Deep Specifications and Certified Abstraction Layers

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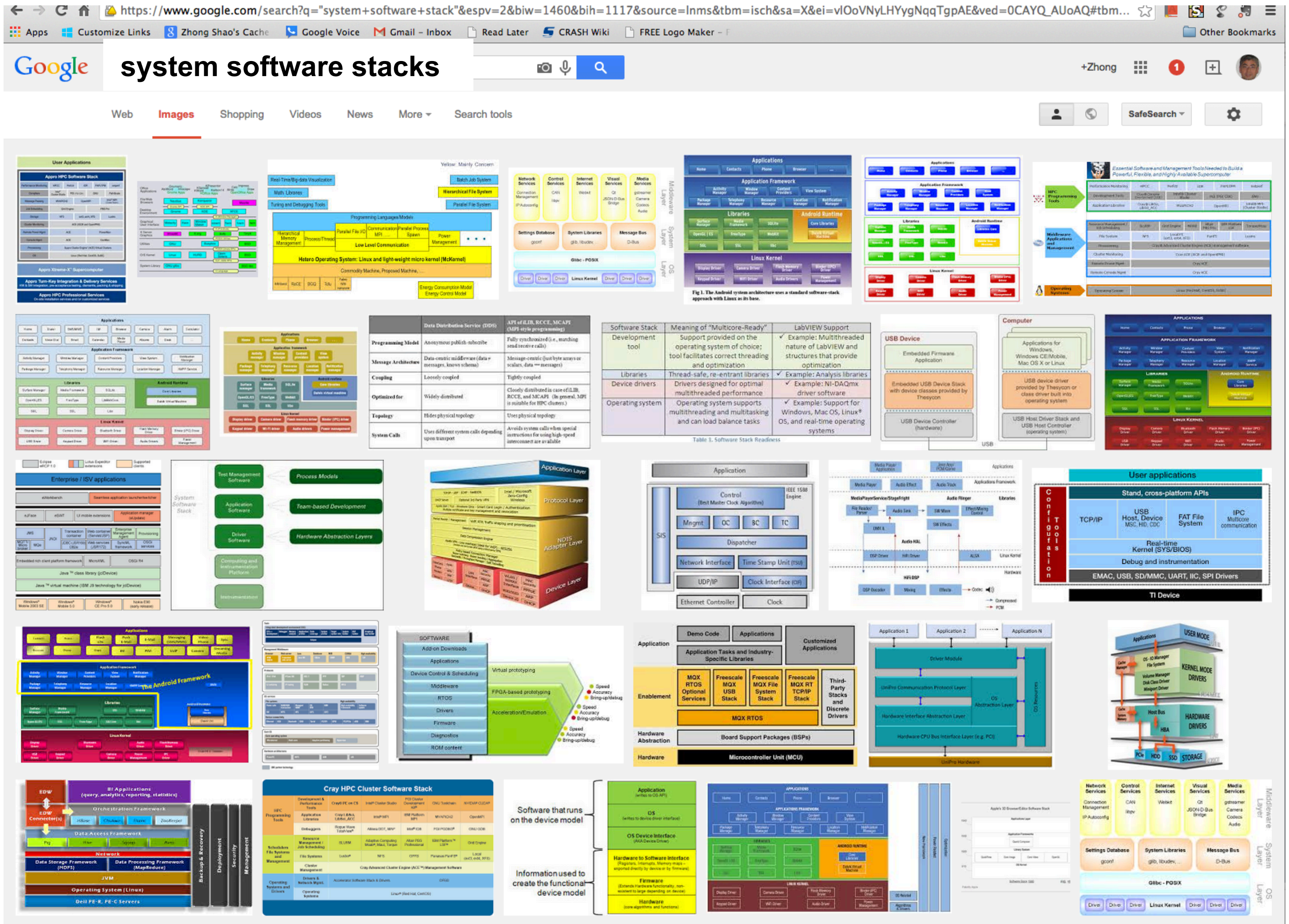
http://flint.cs.yale.edu

Motivation

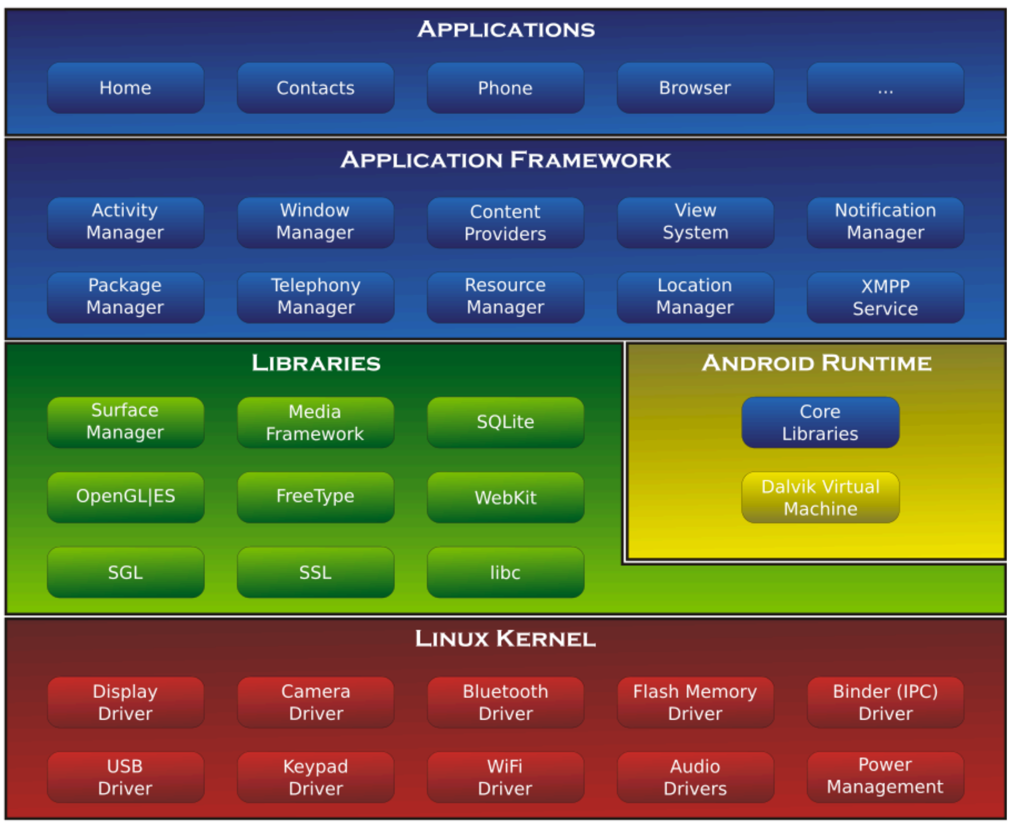
How to build reliable & secure ***system software stacks****?*

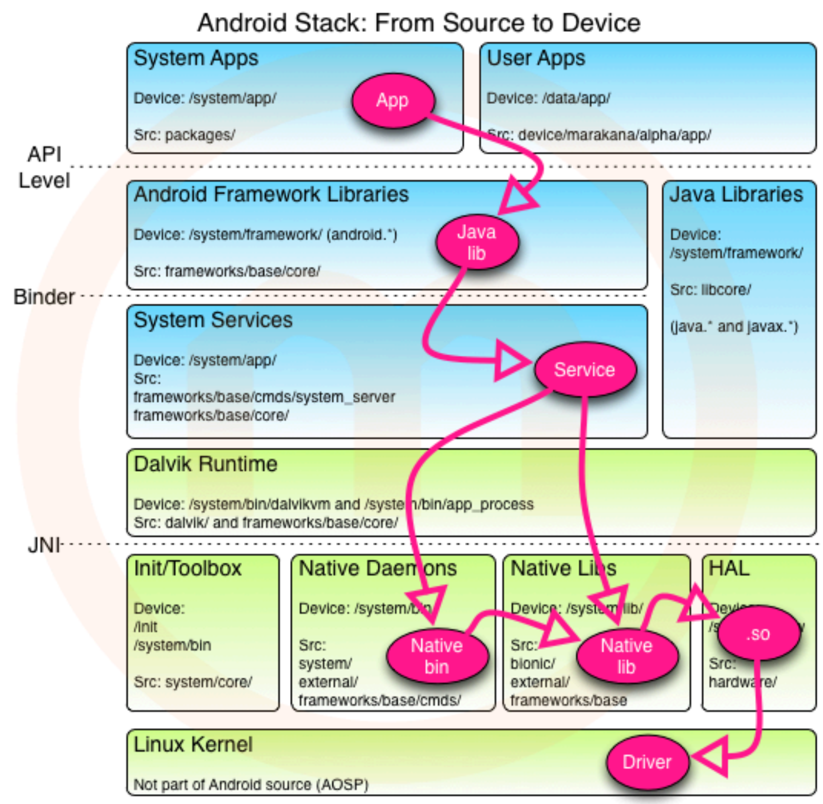


Motivation

Android architecture & system stack

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

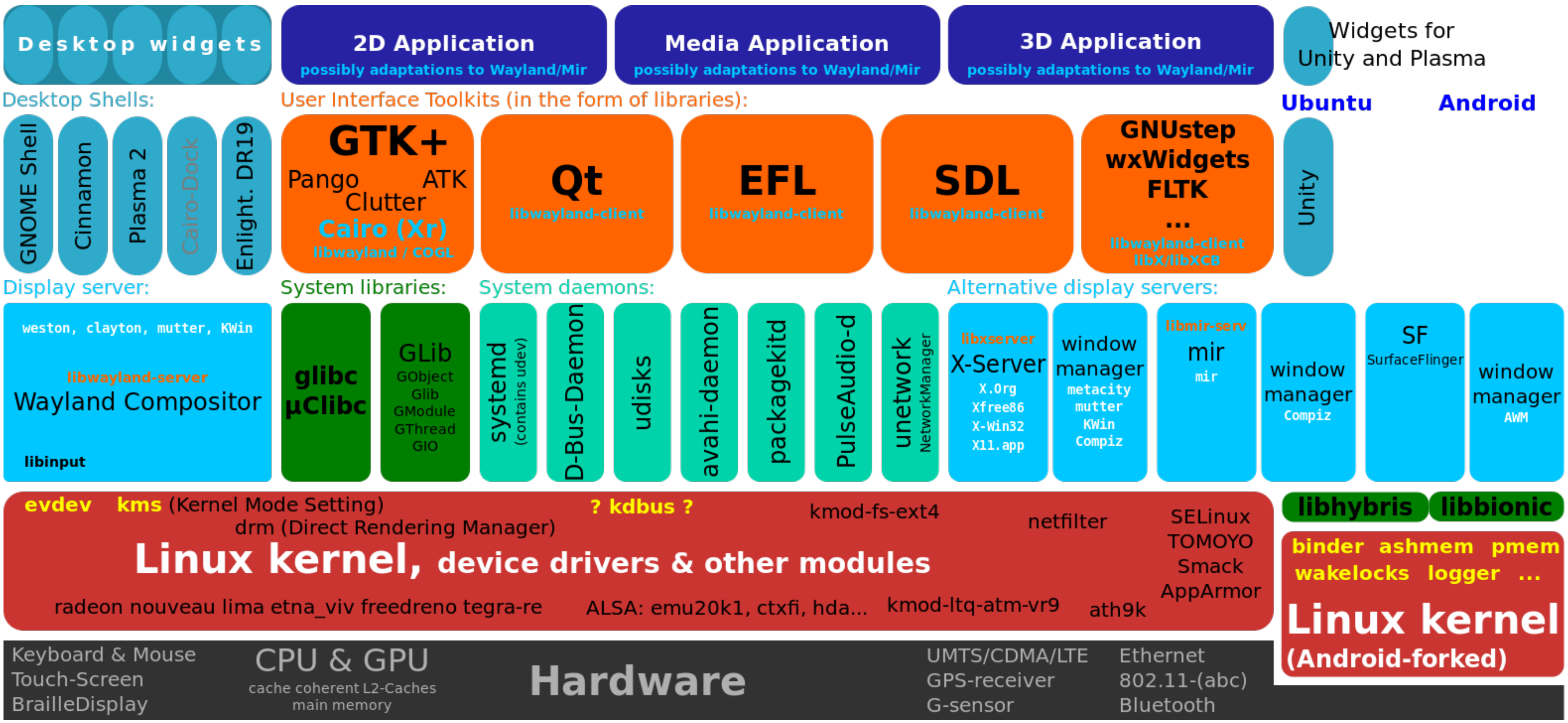




Motivation

Visible software components of the Linux desktop stack

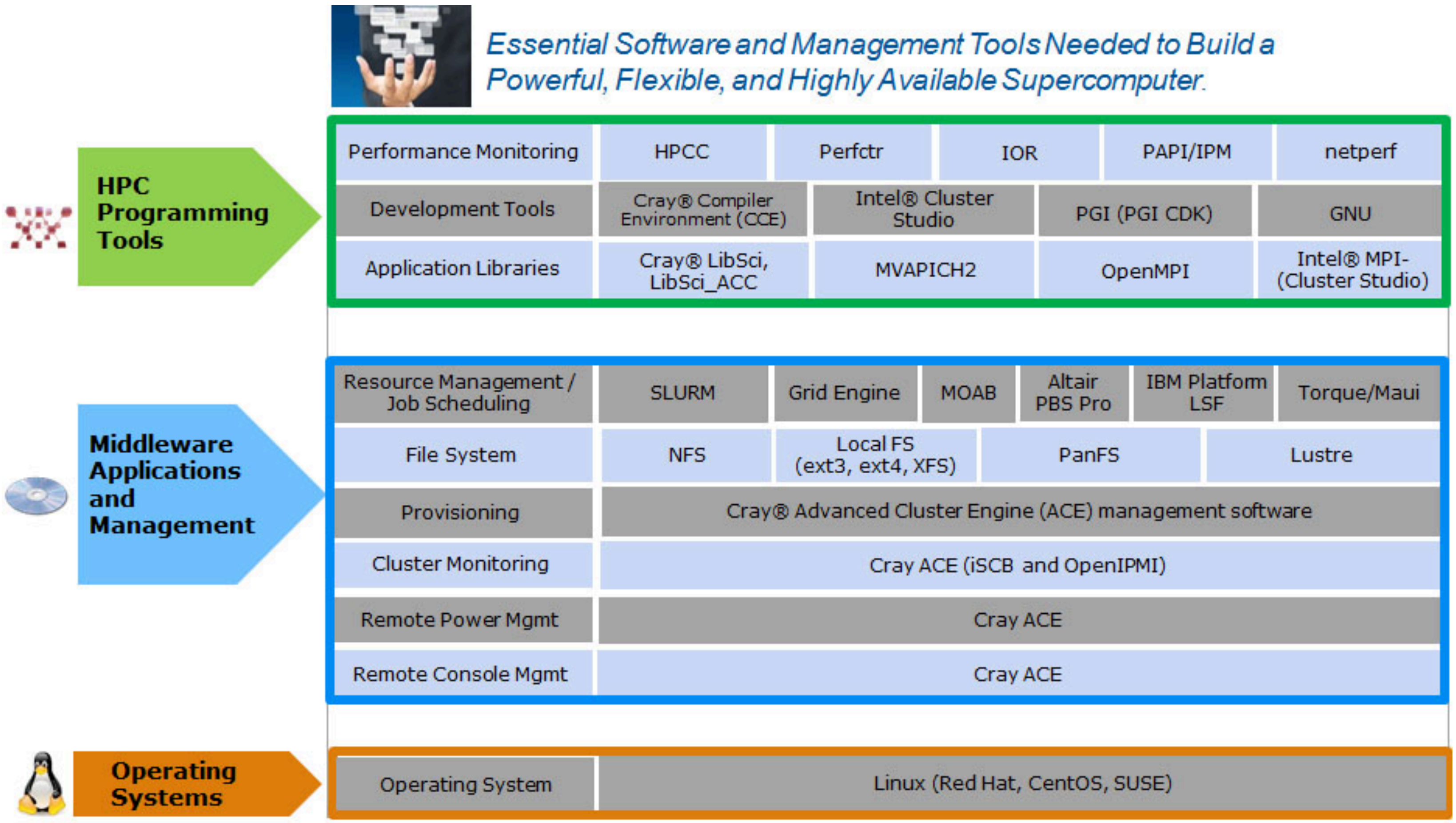
From http://en.wikipedia.org/wiki/Linux



Motivation

Software stack for HPC clusters

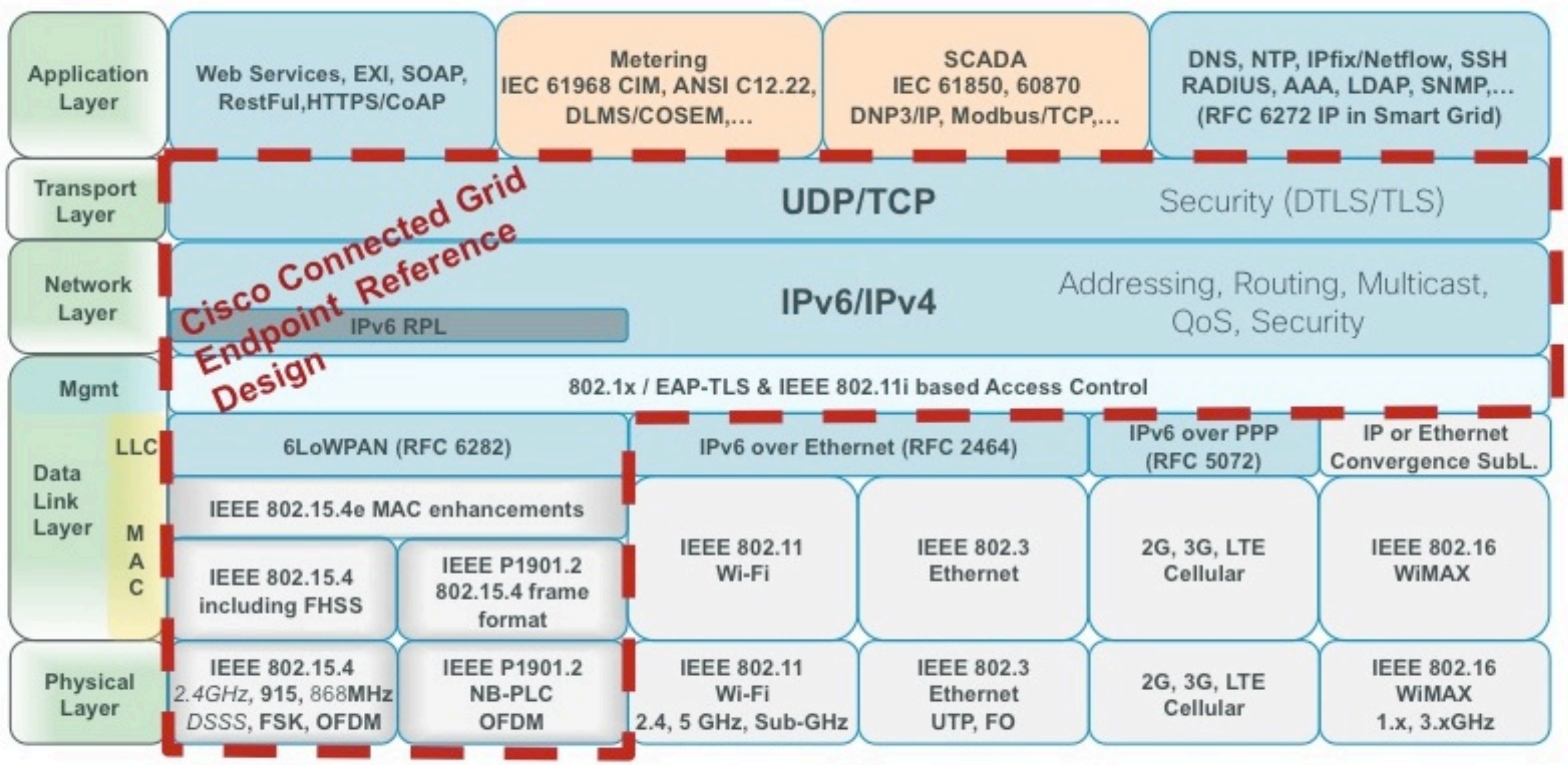
From http://www.hpcwire.com/2014/02/24/comprehensive-flexible-software-stack-hpc-clusters/



Motivation

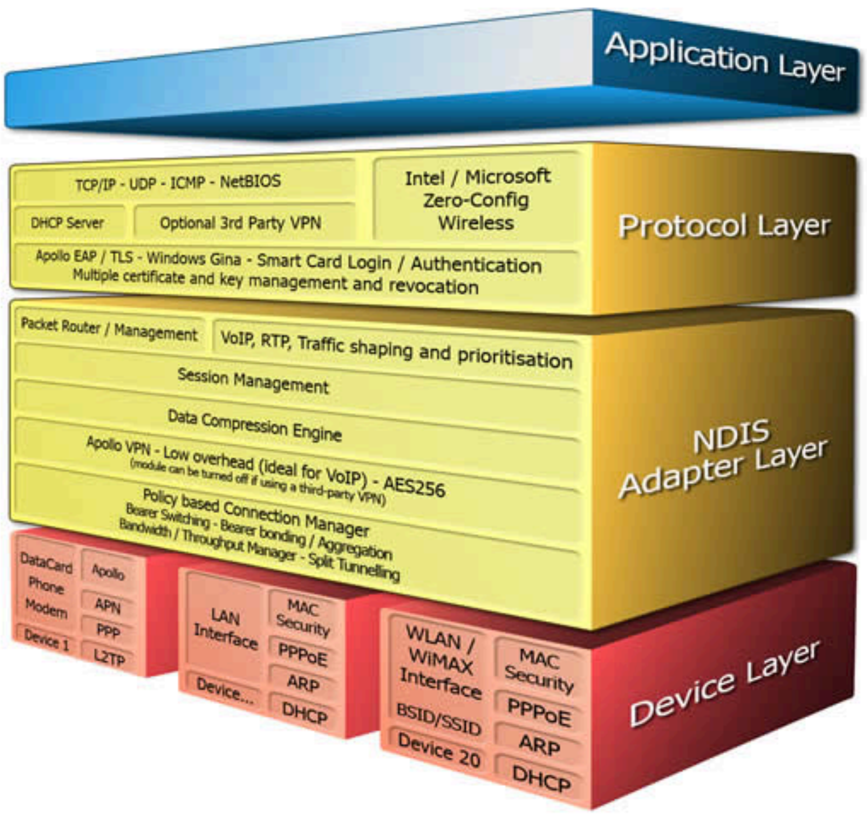
Cisco's FAN (Field-Area-Network) protocol layering

From https://solutionpartner.cisco.com/web/cegd/overview

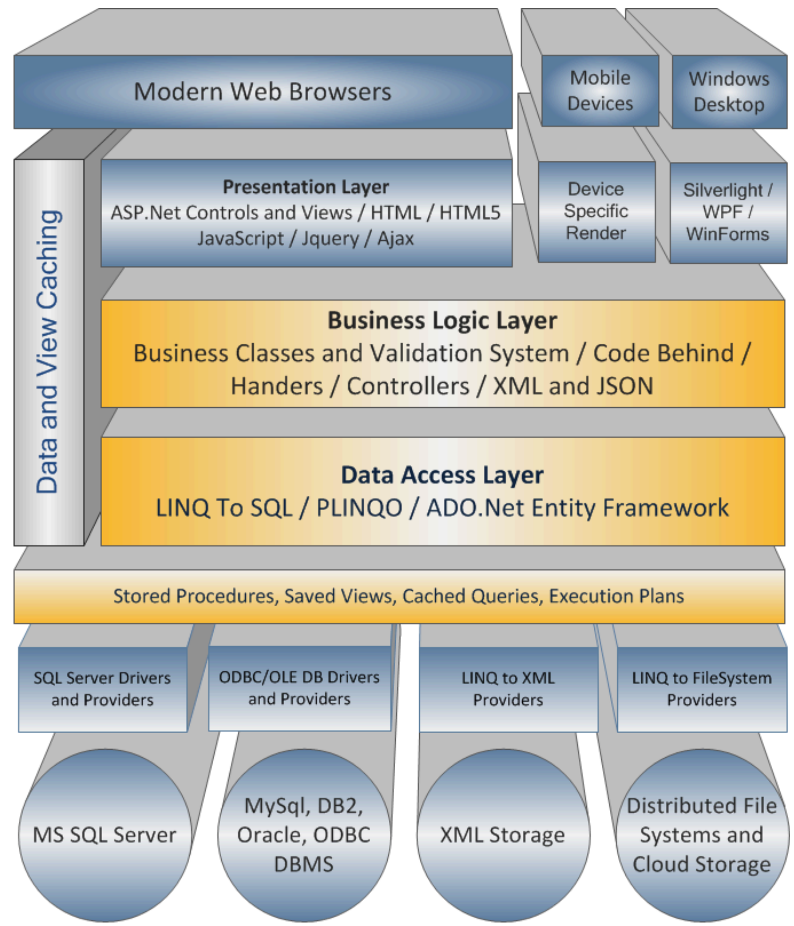


Motivation

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



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



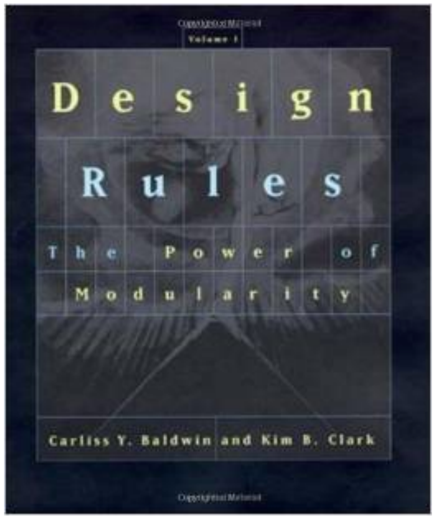
Motivation (cont'd)

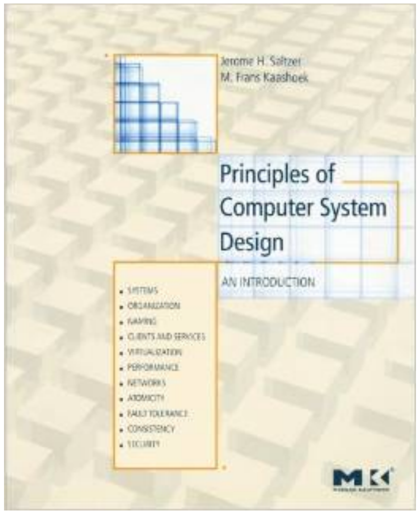
- Common themes: all system stacks are built based on abstraction, modularity, and layering

- Abstraction layers are ubiquitous!

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





Do We Understand Abstraction?

In the PL community:

(abstraction **in the small**)

- Mostly formal but tailored within a single programming language (ADT, objects, existential types)
- Specification only describes type or simple pre- & post condition
- Hide concrete data representation (we get the nice *repr. independence* property)
- Well-formed *typing* or *Hoare-style judgment* between the impl. & the spec.

In the System world:

(abstraction **in the large**)

- Mostly informal & language-neutral (APIs, sys call libraries)

Something magical going on … What is it?

between the impl. & the spec

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?

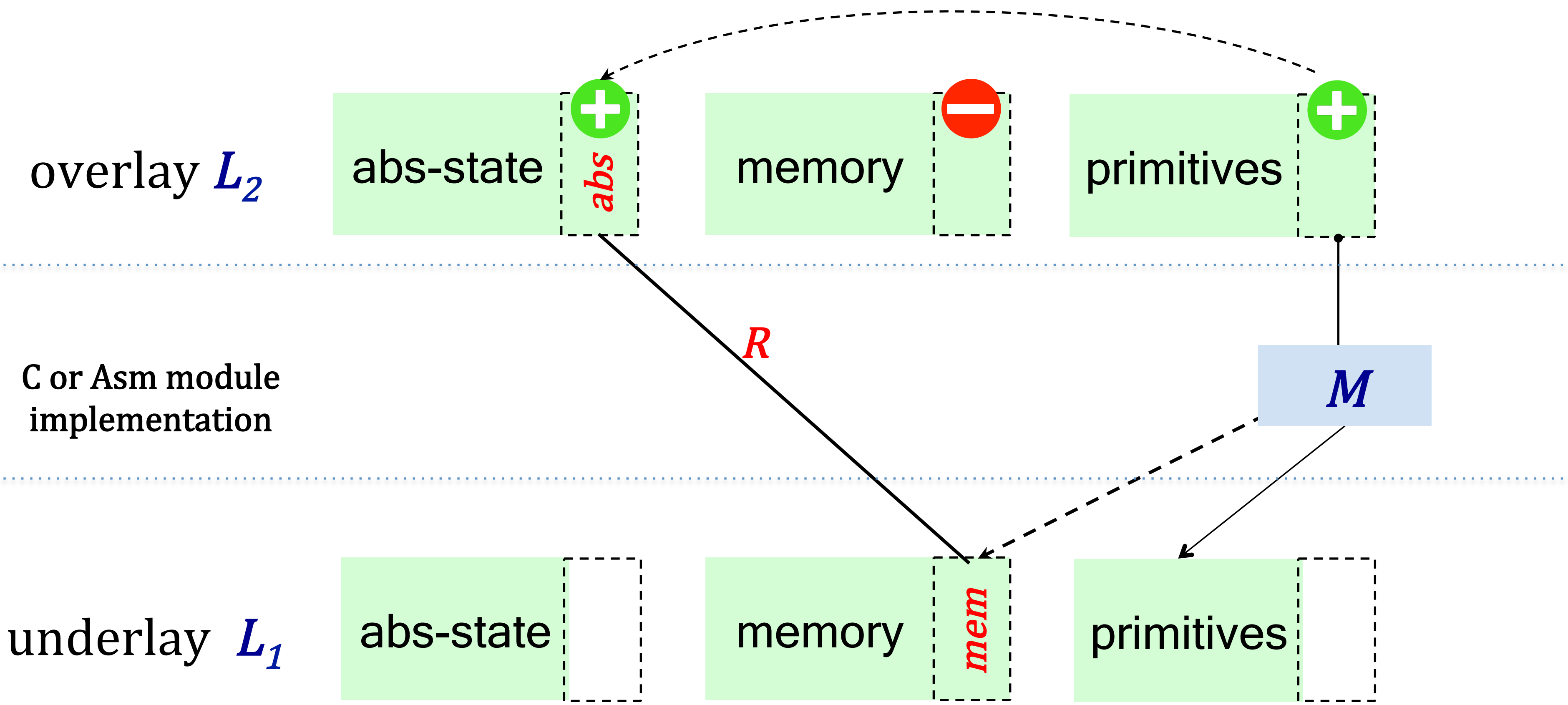
Our Contributions

- 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
  - LAsm for writing certified layers in assembly
  - CompCertX that compiles ClightX layers into LAsm 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

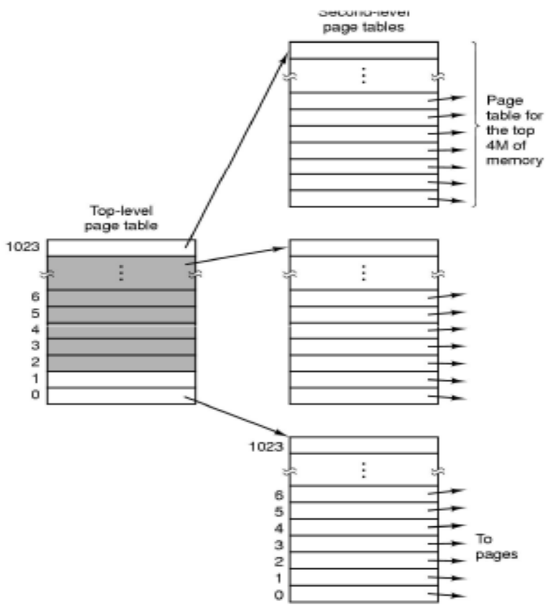
What is an Abstraction Layer?



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)

Function page_table_init = …
Function page_table_insert =…
Function page_table_rmv = …
Function page_table_read = …

concrete C implementation

memory

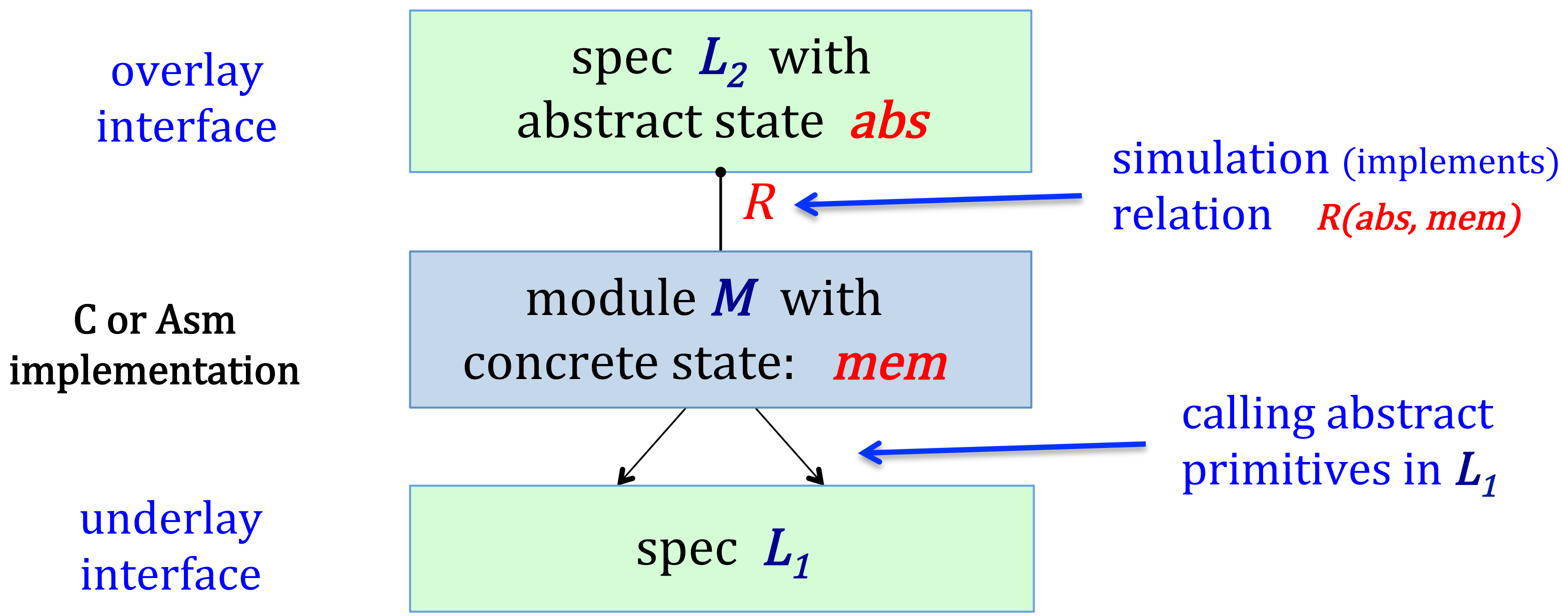
```
char * page_dir[1024];

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

C functions

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

Formalizing Abstraction Layers

What is a ***certified*** abstraction layer $(L_1,\ M,\ L_2)$?



Recorded as the *well-formed layer* judgment $\boxed{L_1 \vdash_R M : L_2}$

The Simulation Relation

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

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

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

$$
\begin{tikzcd}
\text{abs1} \arrow[r, "L_2(\mathrm{f})"] \arrow[d, dash, "R"'] & \text{abs2} \arrow[d, dash, dotted, "R"] \\
\text{mem1} \arrow[r, dashed, "{[\![M]\!](L_1)(\mathrm{f})}"'] & \text{mem2}
\end{tikzcd}
$$

Forward Simulation:

- Whenever L_2(f) takes abs1 to abs2 in one step, and R(abs1, mem1) holds,
- then there exists mem2 such that $[\![M]\!](L_1)$(f) takes mem1 to mem2 in zero or more steps , and R(abs2, mem2) also holds.

Reversing the Simulation Relation

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

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

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

$\boxed{[\![M]\!] L_1 \sim_R L_2}$

$[\![M]\!](L_1)$ and L_2 simulates each other!

L_2 captures everything about running M over L_1

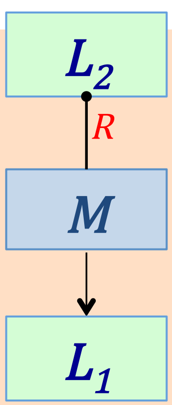
Deep Specification

$[\![M]\!] L_1 \sim_R L_2$

$[\![M]\!] (L_1)$ and L_2 simulates each other!

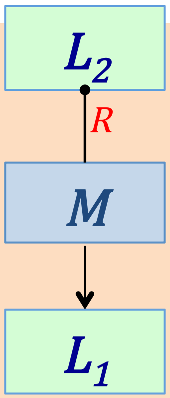
L_2 captures everything about running M over L_1

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



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

Deep spec L 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 alone.

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

Is Deep Spec Too Tight?

- Not really! It still *abstracts* away:
  - the *efficient* concrete data repr & impl. algorithms & strategies
- It can still be nondeterministic:
  - External nondeterminism (e.g., I/O or scheduler events) modeled as a set of deterministic traces relative to external events (*a la* CompCert)
  - Internal nondeterminism (e.g., sqrt, rand, resource-limit) is also OK, but any two implementations must still be *observationally equivalent*
- It *adds* new logical info to make it *easier-to-reason-about*:
  - auxiliary abstract states to define the full functionality & invariants
  - accurate precondition under which each primitive is valid

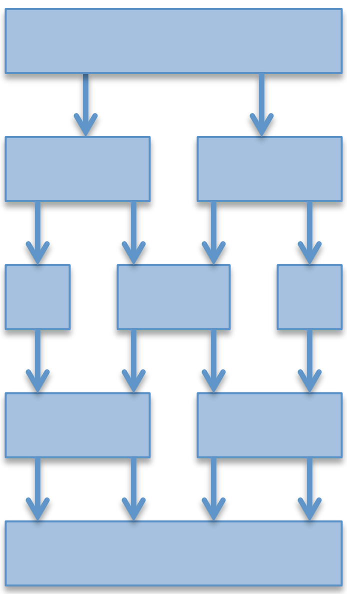
Problem w. Shallow Specs

C or Asm module

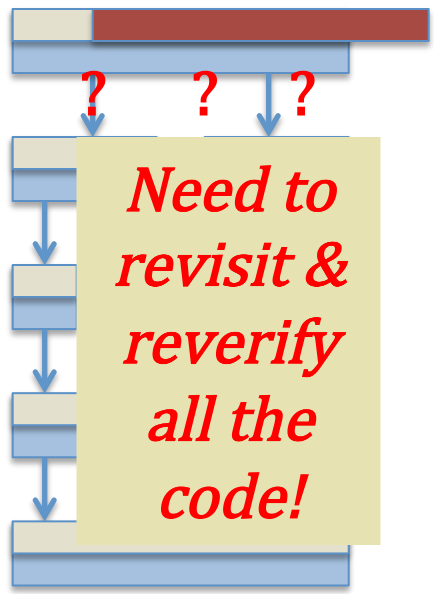
shallow spec A

shallow spec B

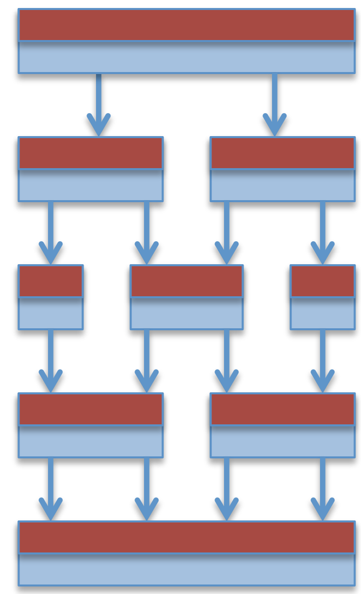
C & Asm Module Implementation



C & Asm Modules w. Shallow Spec A



Want to prove another spec B ?



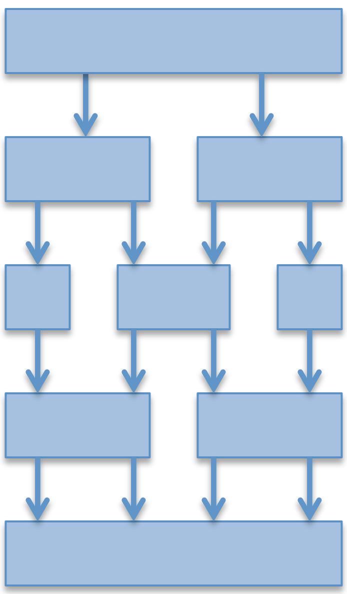
Shallow vs. Deep Specifications

C or Asm module

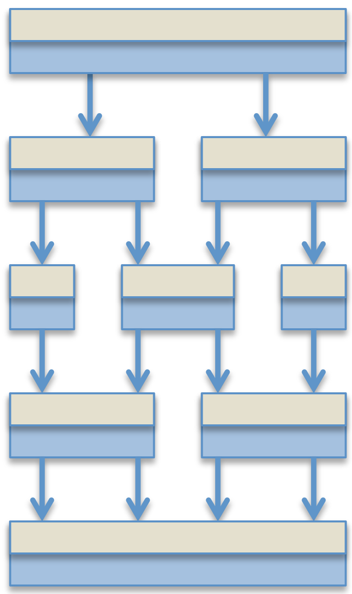
shallow spec

deep spec

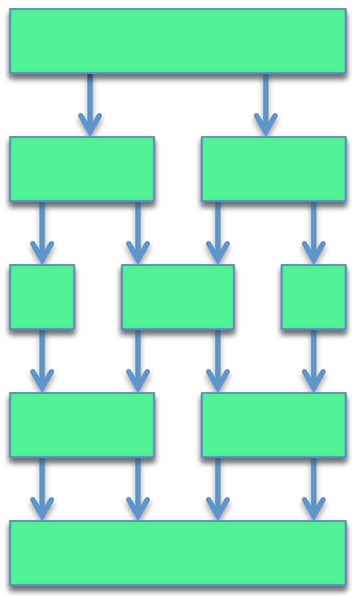
C & Asm Module Implementation



C & Asm Modules w. Shallow Specs



C & Asm Modules w. Deep Specs



How to Make Deep Spec Work?

No languages/tools today support deep spec & certified layered programming

Challenges:

- Implementation done in C or assembly or …
- Specification done in richer logic (e.g., Coq)
- Need to mix both and also simulation proofs
- Need to compile C layers into assembly layers
- Need to compose different layers

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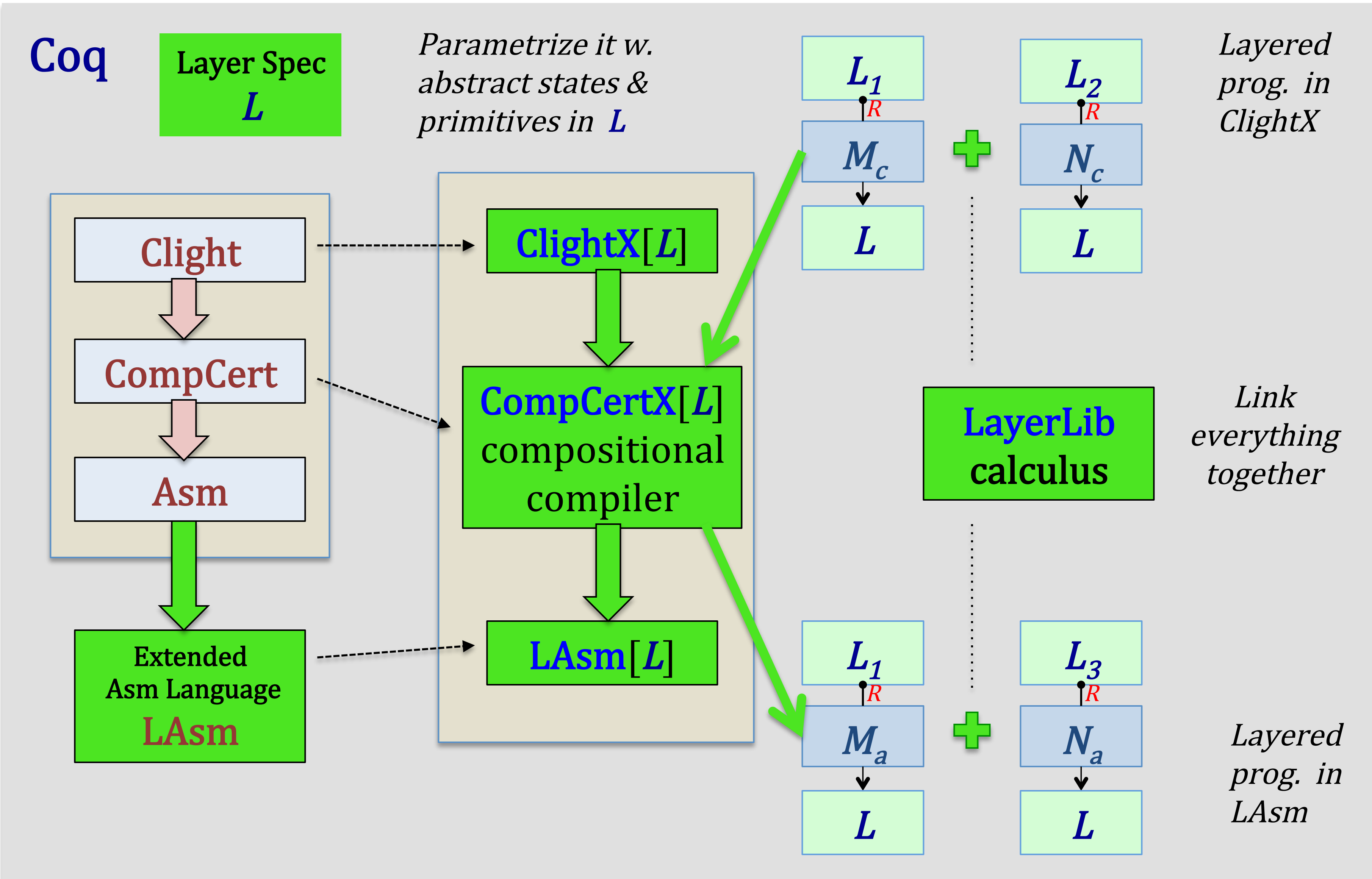
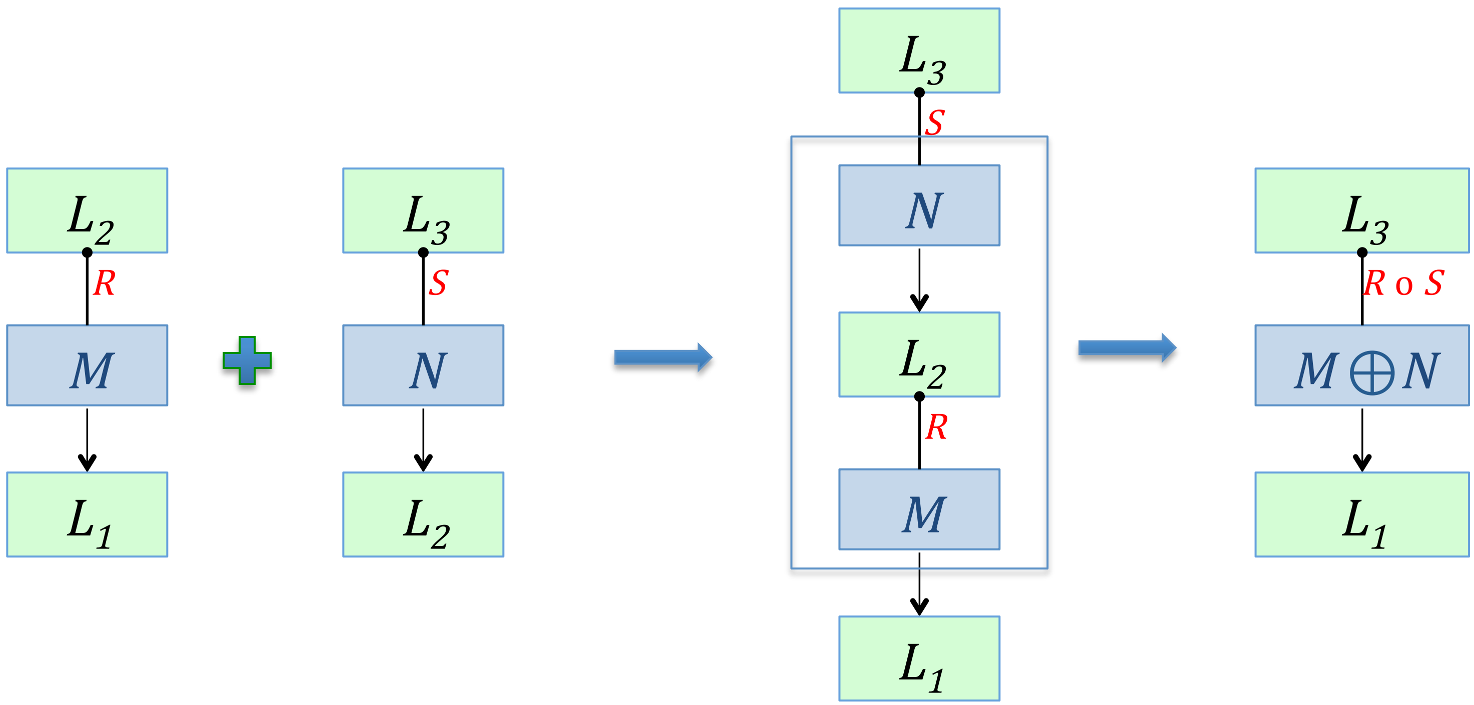
What We Have Done

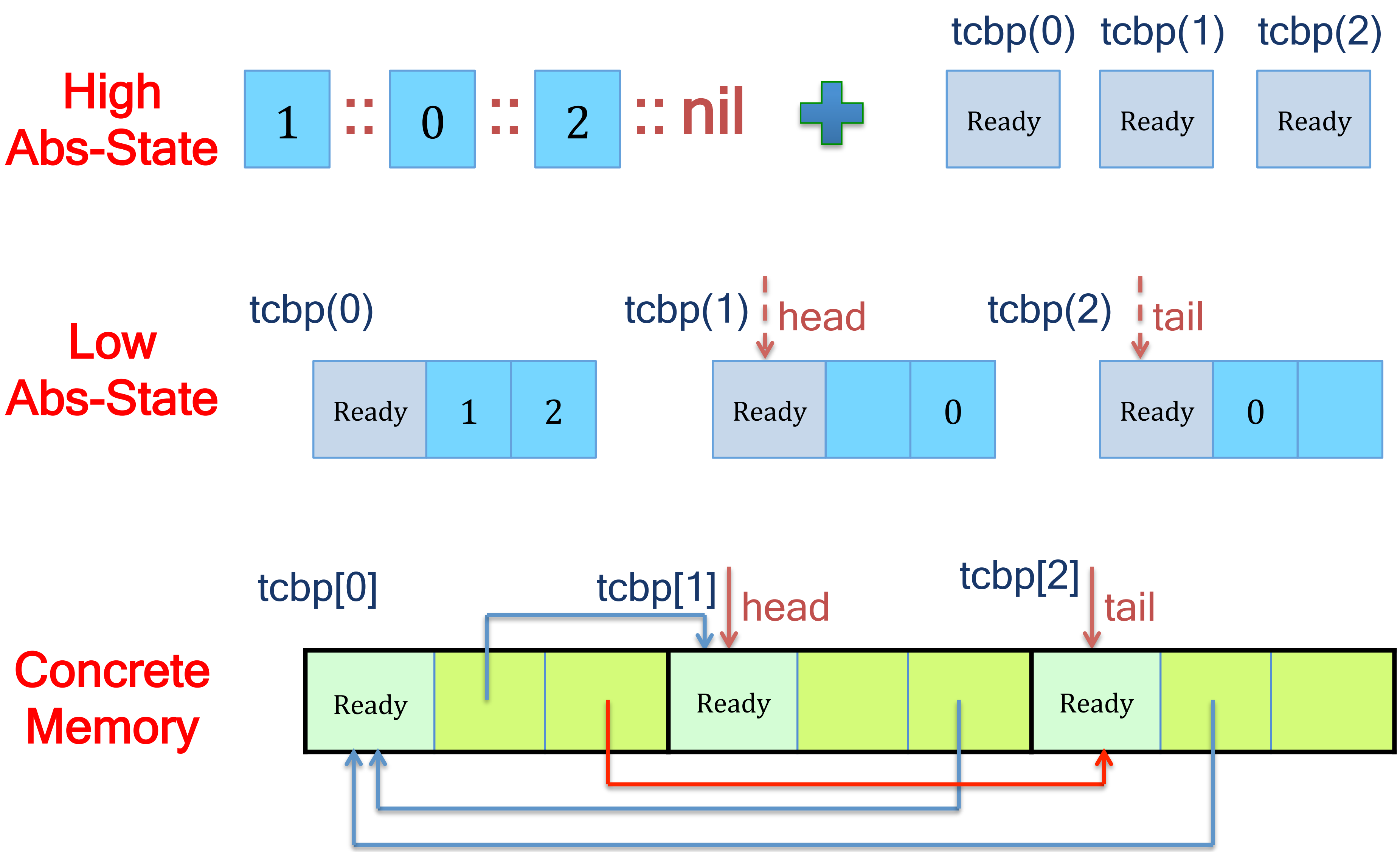


LayerLib: Vertical Composition



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

Example: Thread Queues



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];

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

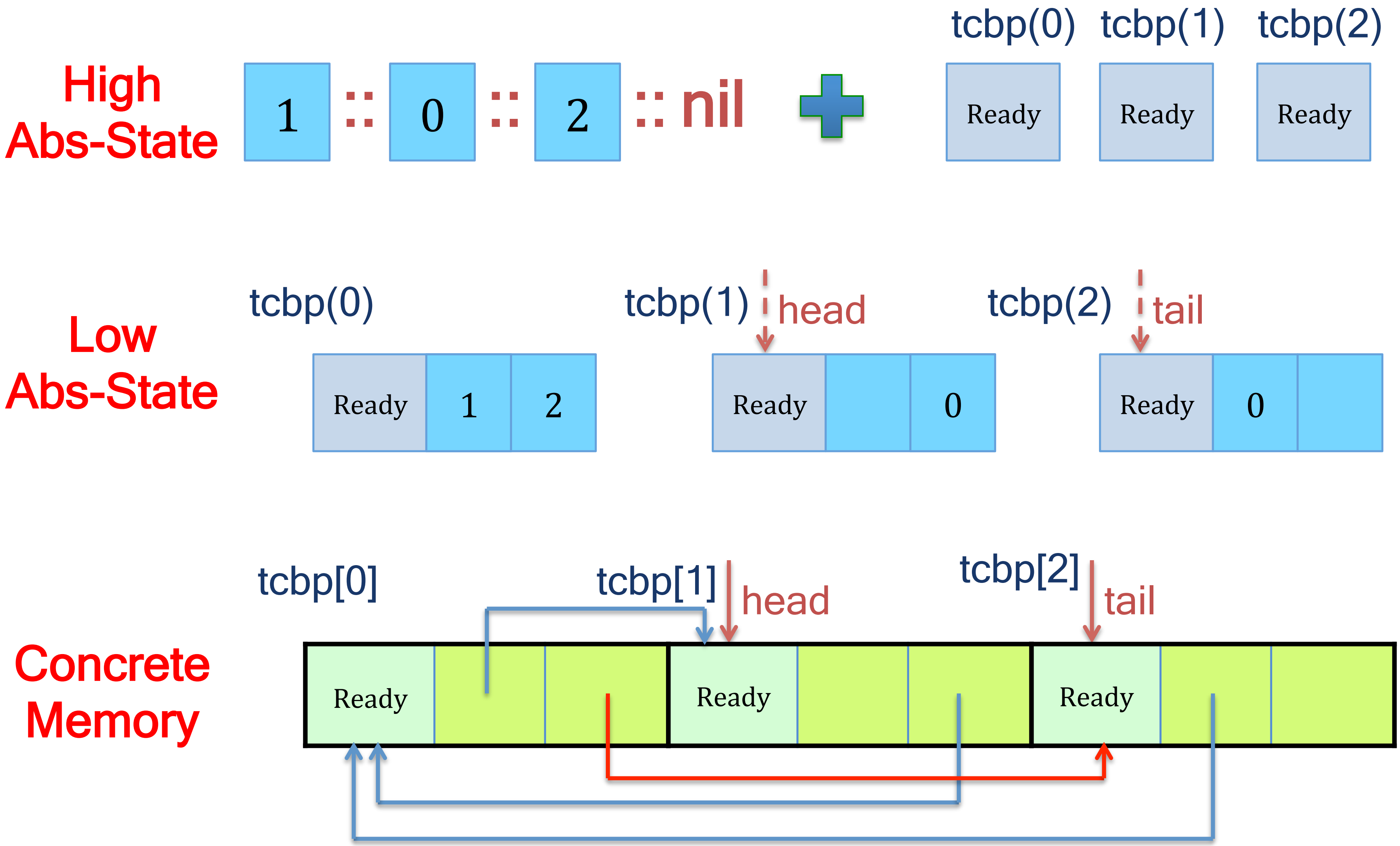
Low Layer Spec in Coq

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

Inductive tcb :=
| TCBV (tds : td_state)
           (prev next : Z)

Inductive tdq :=
| TDQV (head tail: Z)

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

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

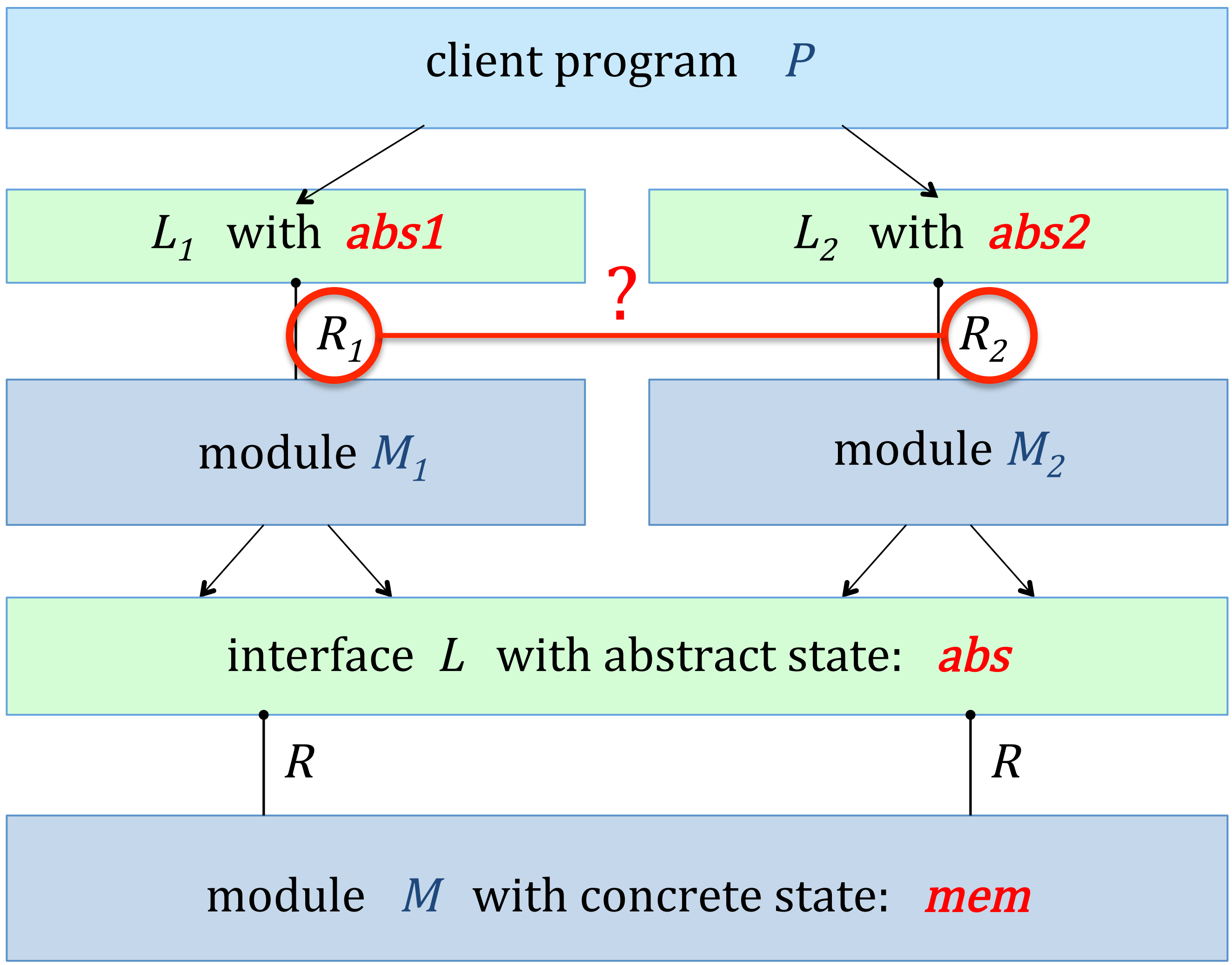
High Layer Spec in Coq

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

Definition tcb := td_state.

Definition tdq := List Z.

Record abs':={
          tcbp : ZMap.t tcb;
          tdqp : ZMap.t tdq }

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

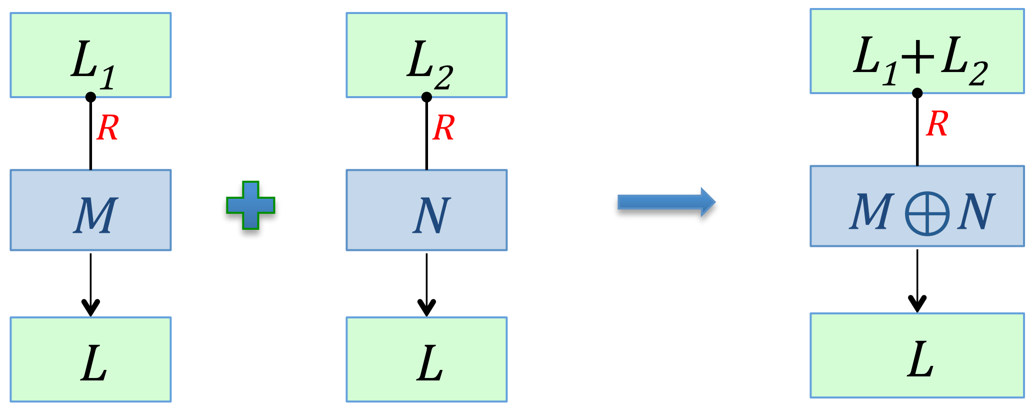
Example: Dequeue



Conflicting Abstract States?



LayerLib: Horizontal Composition



$$\frac{L \vdash_R M : L_1 \qquad L \vdash_R N : L_2}{L \vdash_R M \oplus N : L_1 \oplus L_2} \textsc{HComp}$$

- L_1 and L_2 must have the same abstract state
- both layers must follow the same simulation relation R

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 special kind of memory injection)

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

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

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

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

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

LAsm

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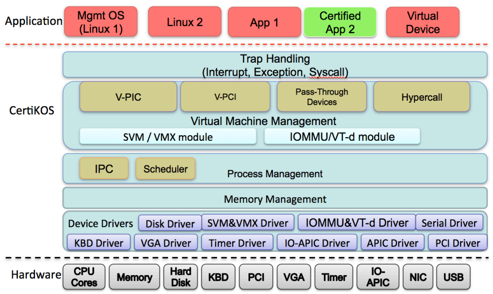
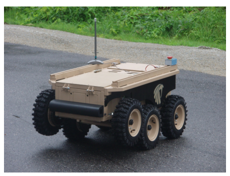
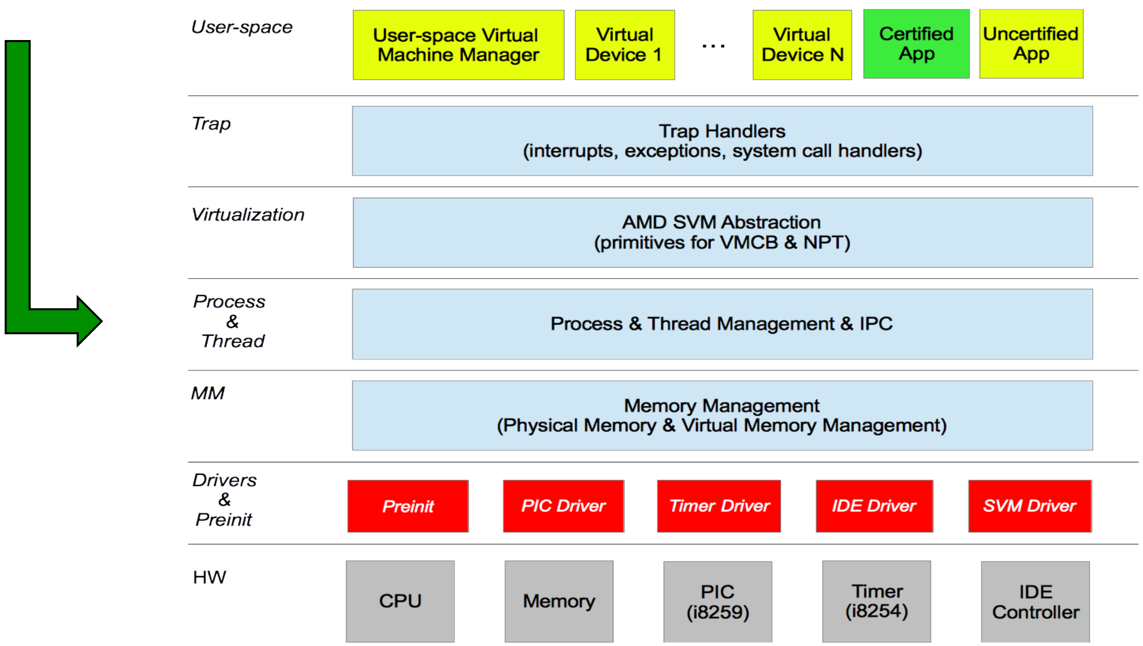
Case Study: mCertiKOS

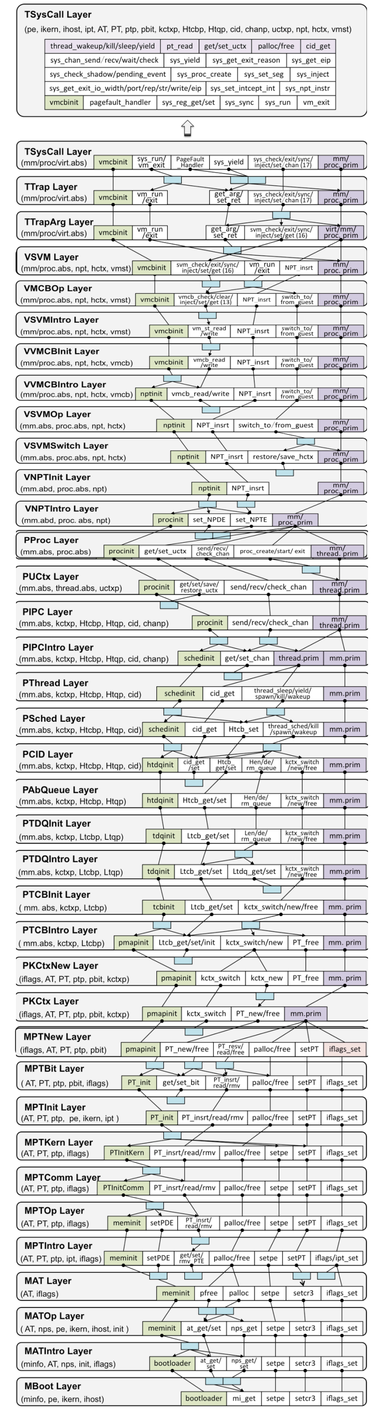




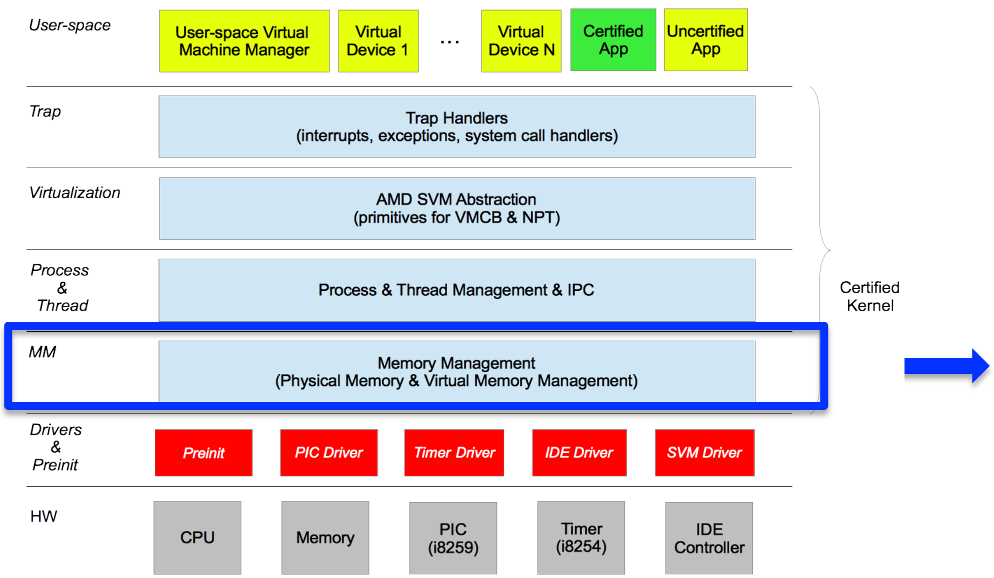
Single-core version of CertiKOS (developed under DARPA CRASH & HACMS programs), 3 kloc, can boot Linux

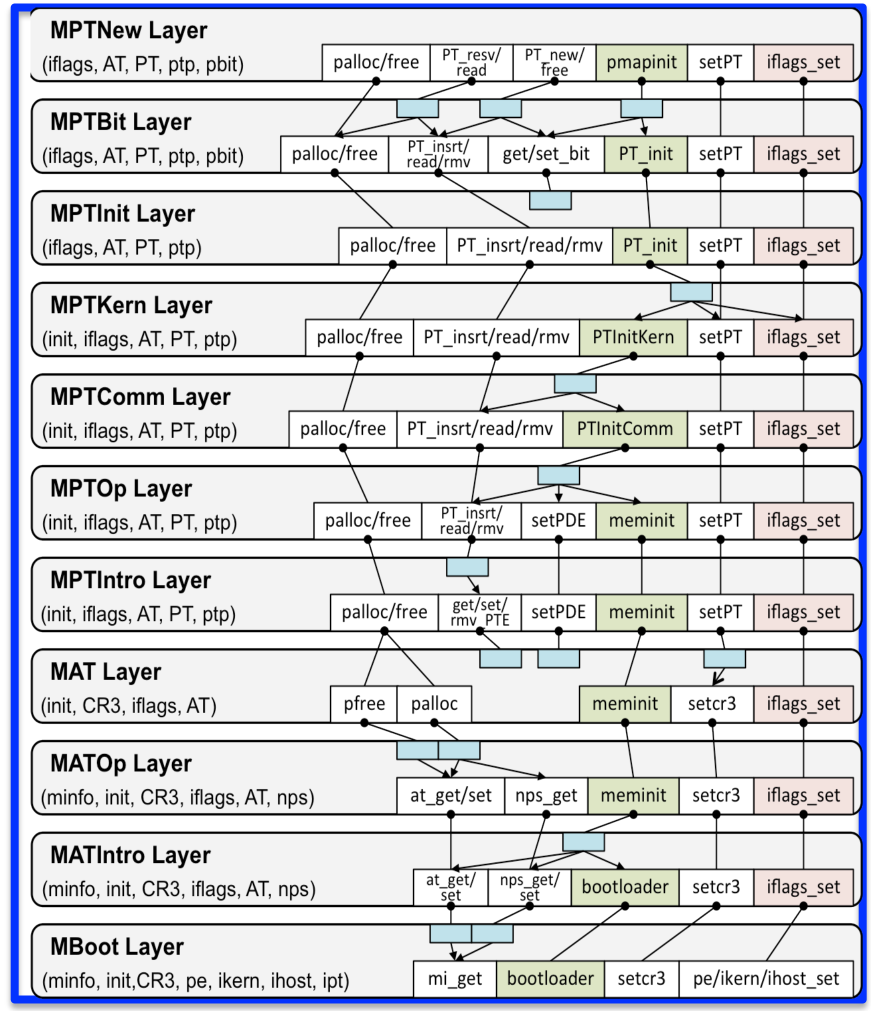
Aggressive use of abstraction over deep specs (37 layers in ClightX & LAsm)





Decomposing mCertiKOS

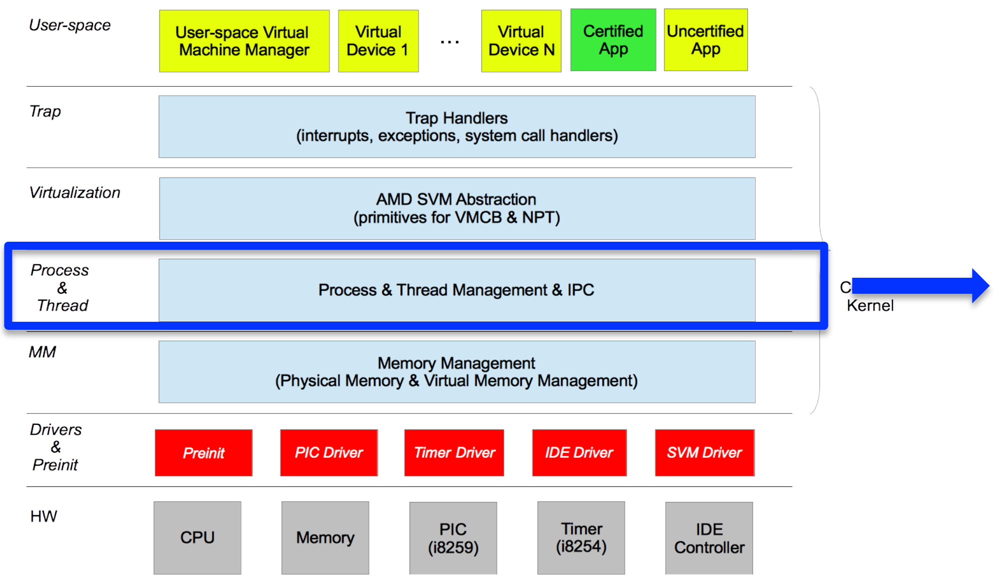


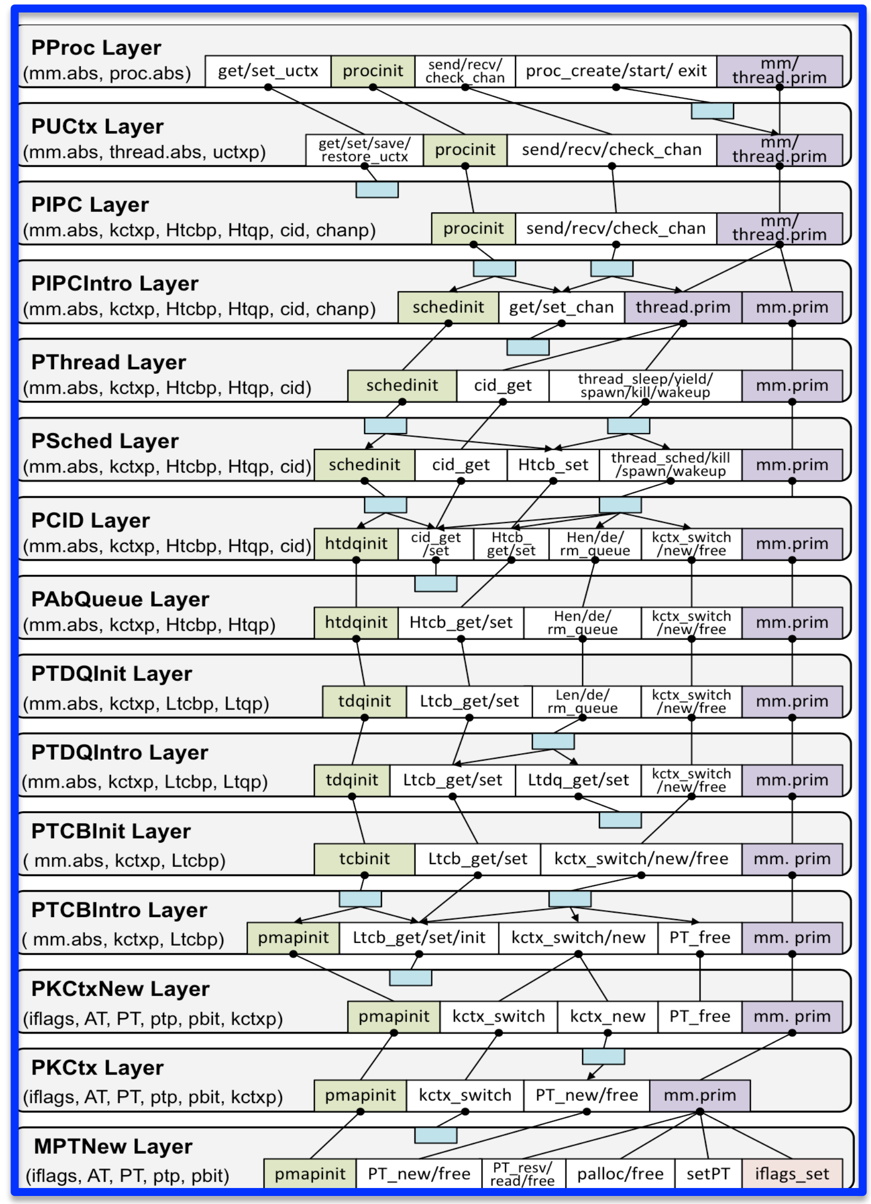


Physical Memory and Virtual Memory Management (11 Layers)

Based on the abstract machine provided by boot loader

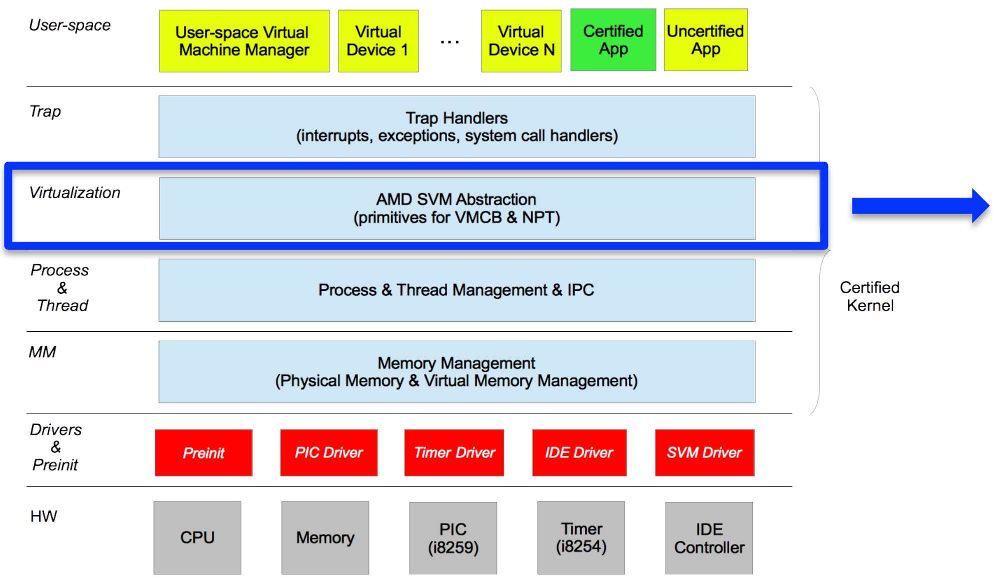
Decomposing mCertiKOS (cont'd)

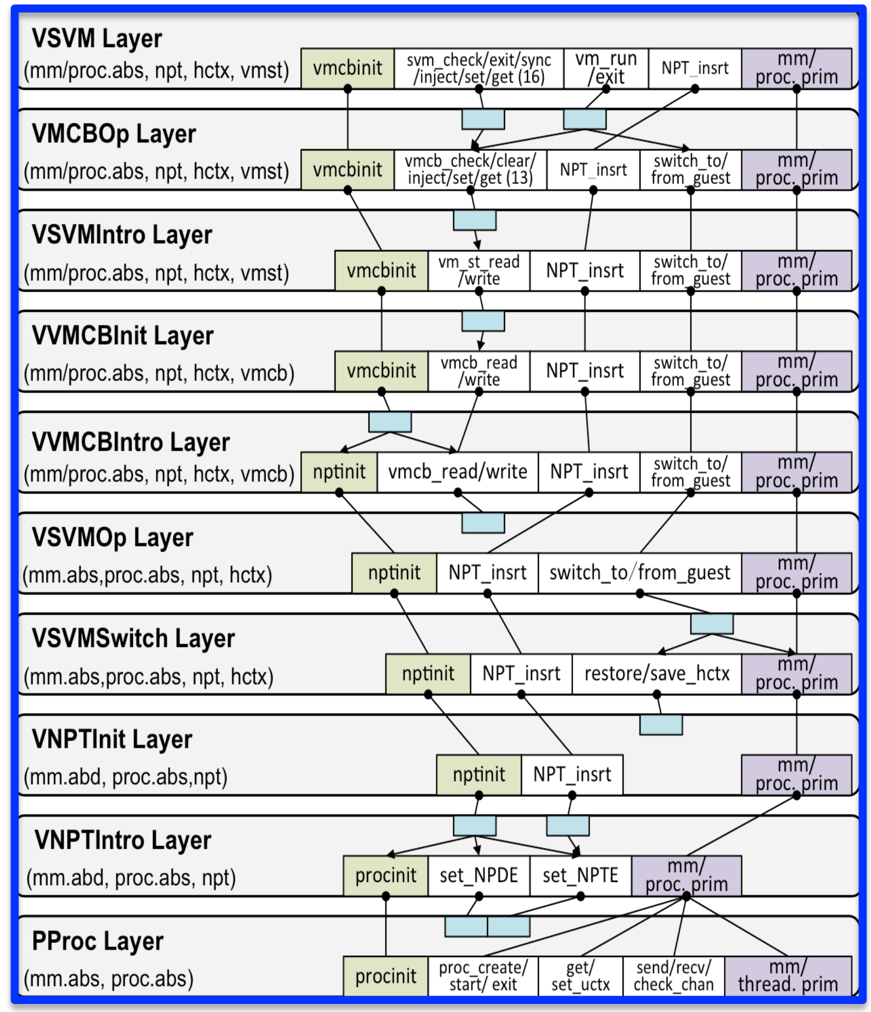




Thread and Process Management (14 Layers)

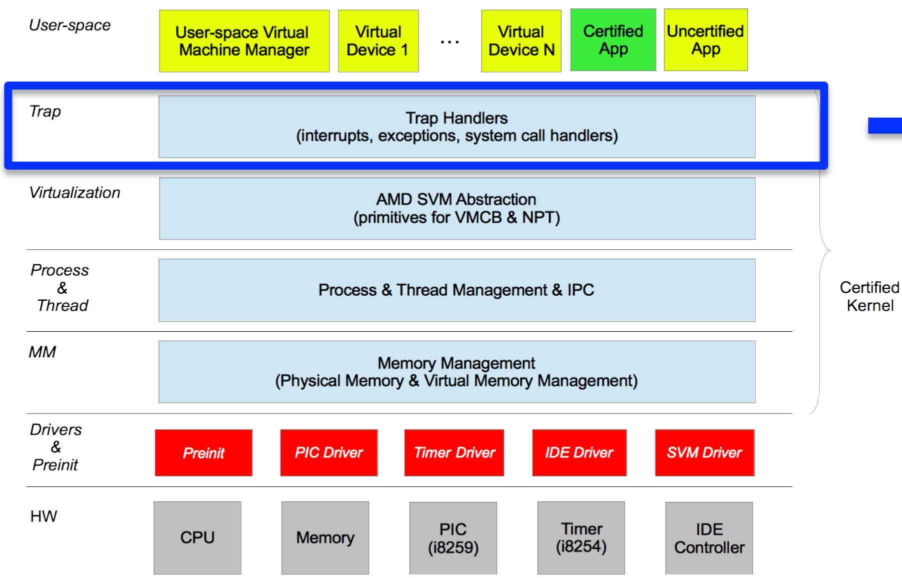
Decomposing mCertiKOS (cont'd)

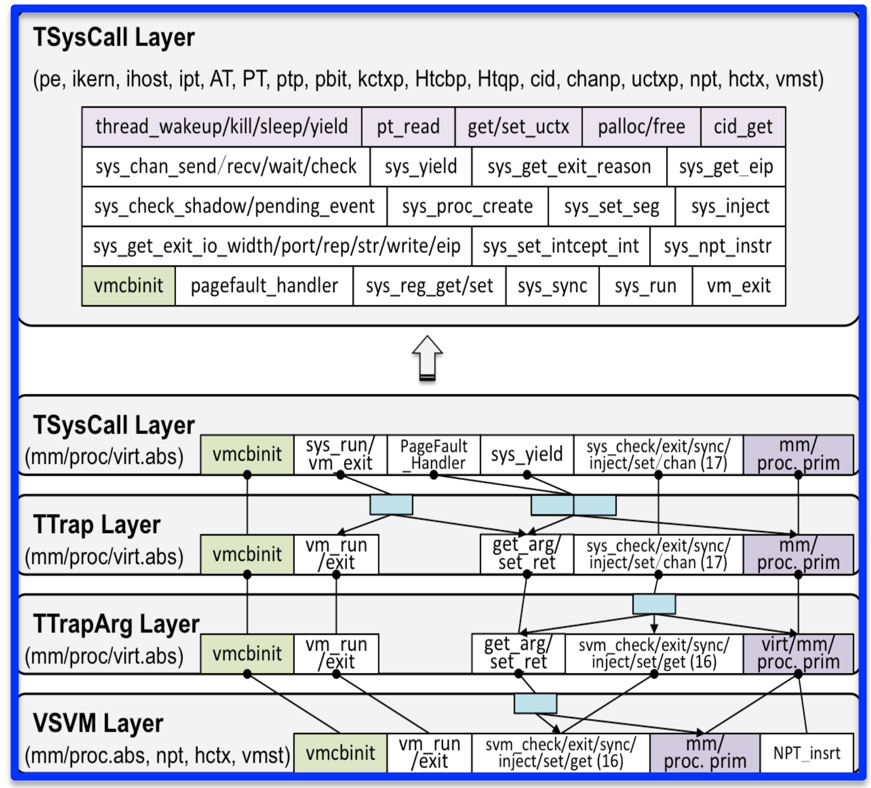




Virtualization Support (9 Layers)

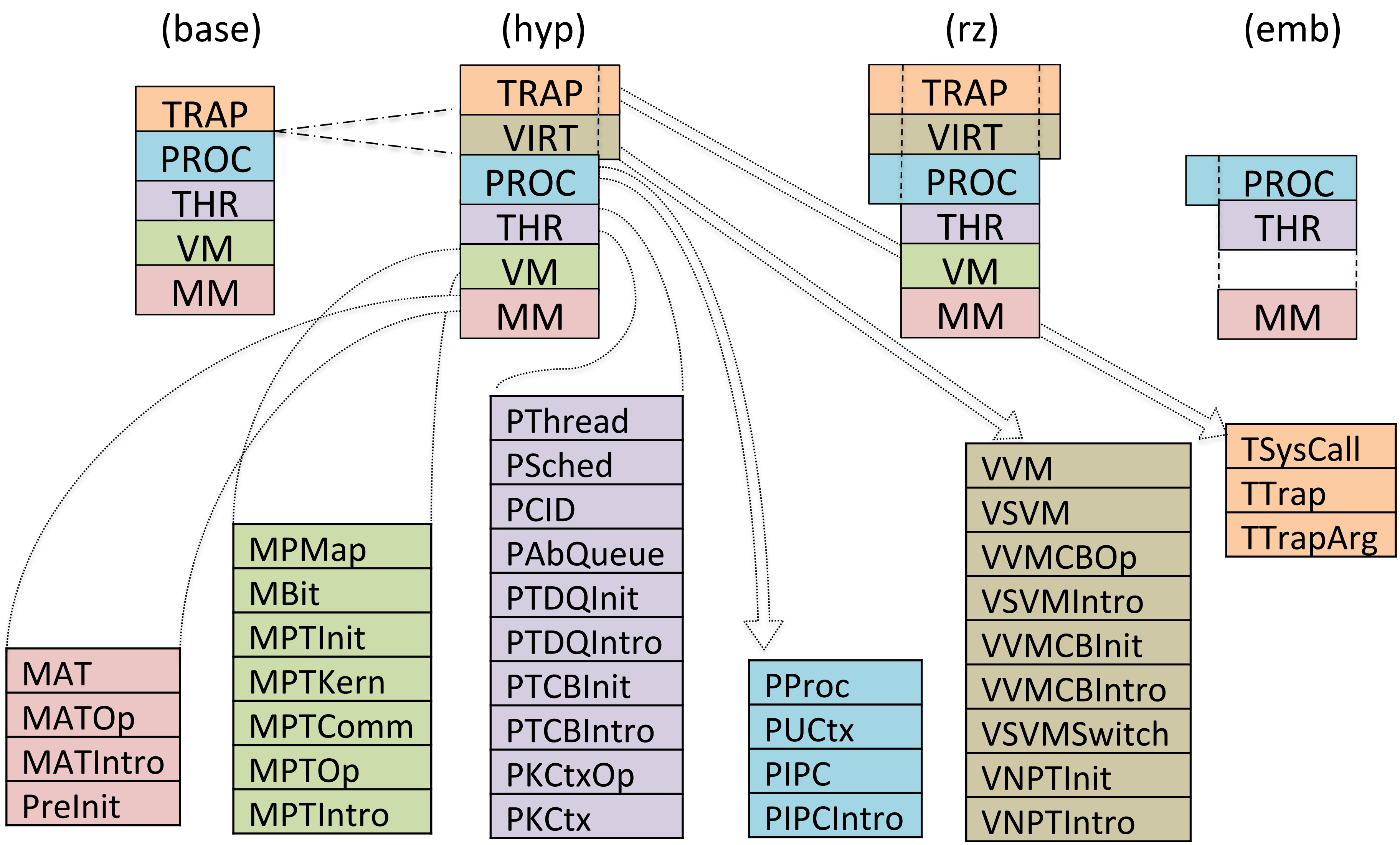
Decomposing mCertiKOS (cont'd)



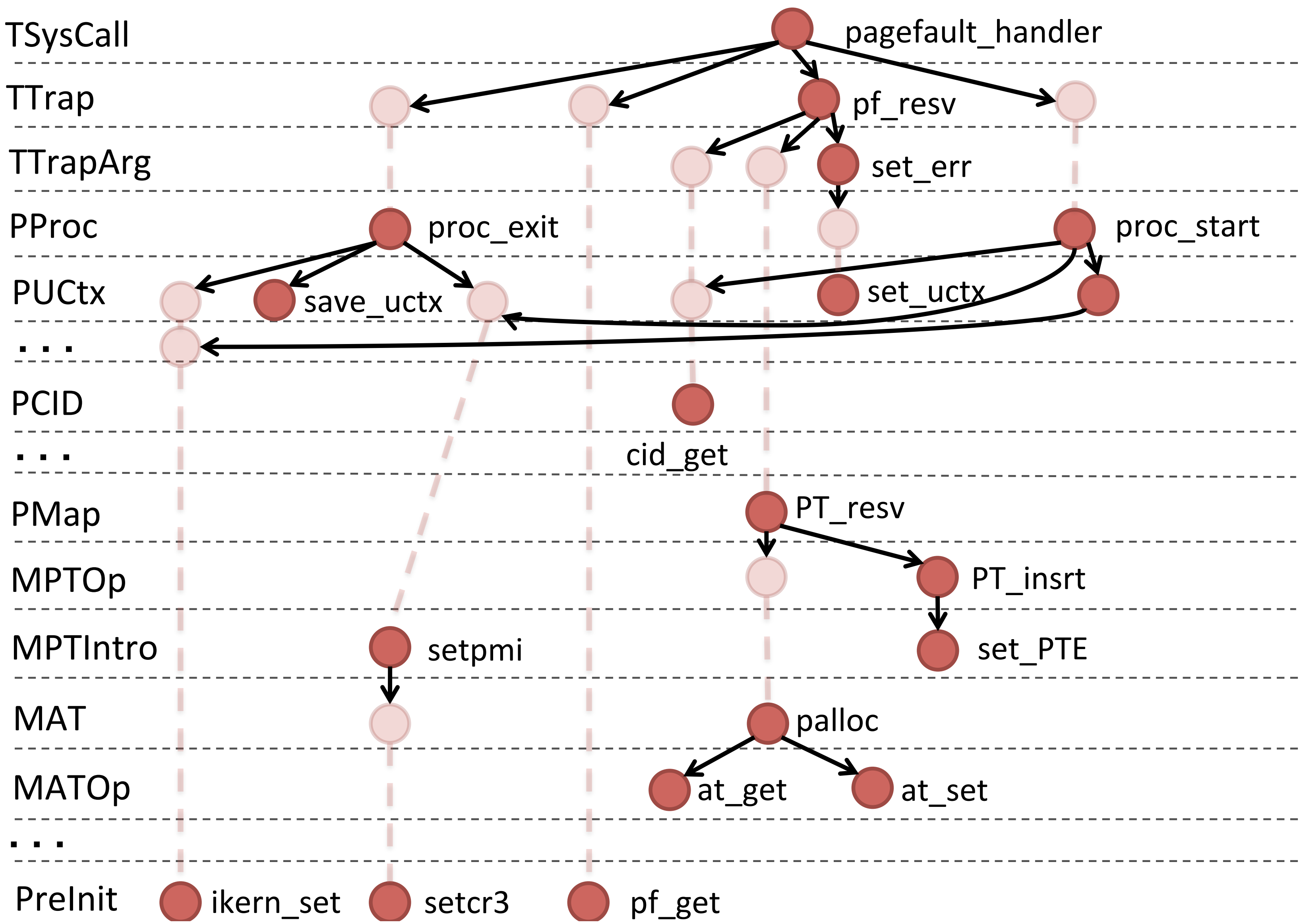


Syscall and Trap Handlers (3 Layers)

Variants of mCertiKOS Kernels



Example: Page Fault Handler



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
- Still need better PL and tool support (Coq / ClightX / LAsm)

Thank You!

Interested in working on the CertiKOS project?
we are hiring & recruiting at all levels:

postdocs,

research scientists,

PhD students, and visitors

A Subtlety for LAsm

Some functions (e.g., kernel context switch) do not follow the C calling convention and must be programmed in LAsm[L].

$\boxed{L \vdash_R M_a : L_2}$ $\longrightarrow$ $\boxed{L_2 \leq_R [\![M_a]\!]_{\text{LAsm}} (L)}$

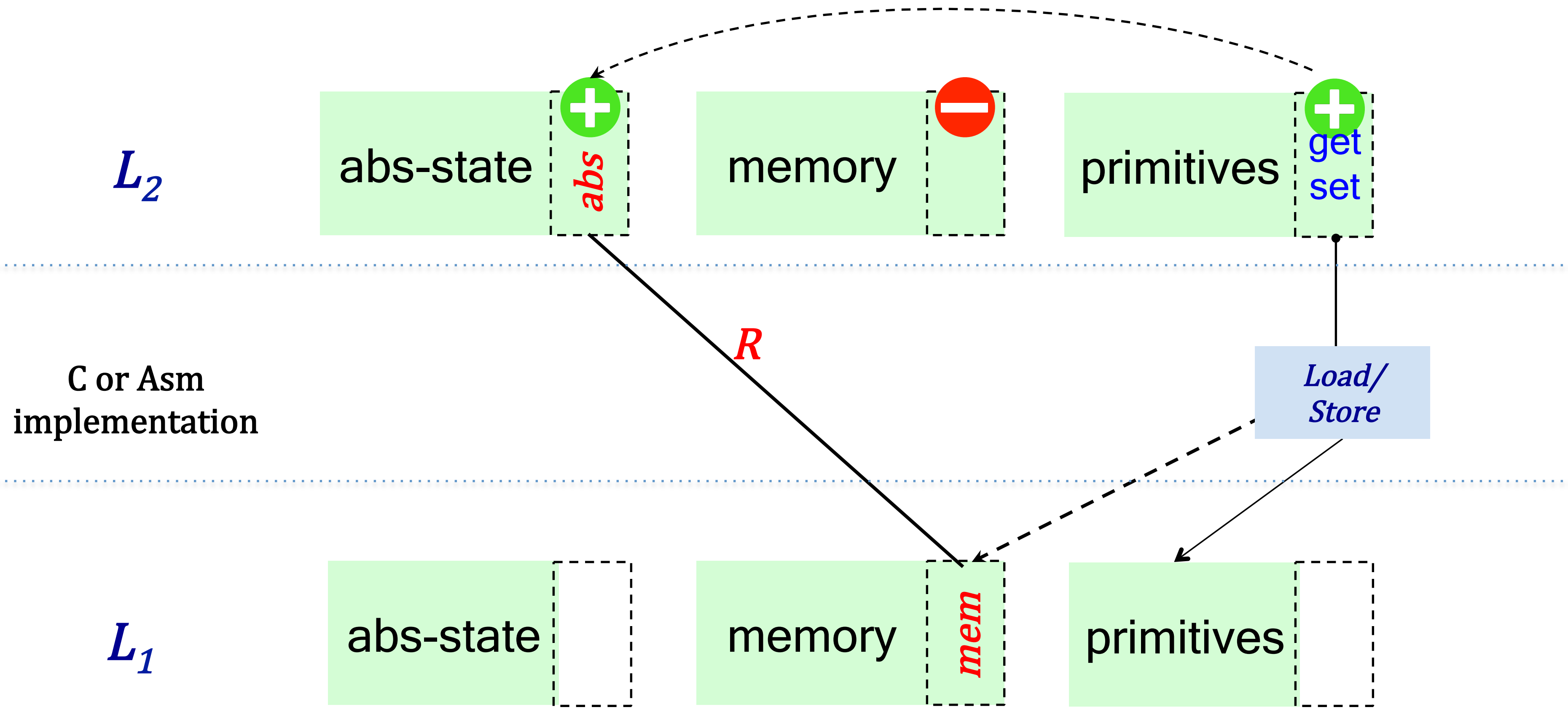
Problem: per-module semantics $[\![M_a]\!]_{\text{LAsm}} (L)$ is *NOT deterministic* relative to external events

$\boxed{[\![M_a]\!]_{\text{LAsm}} (L) \leq_R L_2}$

Fortunately, whole-machine semantics $[\![\bullet]\!]_{\text{LAsm}} (L)$ is deterministic relative to external events, so it can still be reversed:

$$\forall P.\ [\![P \oplus M_a]\!]_{\text{LAsm}} (L) \sim_R [\![P]\!]_{\text{LAsm}} (L_2)$$

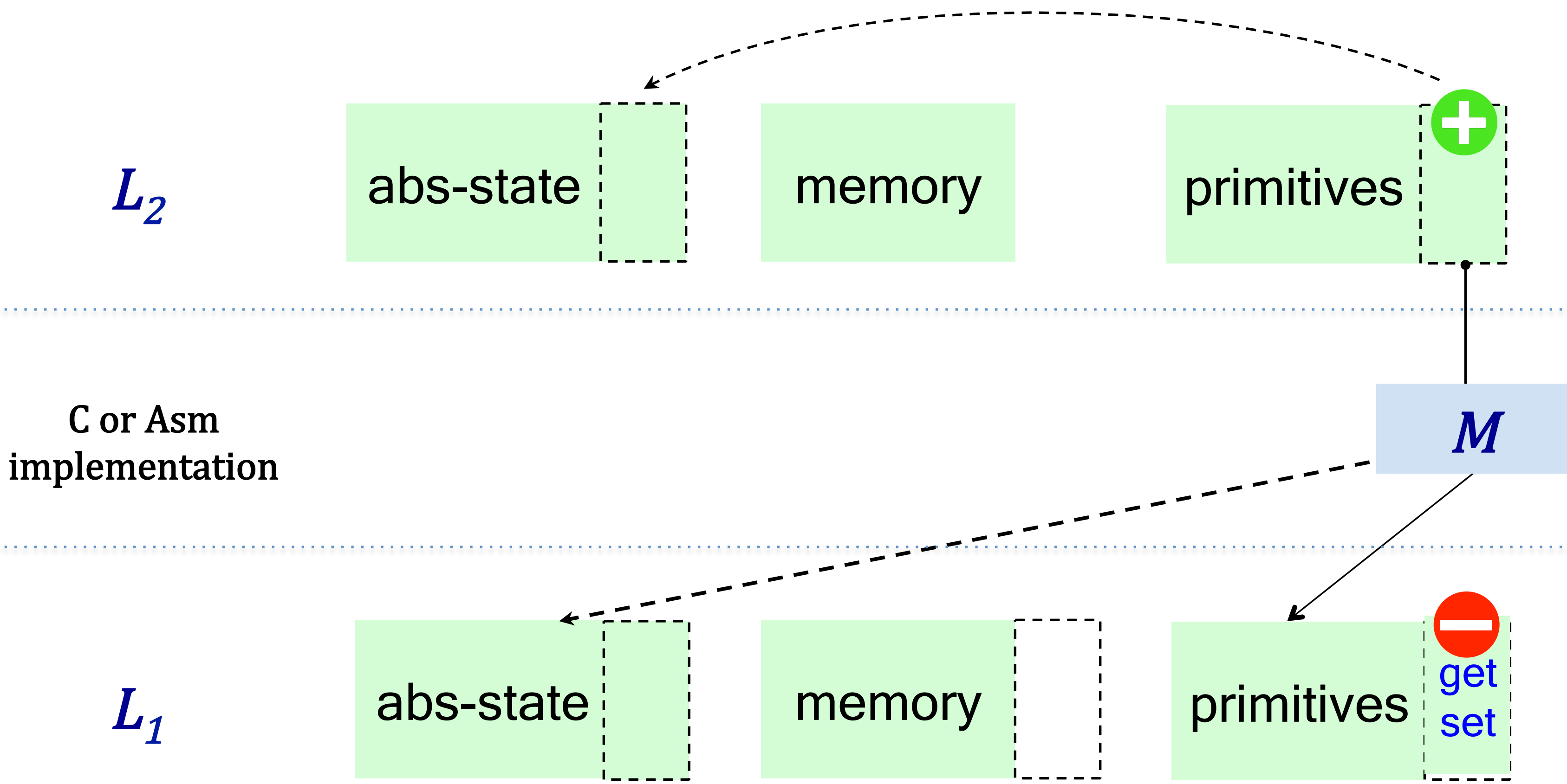
Layer Pattern 1: Getter/Setter



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!

Development Cost

Development of ClightX and CompCertX		10 pm
Development of VCGen for ClightX		1.5 pm
Verification of mm 5.7 pm	Design: first 3 layers	0.5 pm
	Design: the rest 8	0.5 pm
	Refinement Proof: first 2	1.2 pm
	Refinement Proof: the rest	1 pm
	C verification	2.5 pm
Verification of proc 2.5 pm	Design: 14 layers	1 pm
	Refinement Proof	0.5 pm
	C Verification	1 pm
Verification of virt 1.3 pm	Design: 9 layers	0.6 pm
	Refinement Proof	0.4 pm
	C Verification	0.3 pm
Verification of trap 0.4 pm	Design: 3 layers	0.2 pm
	Refinement Proof	0.1 pm
	C Verification	0.1 pm

Total: 9.9 pm + VCG Dev: 1.5 pm