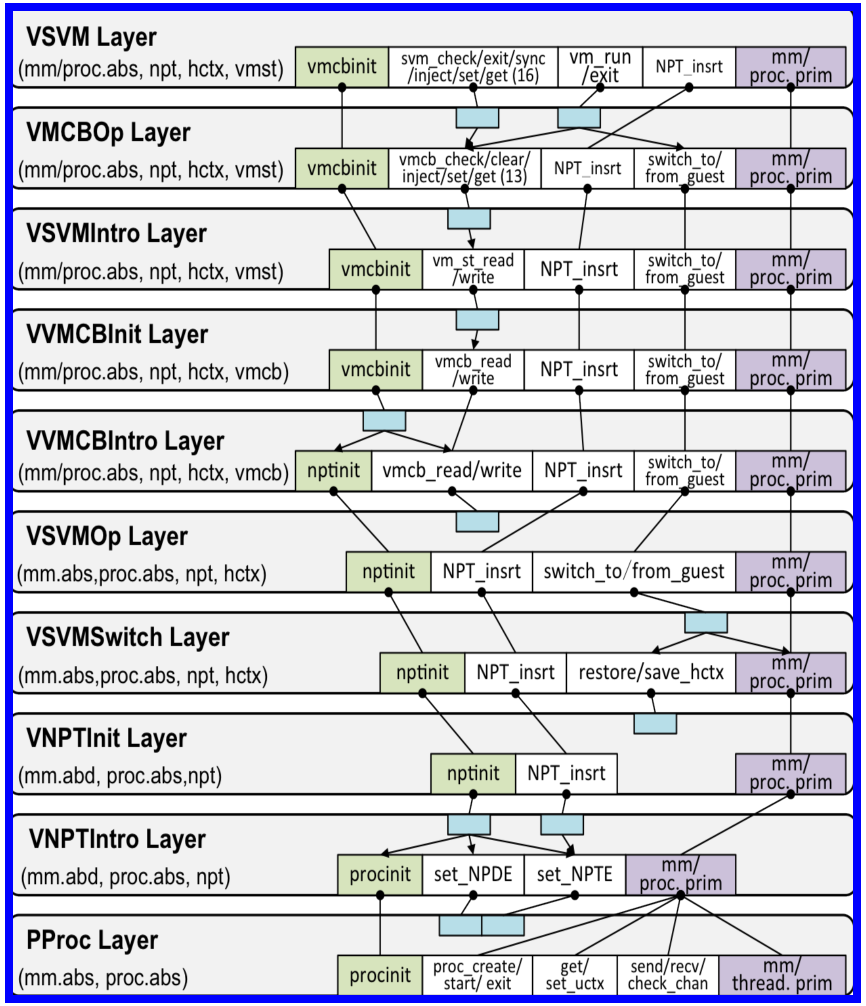
Process & Thread
Process & Thread Management & IPC

MM
Memory Management
(Physical Memory & Virtual Memory Management)

Certified Kernel

Drivers & Preinit
Preinit
PIC Driver
Timer Driver
IDE Driver
SVM Driver

HW
CPU
Memory
PIC (i8259)
Timer (i8254)
IDE Controller



VSVM Layer
(mm/proc.abs, npt, hctx, vmst)
vmcbinit | svm_check/exit/sync /inject/set/get (16) | vm_run /exit | NPT_insrt | mm/ proc. prim

VMCBOp Layer
(mm/proc.abs, npt, hctx, vmst)
vmcbinit | vmcb_check/clear/ inject/set/get (13) | NPT_insrt | switch_to/ from_guest | mm/ proc. prim

VSVMIntro Layer
(mm/proc.abs, npt, hctx, vmst)
vmcbinit | vm_st_read /write | NPT_insrt | switch_to/ from_guest | mm/ proc. prim

VVMCBInit Layer
(mm/proc.abs, npt, hctx, vmcb)
vmcbinit | vmcb_read /write | NPT_insrt | switch_to/ from_guest | mm/ proc. prim

VVMCBIntro Layer
(mm/proc.abs, npt, hctx, vmcb)
nptinit | vmcb_read/write | NPT_insrt | switch_to/ from_guest | mm/ proc. prim

VSVMOp Layer
(mm.abs,proc.abs, npt, hctx)
nptinit | NPT_insrt | switch_to/from_guest | mm/ proc. prim

VSVMSwitch Layer
(mm.abs,proc.abs, npt, hctx)
nptinit | NPT_insrt | restore/save_hctx | mm/ proc. prim

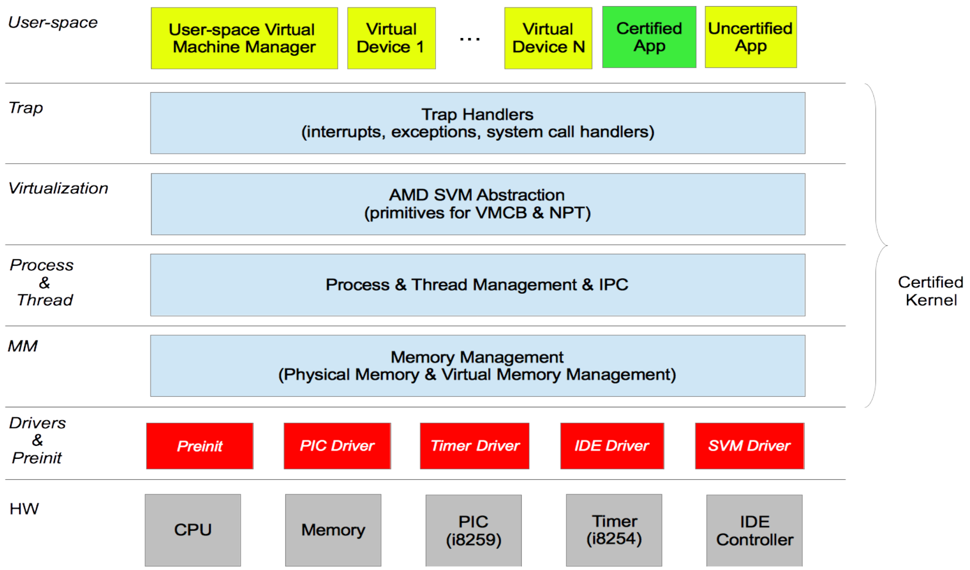
VNPTInit Layer
(mm.abd, proc.abs,npt)
nptinit | NPT_insrt | mm/ proc. prim

VNPTIntro Layer
(mm.abd, proc.abs, npt)
procinit | set_NPDE | set_NPTE | mm/ proc. prim

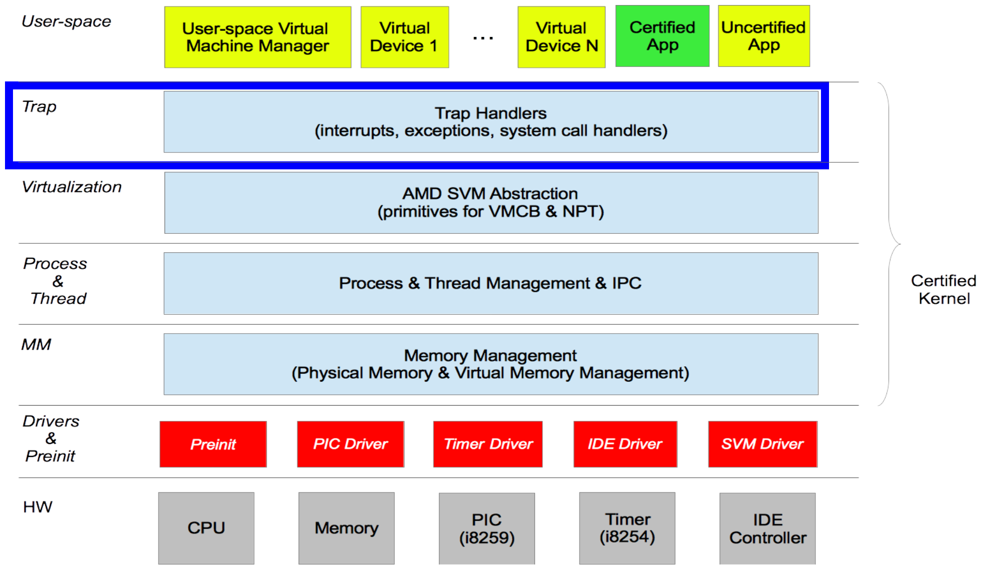
PProc Layer
(mm.abs, proc.abs)
procinit | proc_create/ start/ exit | get/ set_uctx | send/recv/ check_chan | mm/ thread. prim

Virtualization Support (9 Layers)

Decomposing mCertiKOS (cont’d)

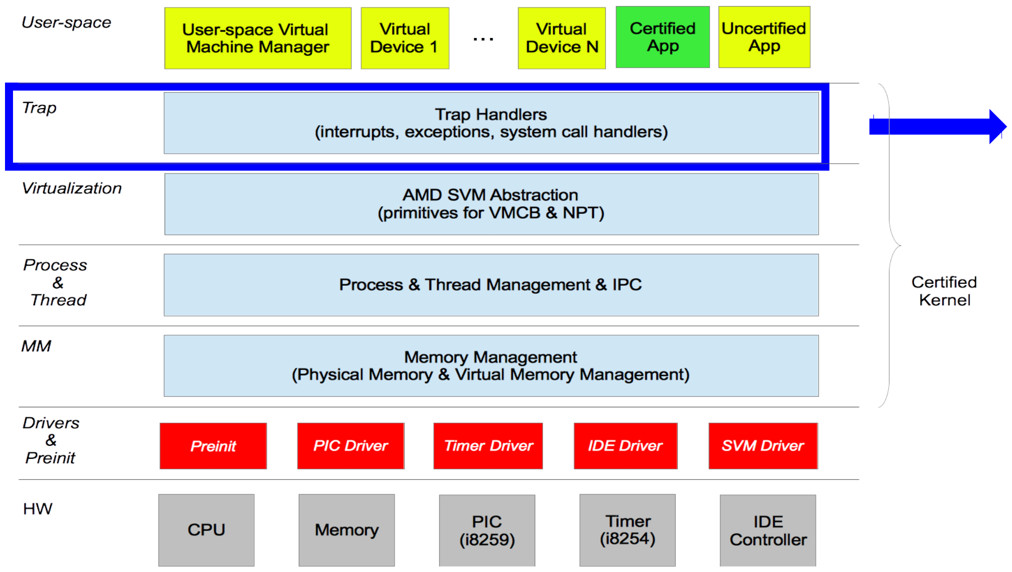


Decomposing mCertiKOS (cont'd)



Syscall and Trap Handlers (3 Layers)

Decomposing mCertiKOS (cont'd)


User-space
User-space Virtual Machine Manager
Virtual Device 1
…
Virtual Device N
Certified App
Uncertified App

Trap
Trap Handlers
(interrupts, exceptions, system call handlers)

Virtualization
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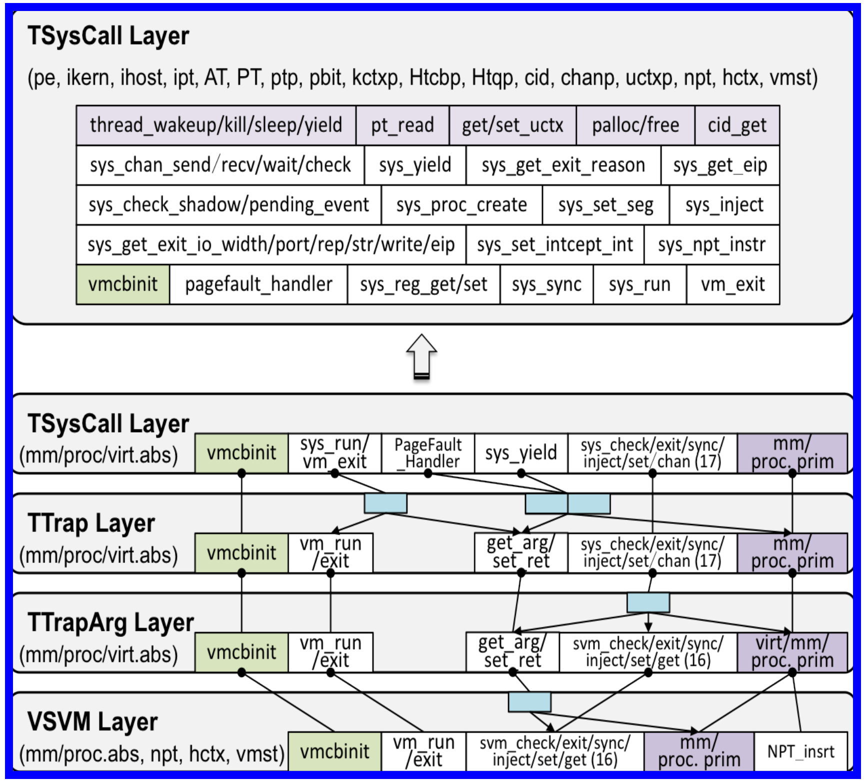

TSysCall Layer
(pe, ikern, ihost, ipt, AT, PT, ptp, pbit, kctxp, Htcbp, Htqp, cid, chanp, uctxp, npt, hctx, vmst)

thread_wakeup/kill/sleep/yield | pt_read | get/set_uctx | palloc/free | cid_get
sys_chan_send/recv/wait/check | sys_yield | sys_get_exit_reason | sys_get_eip
sys_check_shadow/pending_event | sys_proc_create | sys_set_seg | sys_inject
sys_get_exit_io_width/port/rep/str/write/eip | sys_set_intcept_int | sys_npt_instr
vmcbinit | pagefault_handler | sys_reg_get/set | sys_sync | sys_run | vm_exit

TSysCall Layer
(mm/proc/virt.abs)
vmcbinit | sys_run/ vm_exit | PageFault _Handler | sys_yield | sys_check/exit/sync/ inject/set/chan (17) | mm/ proc. prim

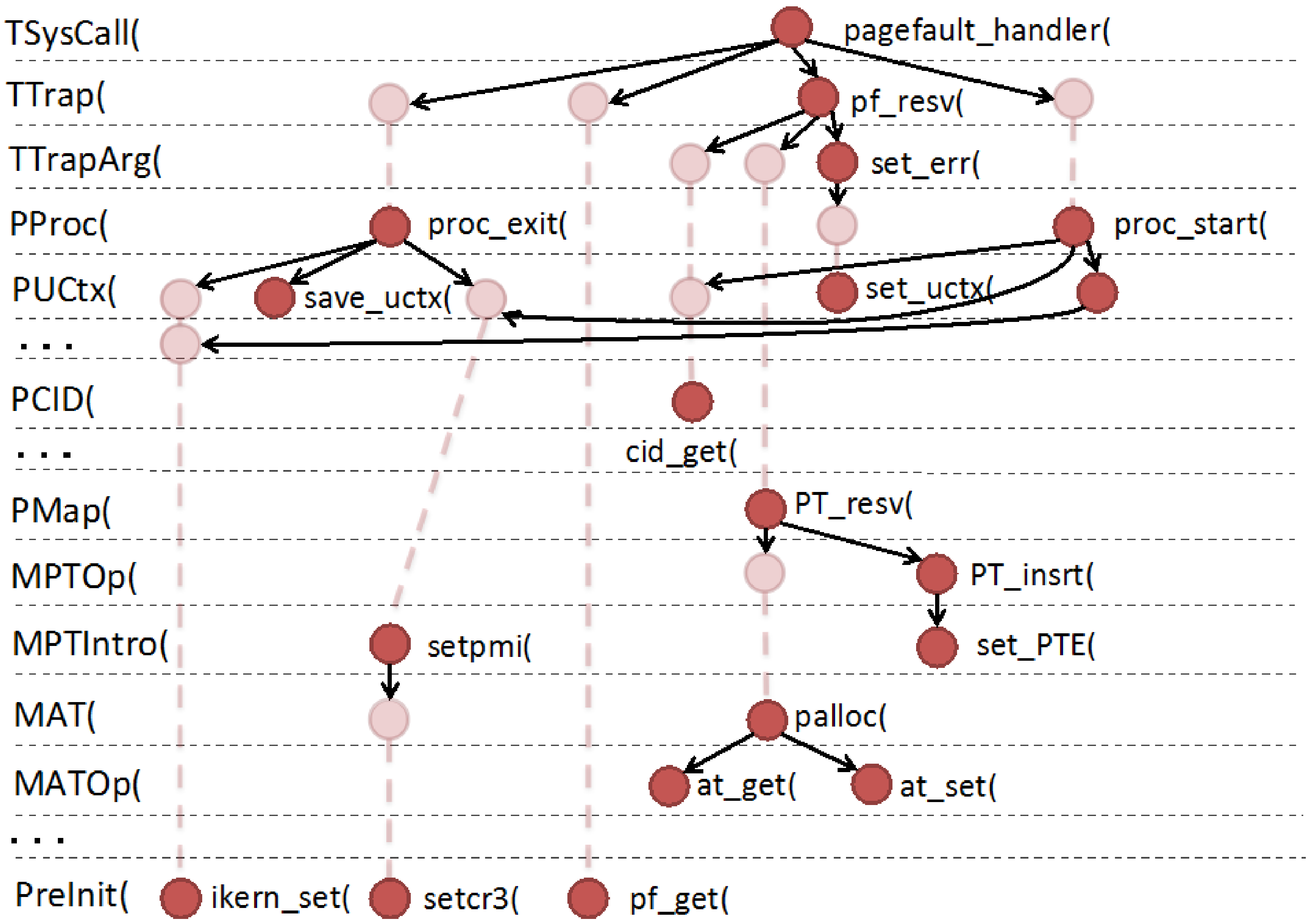
TTrap Layer
(mm/proc/virt.abs)
vmcbinit | vm_run /exit | get_arg/ set_ret | sys_check/exit/sync/ inject/set/chan (17) | mm/ proc. prim

TTrapArg Layer
(mm/proc/virt.abs)
vmcbinit | vm_run /exit | get_arg/ set_ret | svm_check/exit/sync/ inject/set/get (16) | virt/mm/ proc. prim

VSVM Layer
(mm/proc.abs, npt, hctx, vmst)
vmcbinit | vm_run /exit | svm_check/exit/sync/ inject/set/get (16) | mm/ proc. prim | NPT_insrt

Syscall and Trap Handlers (3 Layers)

Example: Page Fault Handler



TSysCall(pagefault_handler(

TTrap(pf_resv(

TTrapArg(set_err(

PProc(proc_exit(proc_start(

PUCtx(save_uctx(set_uctx(

. . .

PCID(

. . . cid_get(

PMap(PT_resv(

MPTOp(PT_insrt(

MPTIntro(setpmi(set_PTE(

MAT(palloc(

MATOp(at_get(at_set(

. . .

PreInit(ikern_set(setcr3(pf_get(

Conclusions

- Great success w. today's system software … but why?
- We identify, sharpen, & formalize two possible ingredients
  - abstraction over deep specs
  - a compositional layered methodology
- We build new lang. & tools to make layered programming *rigorous & certified* --- this leads to huge benefits:
  - simplified design & spec; reduced proof effort; better extensibility
- They also help *verification in the small*
  - hiding implementation details as soon as possible

Ongoing & Future Work

- CompCertX
  - Support for stack consumption (merge with QompCert, PLDI 2014)
  - Concurrency?
- Layer calculus
  - Make horizontal composition more powerful (disjoint abstract states...)
- Compositional verification of layered systems in practice
  - Automatic generation of ClightX code, layer spec and refinement proof
- CertiKOS
  - Device drivers, concurrency (multicore?), etc.
  - Publish the code!
  - Papers available at http://flint.cs.yale.edu