TOWARD COMPOSITIONAL VERIFICATION OF INTERRUPTIBLE OS KERNELS AND DEVICE DRIVERS

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CertiKOS

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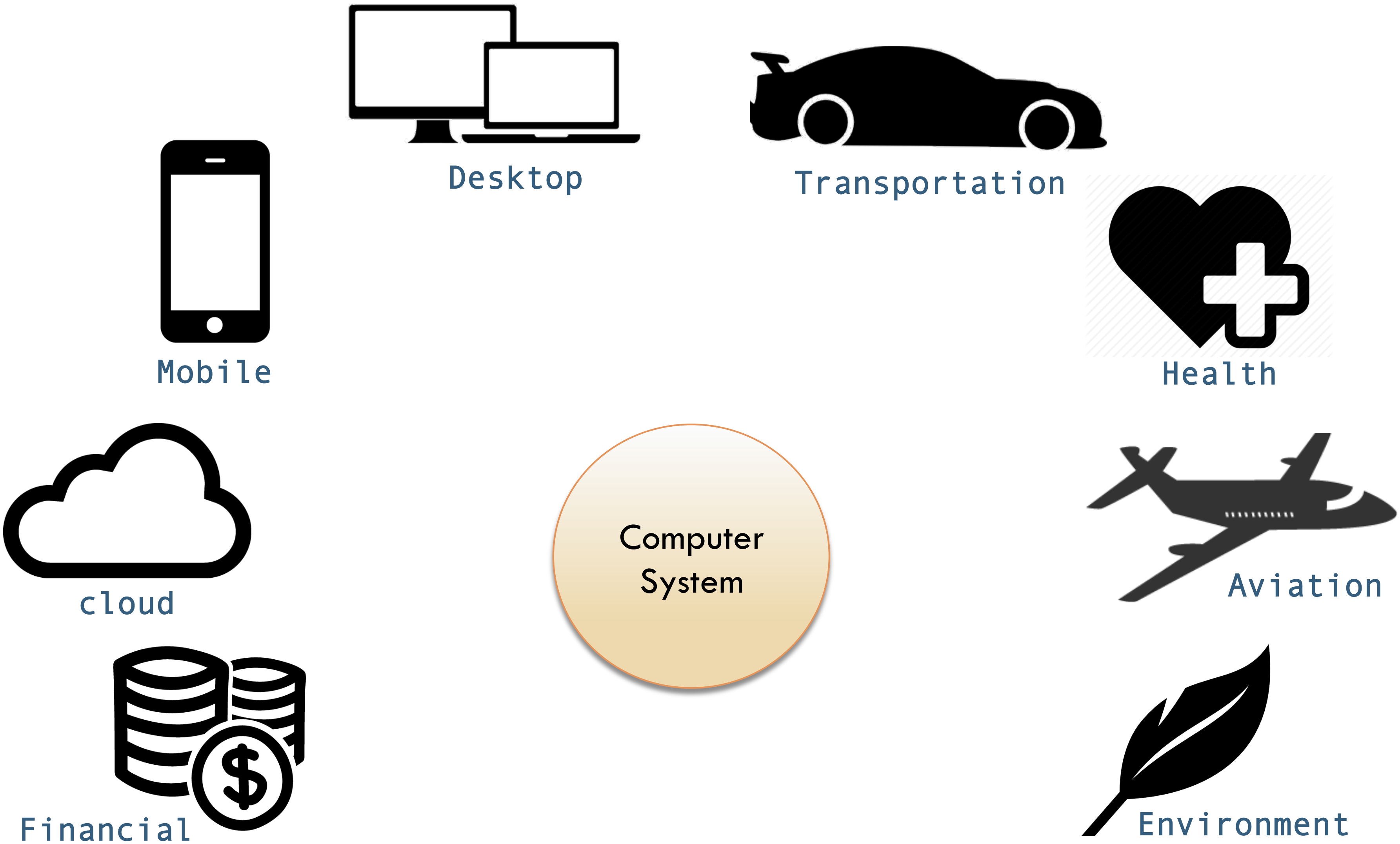
Do we really need high-assurance OS?



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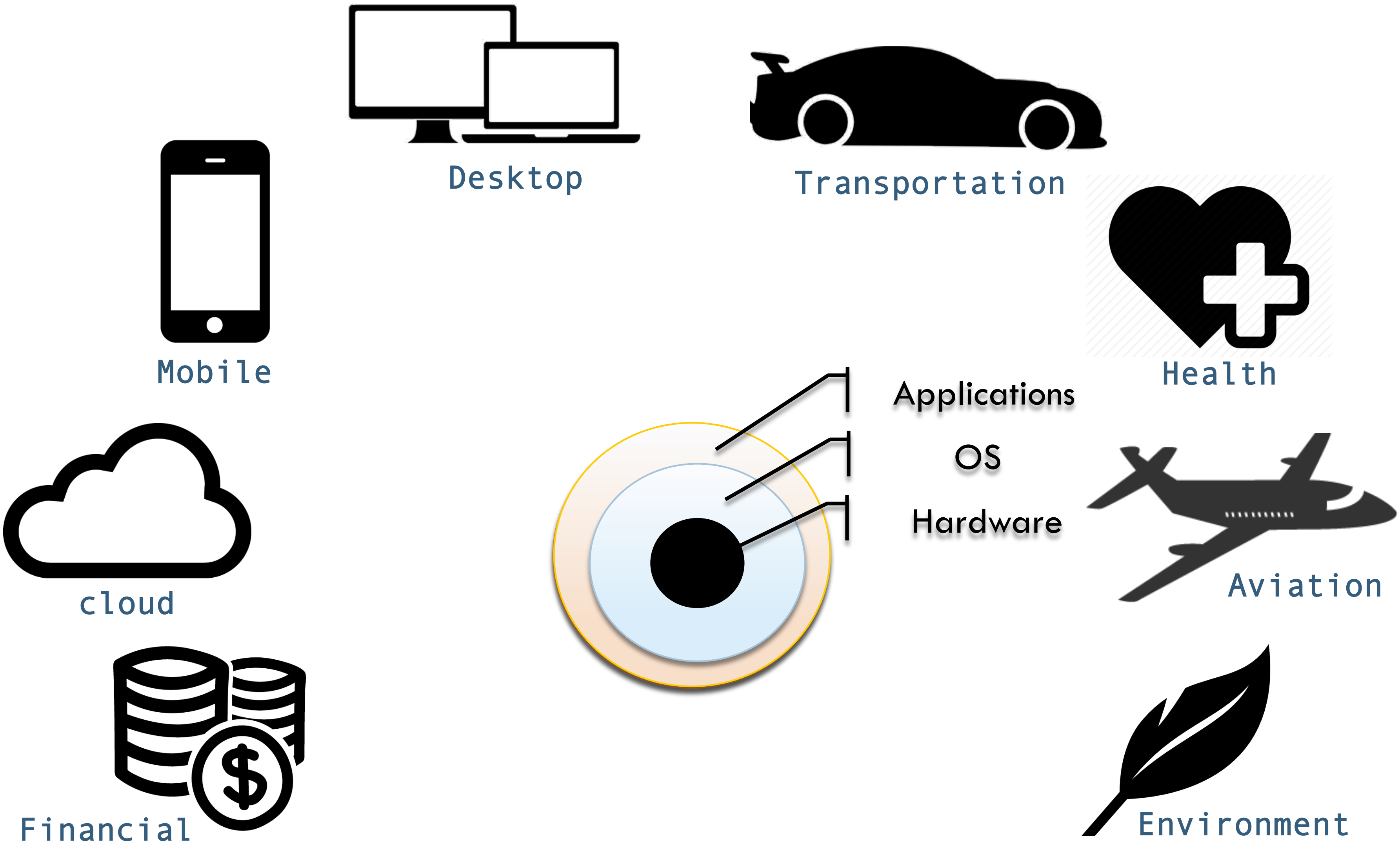

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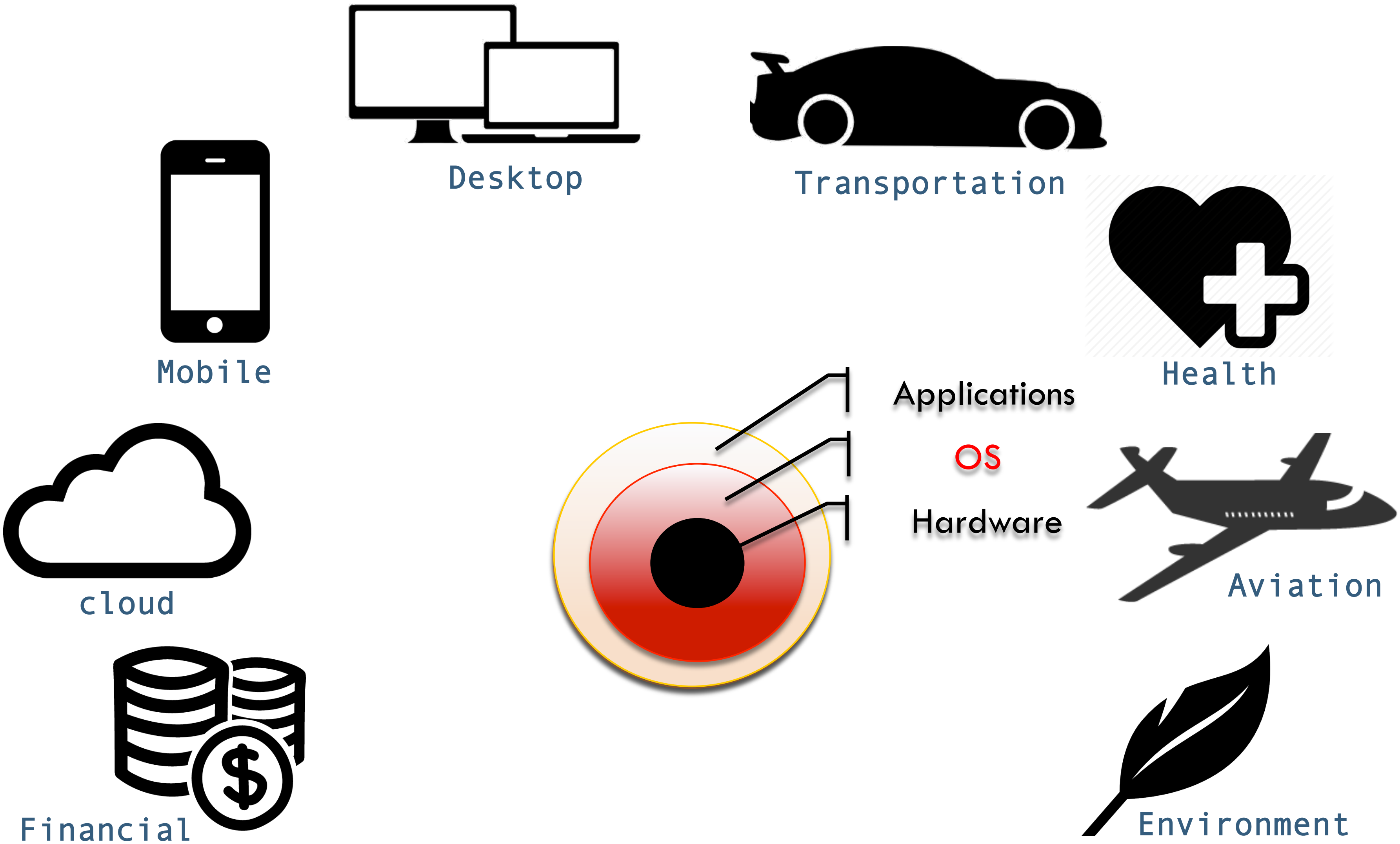

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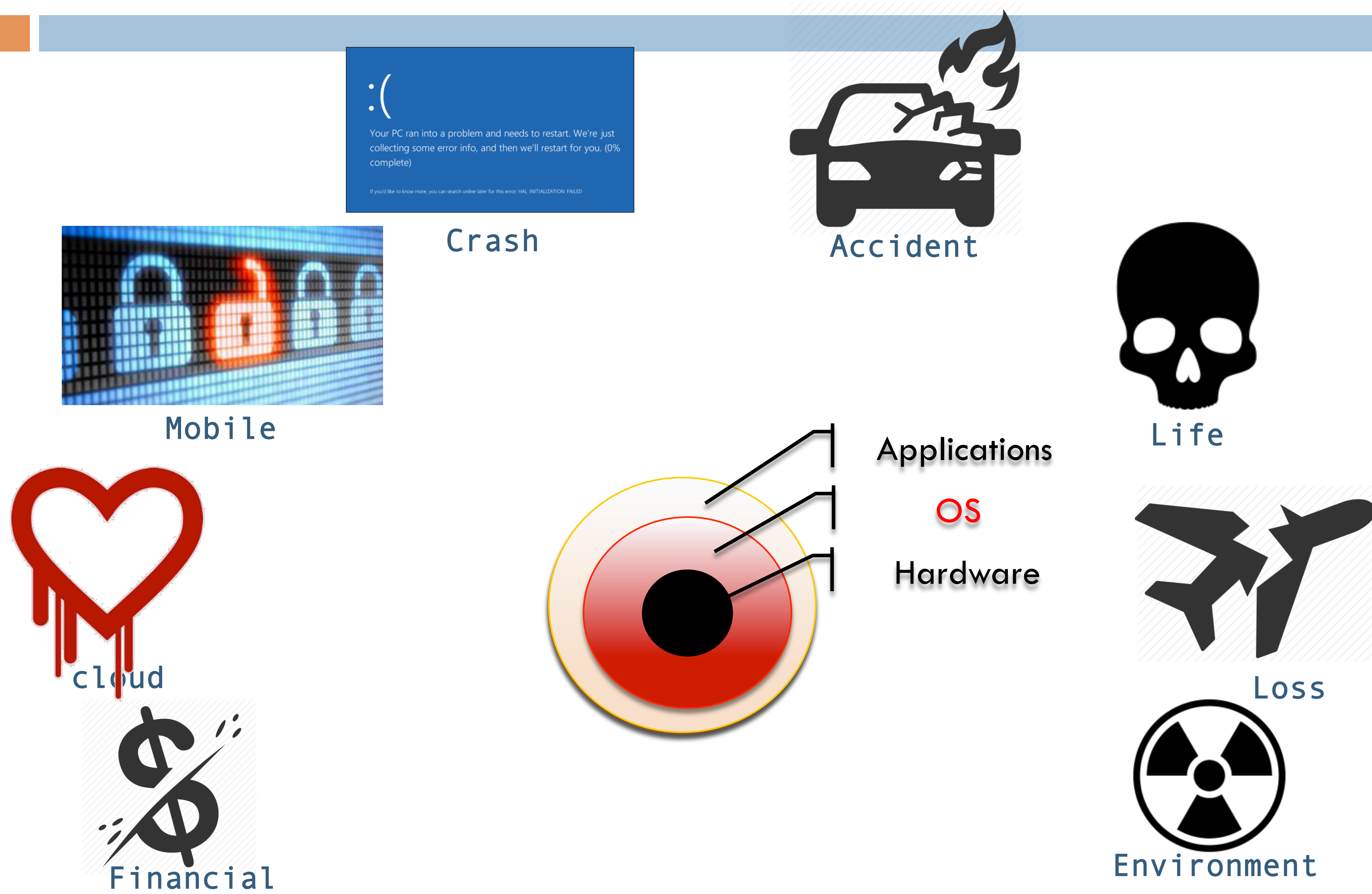
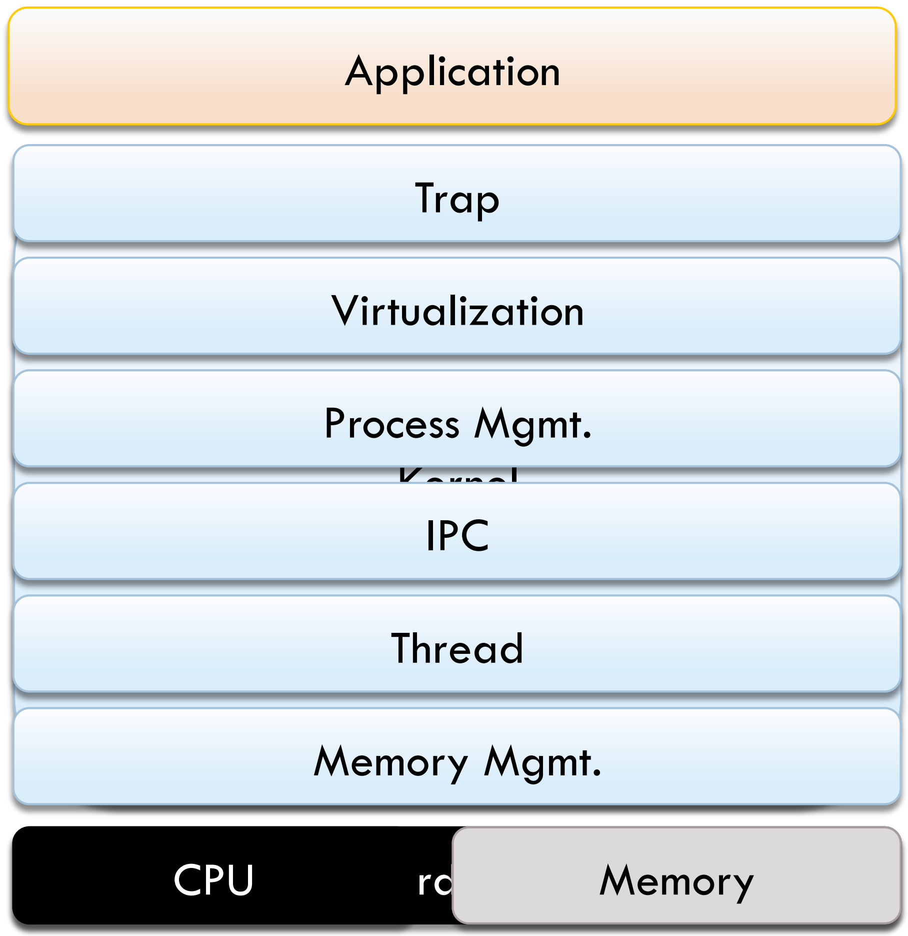


Formal Verification of OS Kernel

- seL4
- CertiKOS
- Verve



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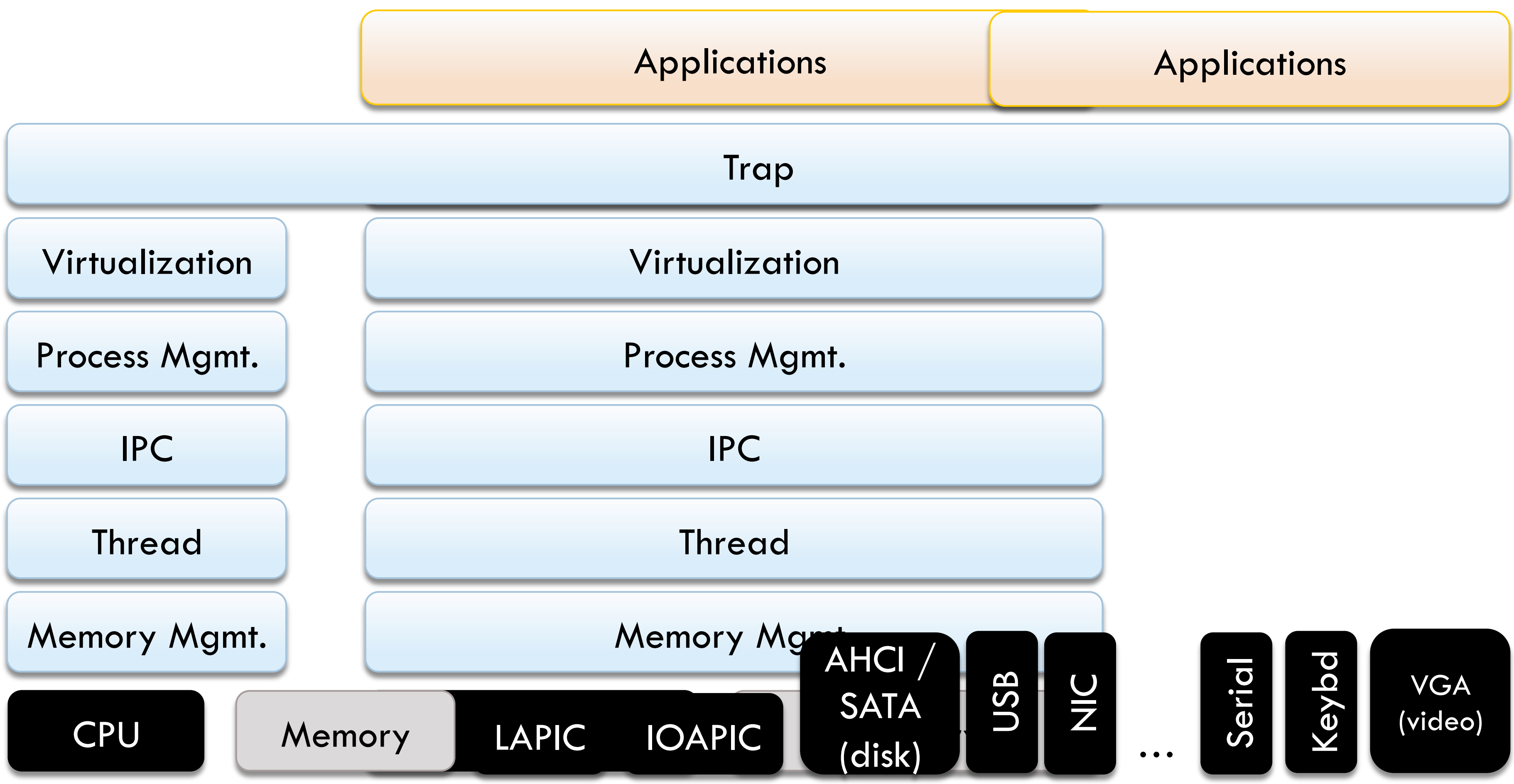

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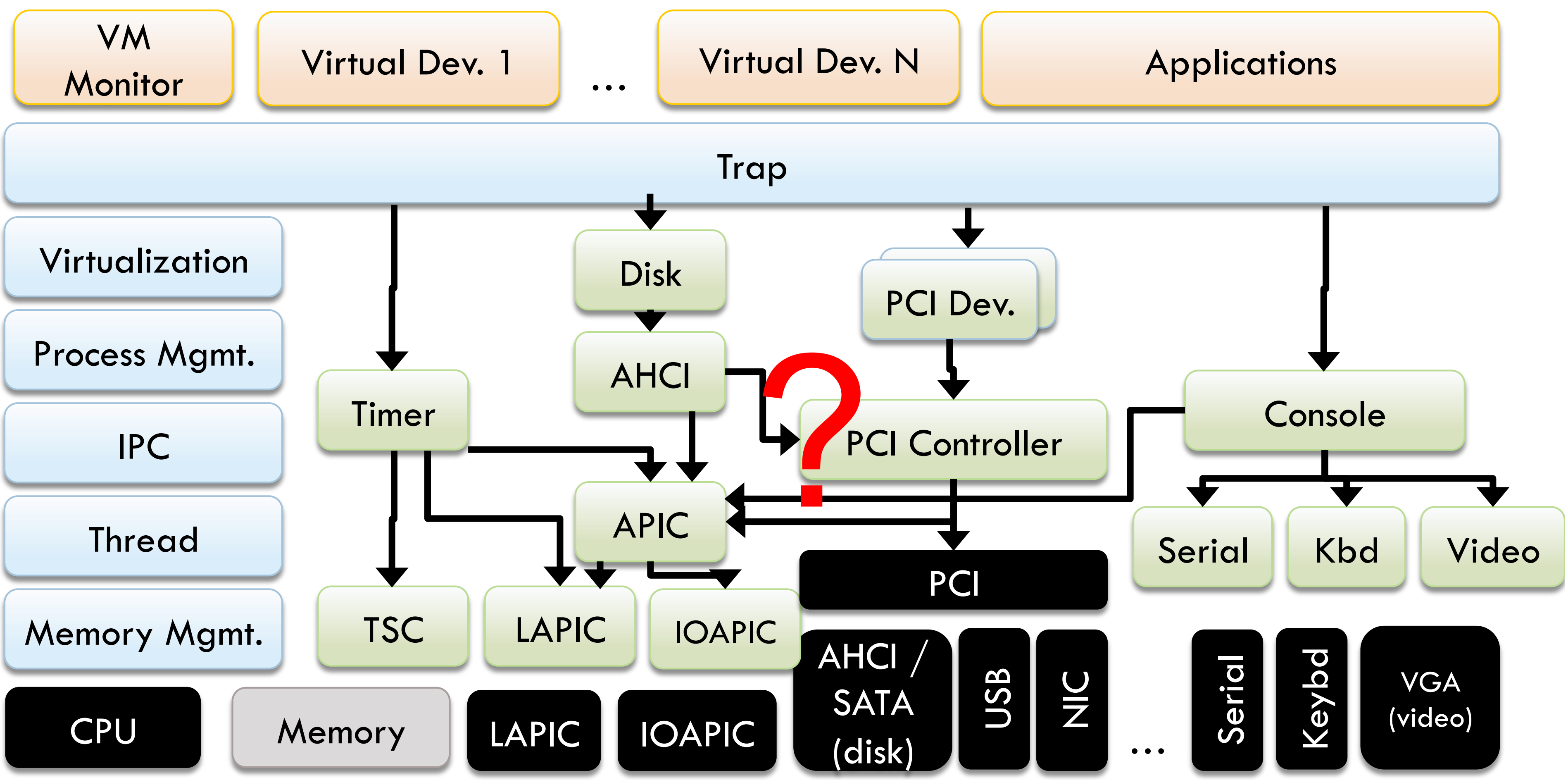
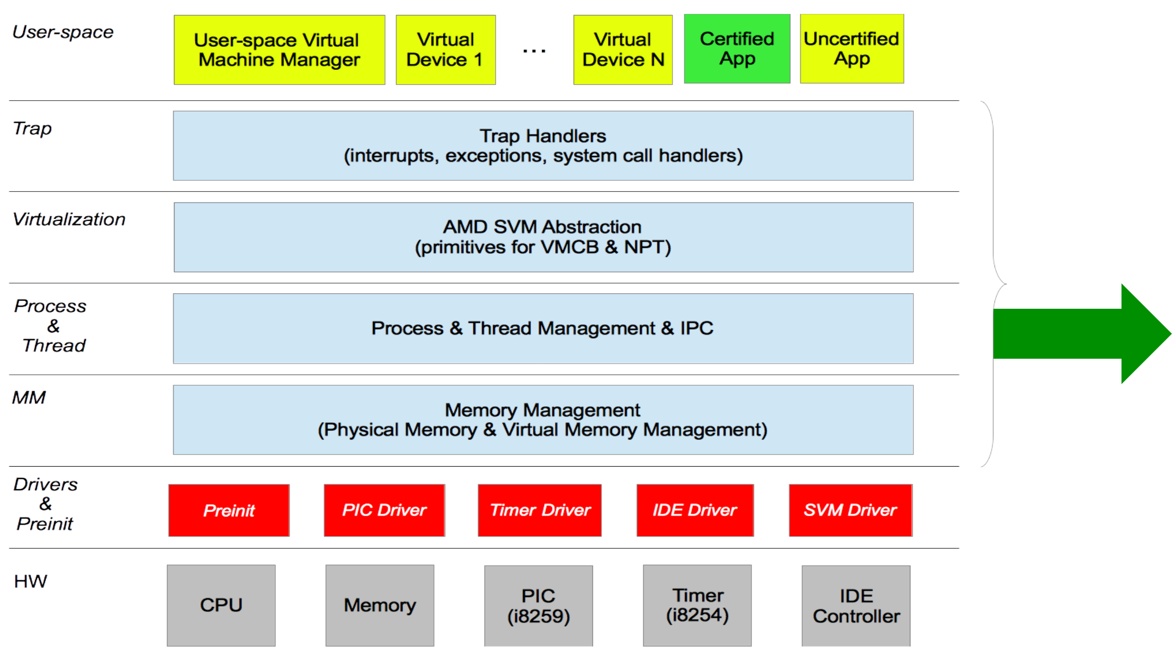


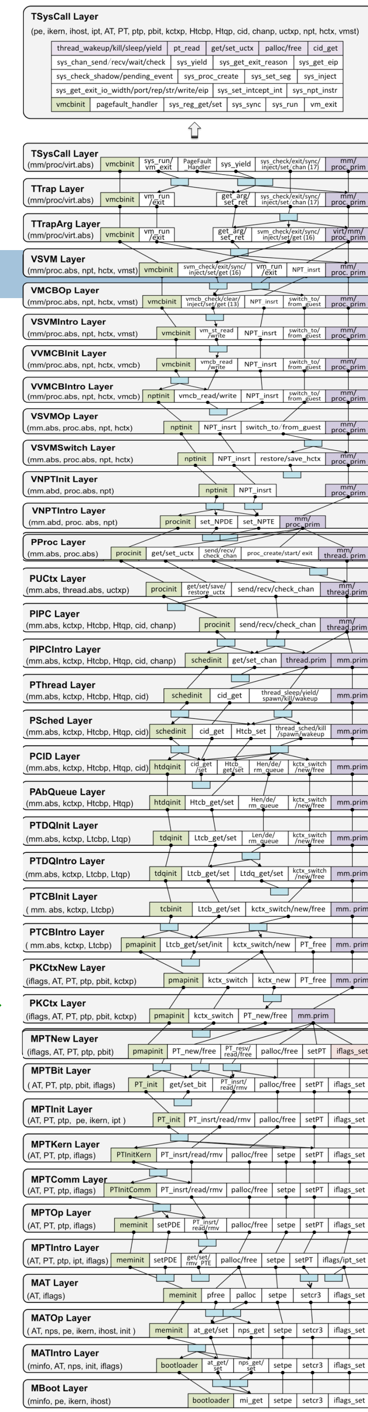
Device Drivers in Mainstream OS

- 70% of Linux 2.4.1 kernel are device drivers.
- 70% of Windows crash are caused by third-party driver code.

mCertiKOS Overview [POPL'15]

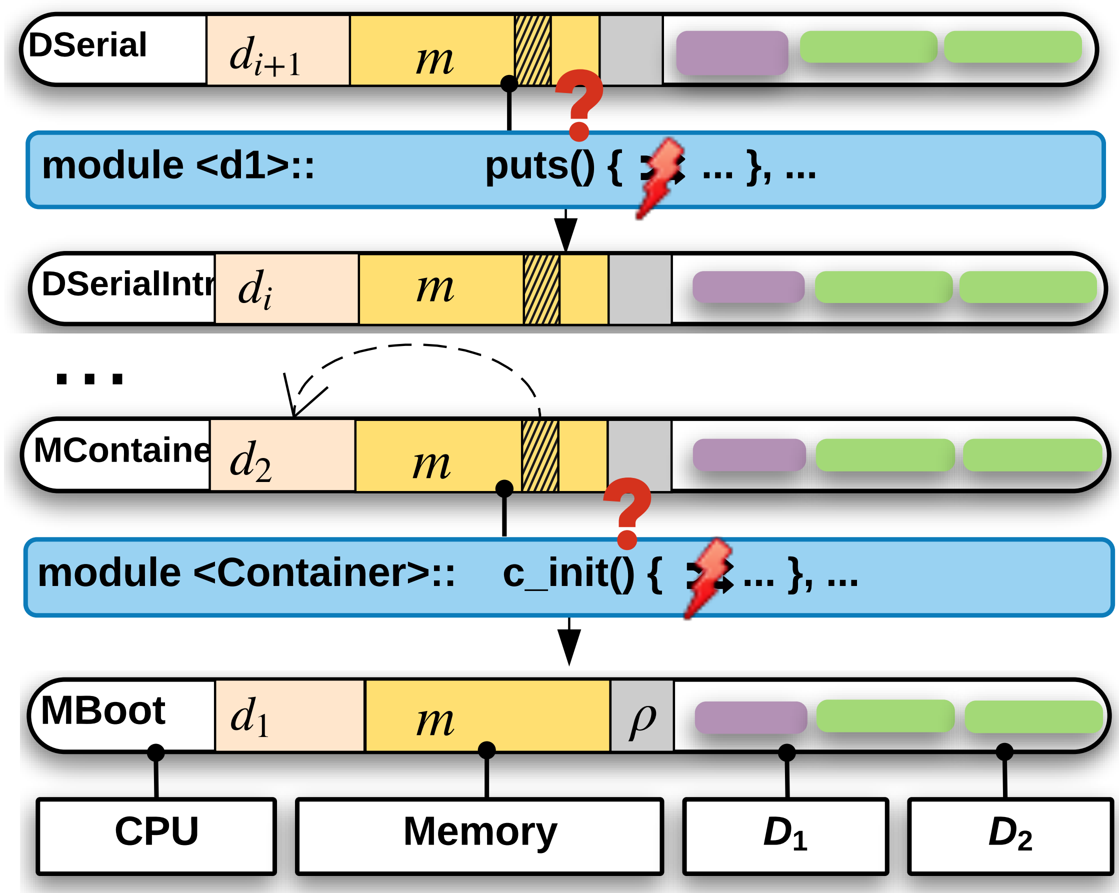
- Single-core version of CertiKOS.
- 3k LOC, can boot Linux as guest.
- Aggressive use of abstraction over deep specification (37 layers).





Main Challenge

Every fine-grained processor step could be interrupted.

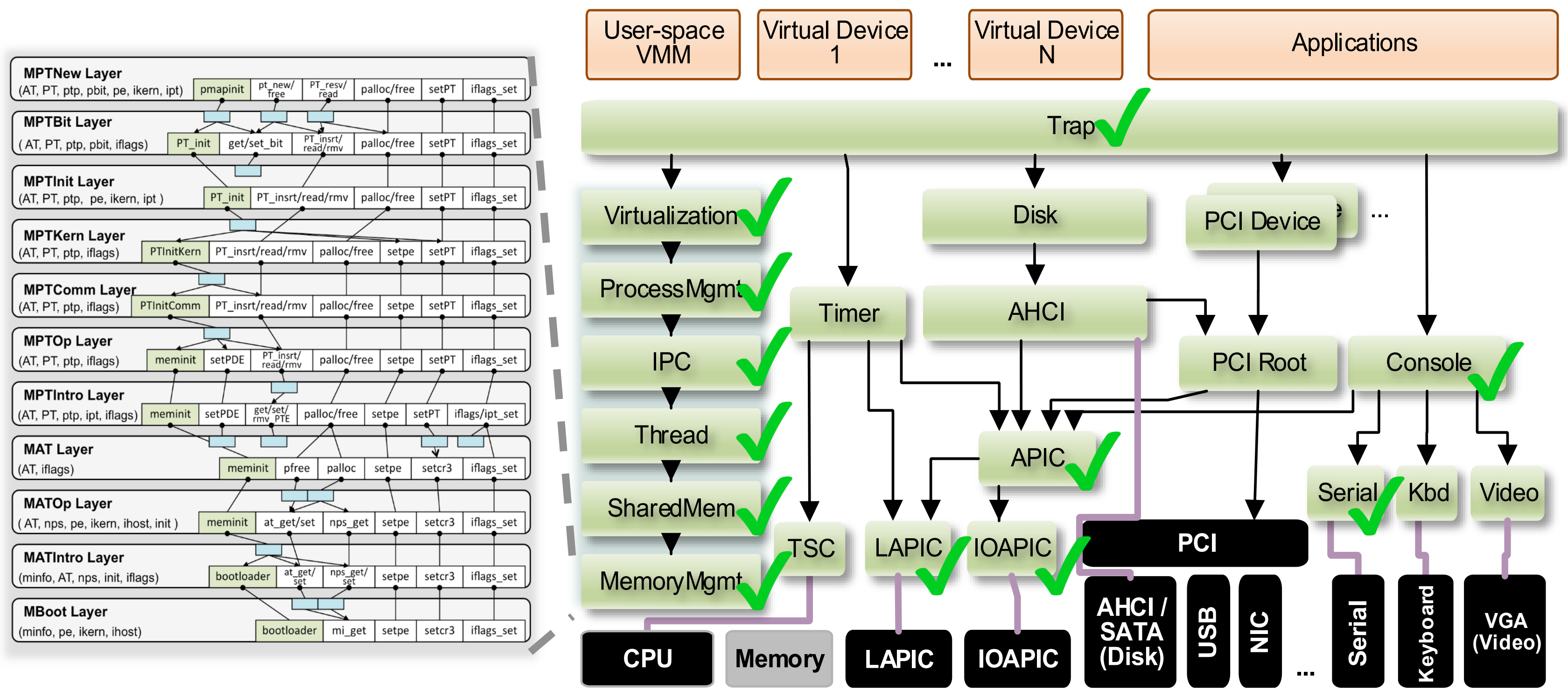


Other Challenges

- Interrupt hardware can be *dynamically* configured.
- Devices and CPU run in *parallel*.
- Device drivers are written in both C and *assembly*.
- The correctness results of different components should be *linked formally*.

Our Contributions

The *first* formally verified *interruptible* OS kernel with *device drivers*.

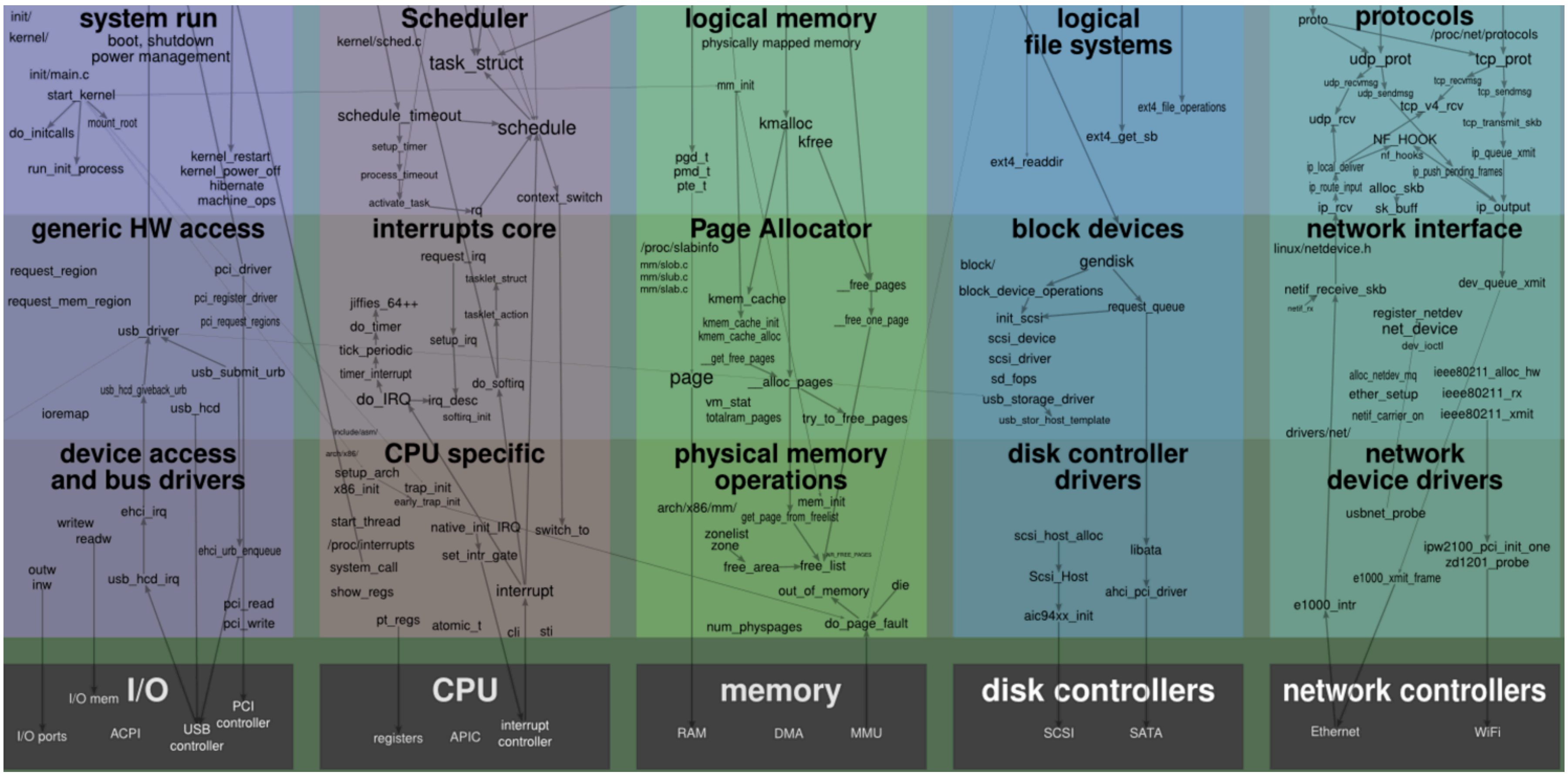


Our Contributions

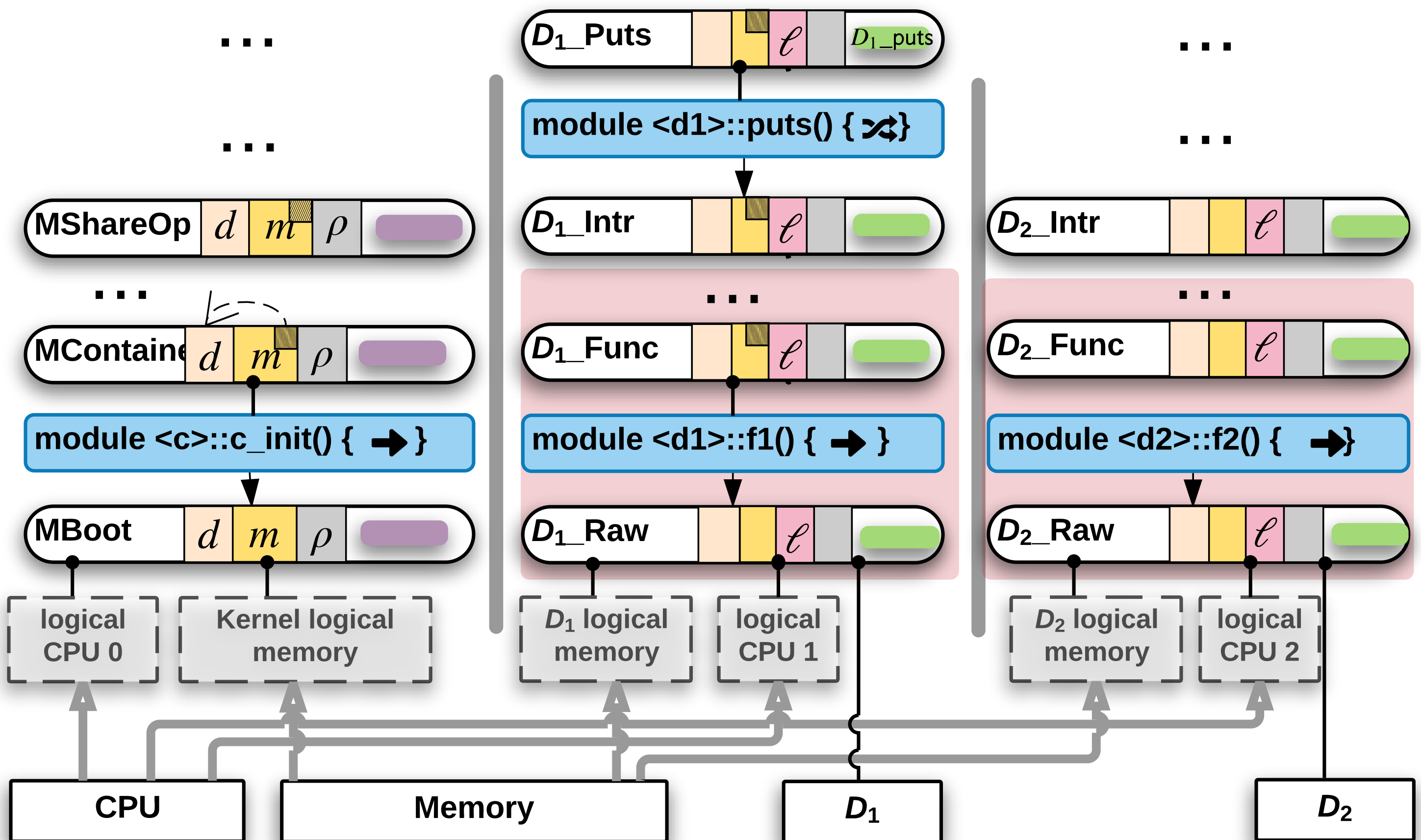
- New techniques for certifying abstraction layers with multiple ***logical CPUs*** and devices.
- New techniques for building formal ***certified device hierarchies***.
- An abstraction-layer-based approach for reasoning about ***interrupts***.
- ***Case study***: interruptible mCertiKOS with device drivers.

Linux Kernel Map

Kernel components are sorted into different stacks of abstraction layers based on their underlying hardware device.



New Machine Model



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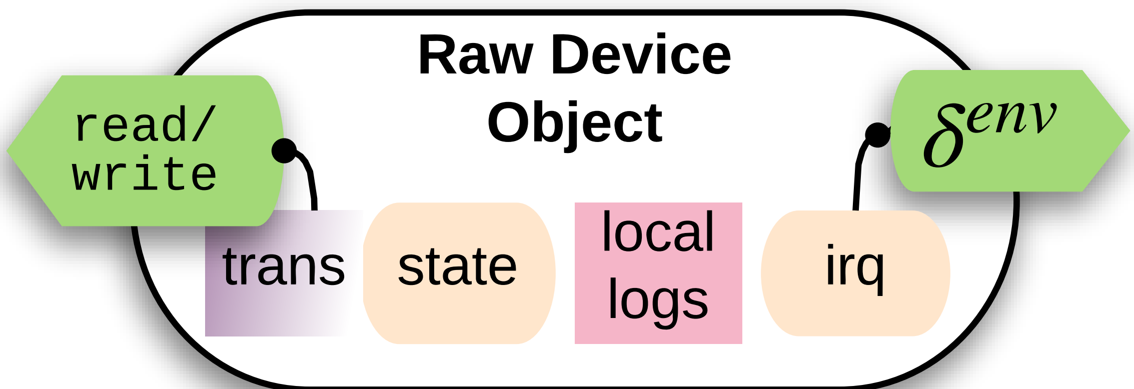
Hardware Device Model

- Devices are modeled as transition systems parameterized by all possible lists of external events.
- Example external events:
  - Recv (s: list char)
  - KeyPressed (c: Z)
- State: observable registers.
- Transition:
  - environmental transition: δ^{env}
  - I/O transition: δ^{CPU}

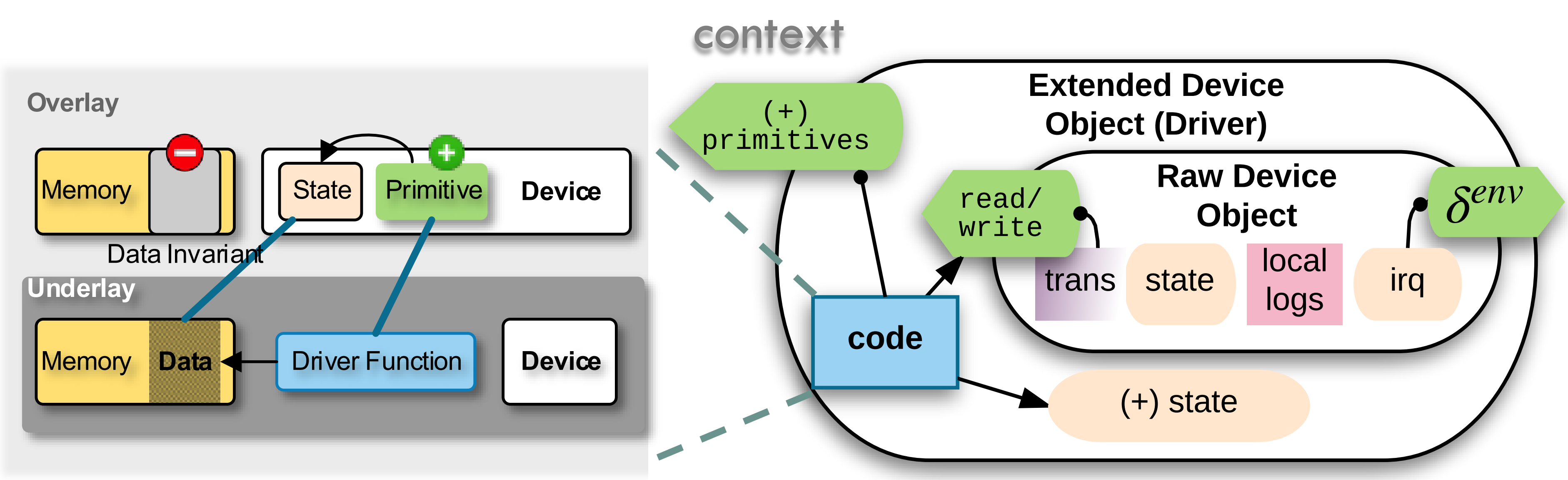
Raw Device Object

- Local log for the list of observed external events.
- Multiple local logs to handle disjoint set of external events asynchronously.
- Read/Write instructions: IN/OUT, memory mapped I/O, *etc.*

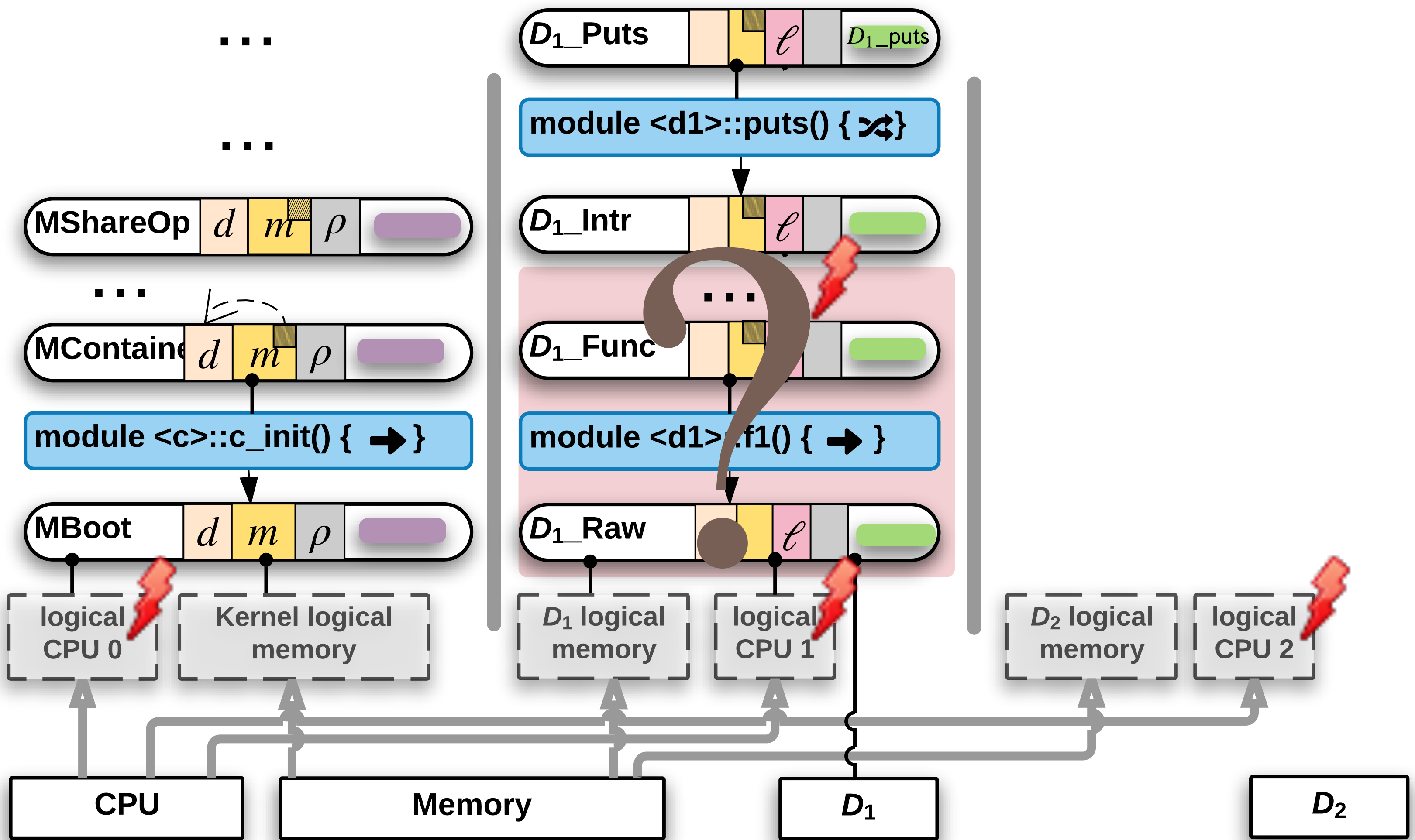


Extended Device Object

Driver as a logical device.



Recap: Machine Model



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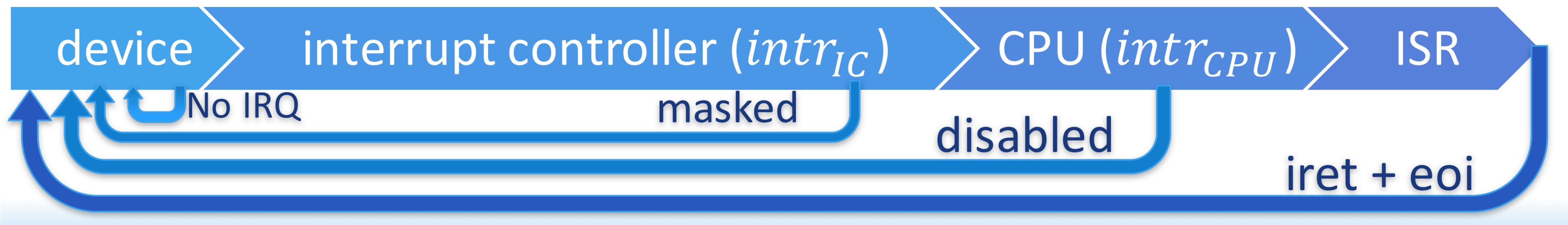
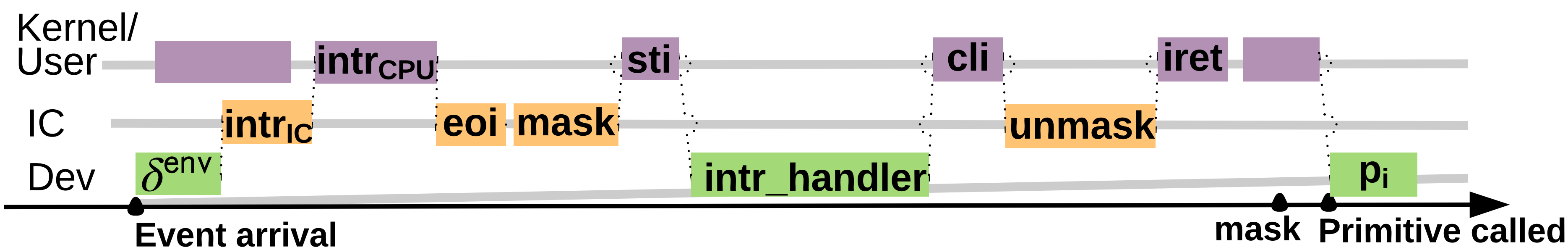
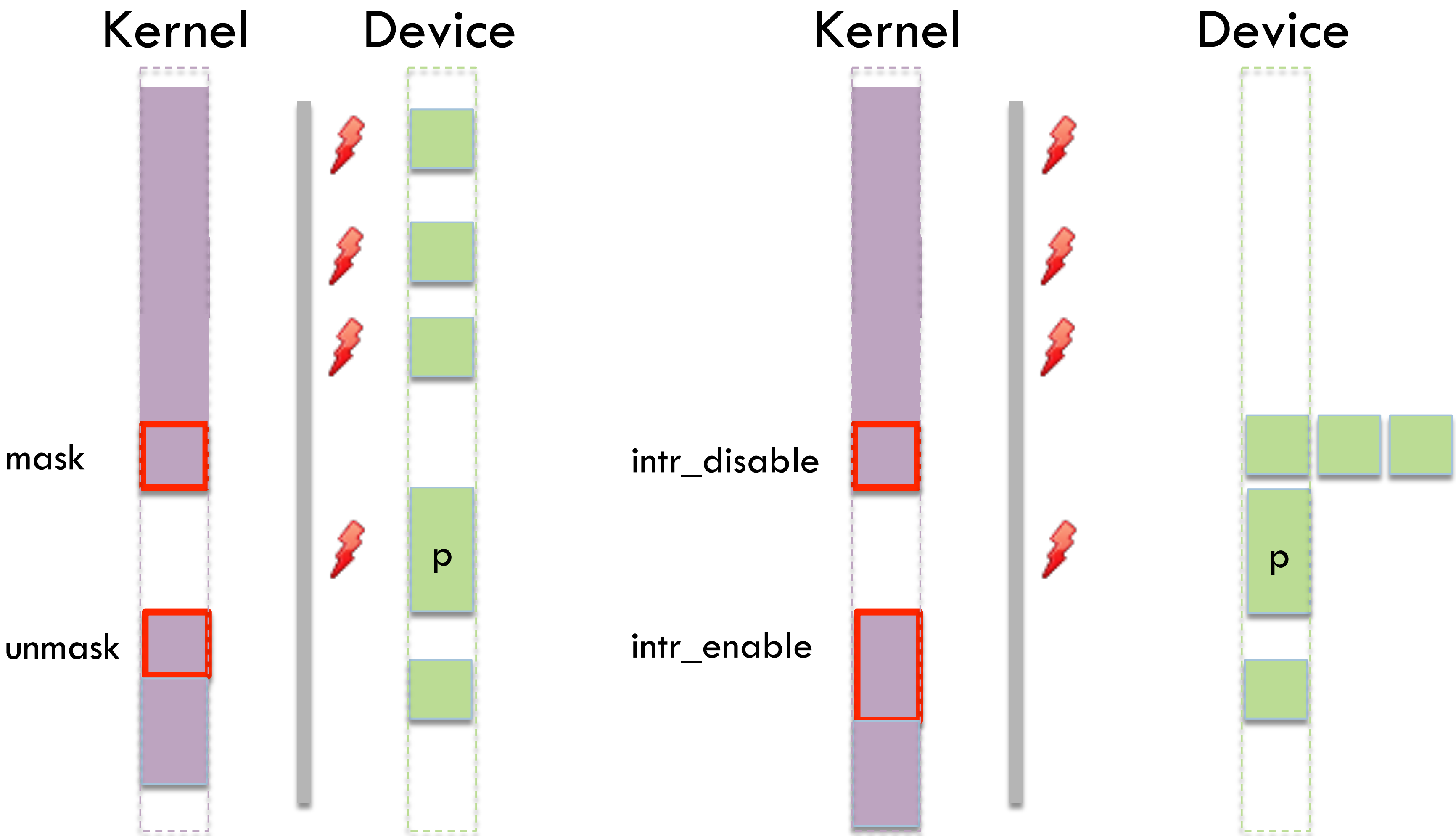
Interrupt Models



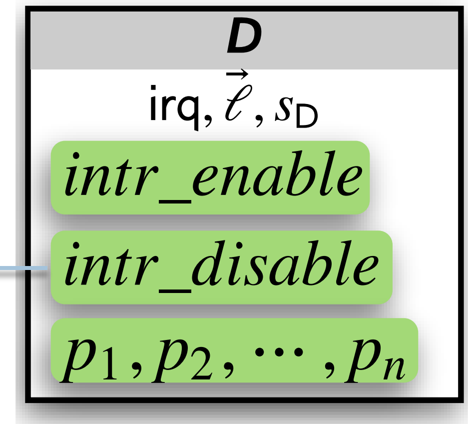


New HW Interrupt Model



Semantics of *intr_disable*

- Scans external events.
- Recursively performs the environmental transition.
- Synchronizes unhandled interrupts.



details in the paper

DISABLENOINTR: Disable with no unhandled interrupt

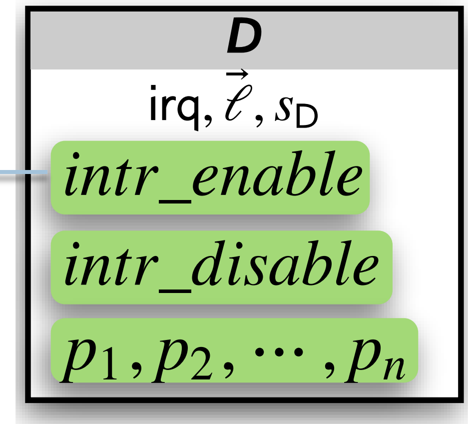
$$\frac{(e, \ell_i') = \mathsf{next}(\ell^{env}, \ell_i) \qquad s_{\mathsf{tmp}} = \delta^{\mathsf{env}}(s, e) \qquad s_{\mathsf{tmp}}.irq = \mathsf{false} \qquad s' = s[\mathsf{iFlag} \leftarrow 0]}{\mathtt{intr\_disable}(s, \ell_i, \ell^{env}) = (s', \ell_i)}$$

DISABLEINTR: Disable with unhandled interrupts

$$\frac{(e, \ell_i') = \mathsf{next}(\ell^{env}, \ell_i) \qquad s' = \delta^{\mathsf{env}}(s, e) \qquad s'.irq = \mathsf{true} \qquad (s'', \ell_i'') = \mathtt{intr\_handler}(s', \ell_i', \ell^{env}) \qquad (s''', \ell_i''') = \mathtt{intr\_disable}(s'', \ell_i'', \ell^{env})}{\mathtt{intr\_disable}(s, \ell_i, \ell^{env}) = (s''', \ell_i''')}$$

Semantics of *intr_enable*

- Recursively discharges pending interrupts.
- Delayed interrupts that occur while the interrupt is disabled.



details in the paper

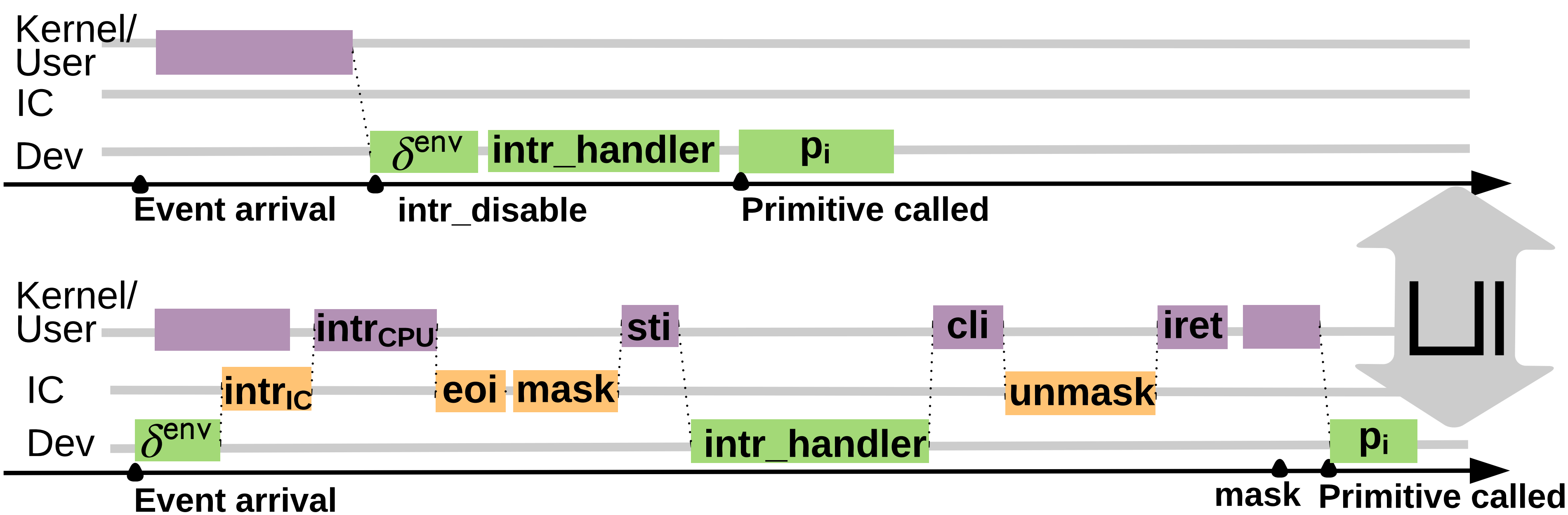
ENABLENOINTR: Enable with no pending interrupt

$$\frac{s.irq = \text{false} \qquad s' = s[\text{iFlag} \leftarrow 1]}{\texttt{intr\_enable}(s, \ell_i, \ell^{env}) = (s', \ell_i)}$$

ENABLEINTR: Enable with pending interrupts

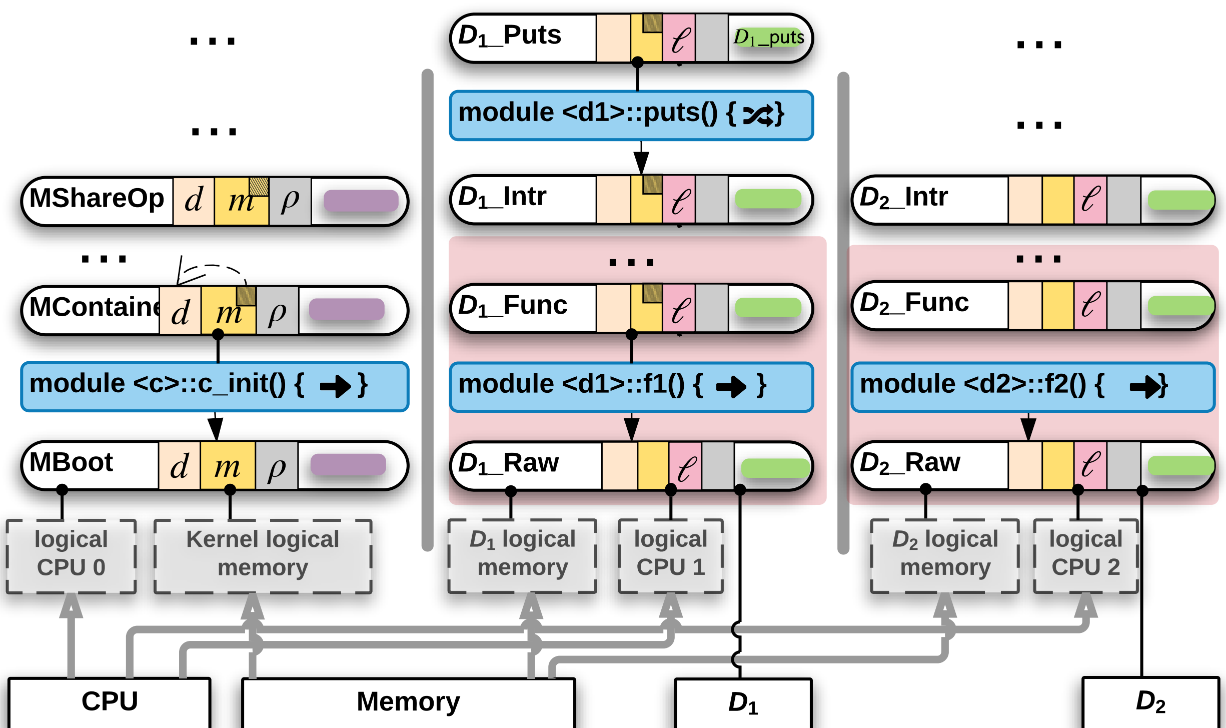
$$\frac{s.irq = \text{true} \qquad (s', \ell_i') = \texttt{intr\_handler}(s, \ell_i, \ell^{env}) \qquad (s'', \ell_i'') = \texttt{intr\_enable}(s', \ell_i', \ell^{env})}{\texttt{intr\_enable}(s, \ell_i, \ell^{env}) = (s'', \ell_i'')}$$

Refinement btw. The HW & Abstract Interrupt Model



Our Approach

- The driver code of each device runs on its own “logical CPU”, operates its own internal states.
- Interruptible code can be naturally reasoned on top of the abstract interrupt model.



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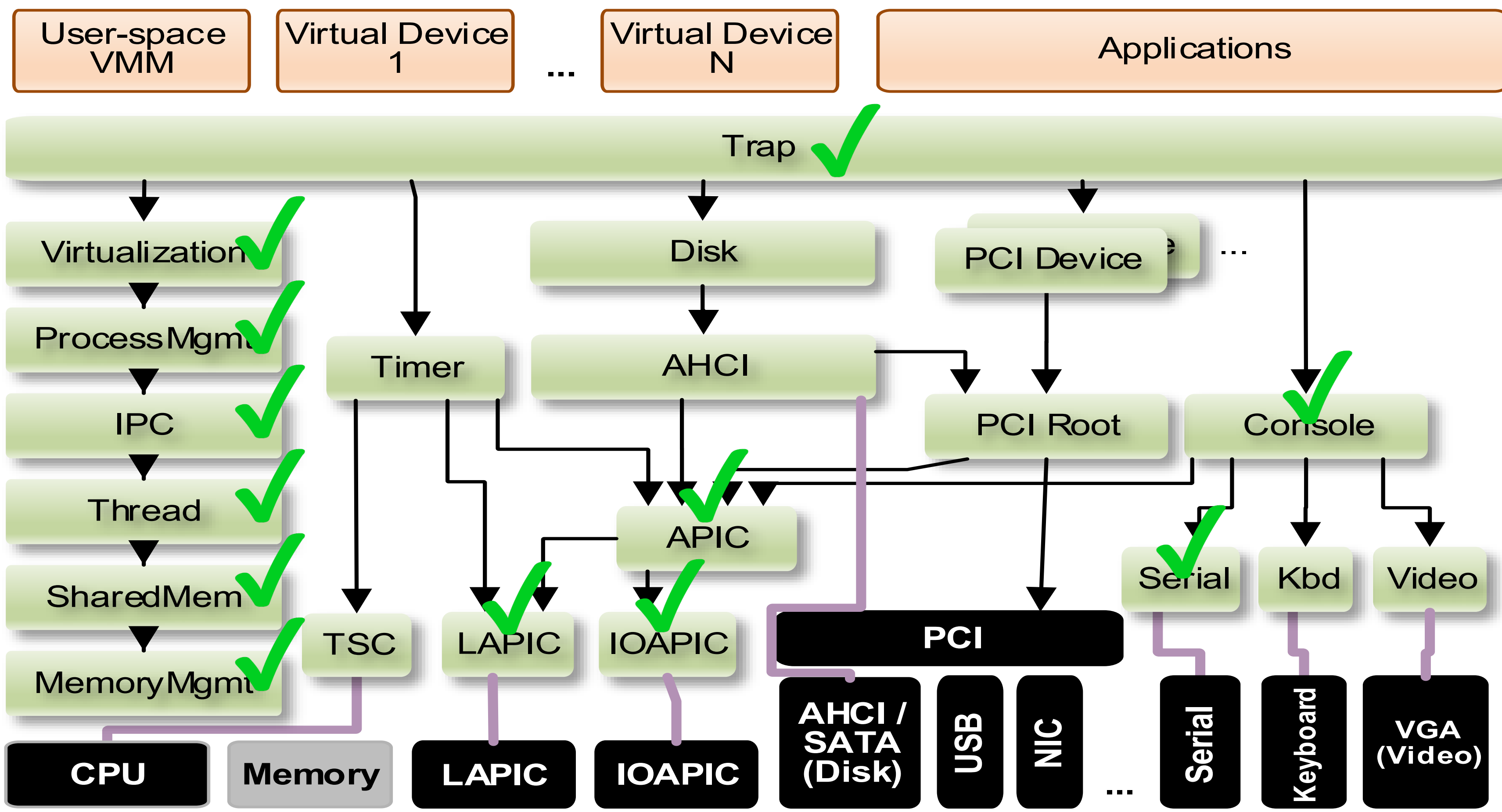
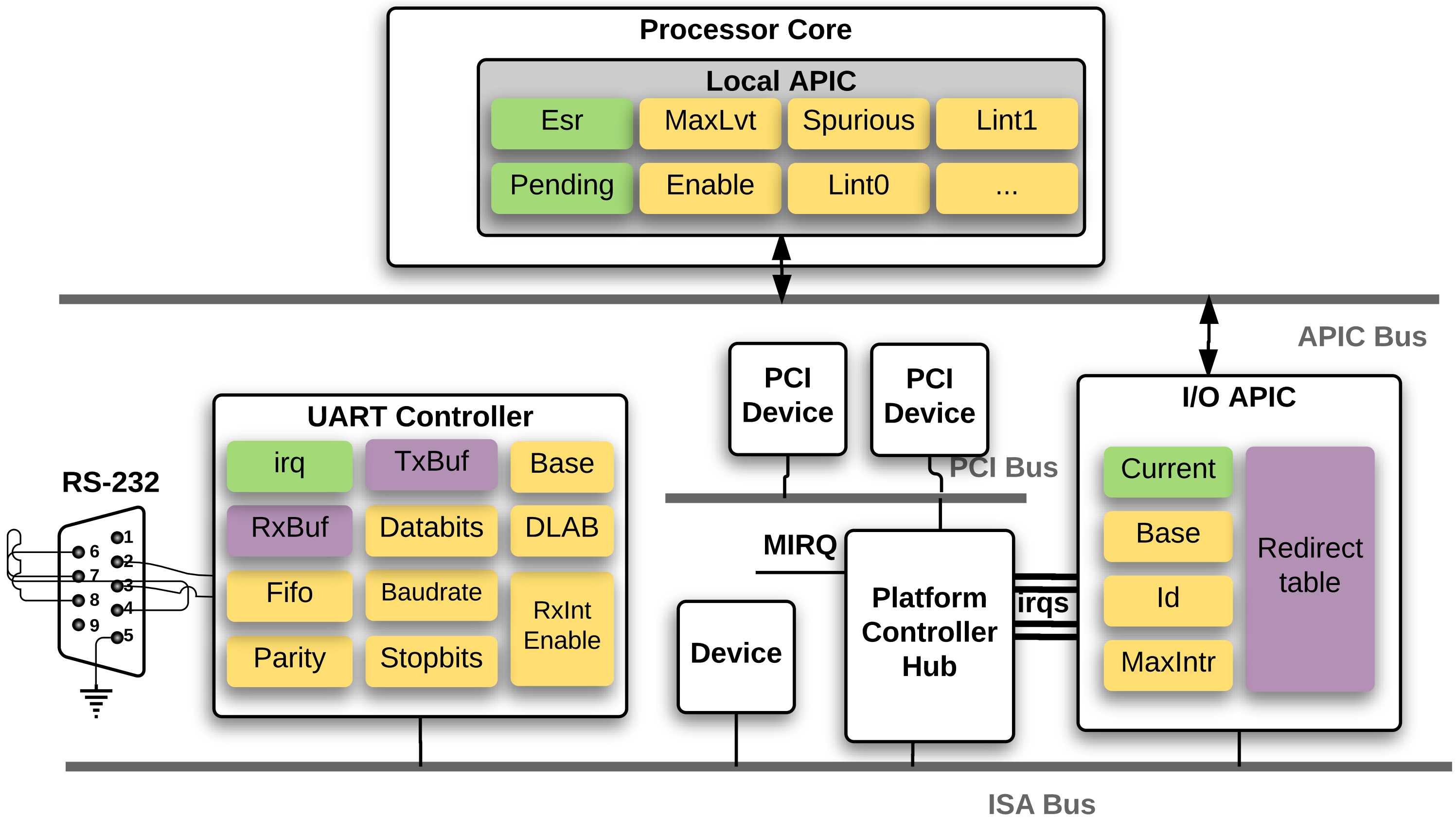
Interruptible mCertiKOS with Drivers



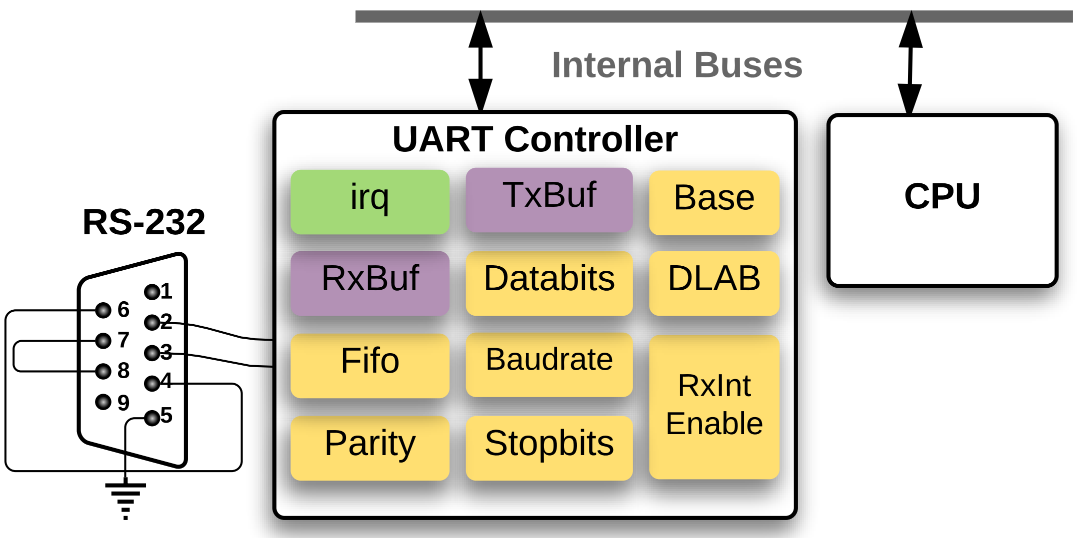
Case Study: Modeling HW Devices

- Serial Port, I/O APIC, Local APIC, CPU interrupt handling.



Case Study: Serial Device

- States: see figure
- Transitions: serial_trans_env + serial_trans_IO
- Read/Write primitives: serial_read / serial_write



Serial Interrupt Handler

```c
void serial_intr () {
  unsigned int hasMore;
  int t = 0;
  hasMore = serial_getc ();
  while (hasMore && t < CONSOLE_BUFFER_SIZE) {
    hasMore = serial_getc ();
    t++;
  }
}
```

```c
unsigned int serial_getc () {
  unsigned int rv = 0;
  unsigned int rx;
  if (serial_exists()) {
    if (serial_read(COM1 + COM_LSR, BIT1) % 2 == 1)
     {
      rx = serial_read(COM1 + COM_RX, M_ALL);
      cons_buf_write(rx);
      rv = 1;
    }
  }
  return rv;
}
```

Serial Driver

```
void serial_puts(char * s, int len) {
  int i = 0;
  while (i < len && s[i] != 0) {
    serial_intr_disable ();
    serial_putc (s[i]);
    serial_intr_enable ();
    i++;
  }
}
```

```
void serial_putc (unsigned int c) {
  unsigned int lsr = 0, i;
  if ( serial_exists() ){
    for (i = 0; !lsr && i < 12800; i++) {
      lsr = serial_read(0x3FD) & 0x20;
      delay();
    }
    serial_write (0x3F8, c);
    ...
```

What We Have Proved

- Total functional correctness.
- Safety.
- *Contextual refinement* between the lowest and the top level abstract machine:
  $\forall P,\ [\![K \bowtie P]\!]_{\mathrm{x86}} \sqsubseteq [\![P]\!]_{\mathrm{mCertiKOS}}.$
- Data invariants:
  - Console's circular buffer is always well-formed.
  - Interrupt controller states are always consistent.
- The framework also ensures that:
  - No code injection attacks, buffer overflow, integer overflow, null pointer access, *etc*.

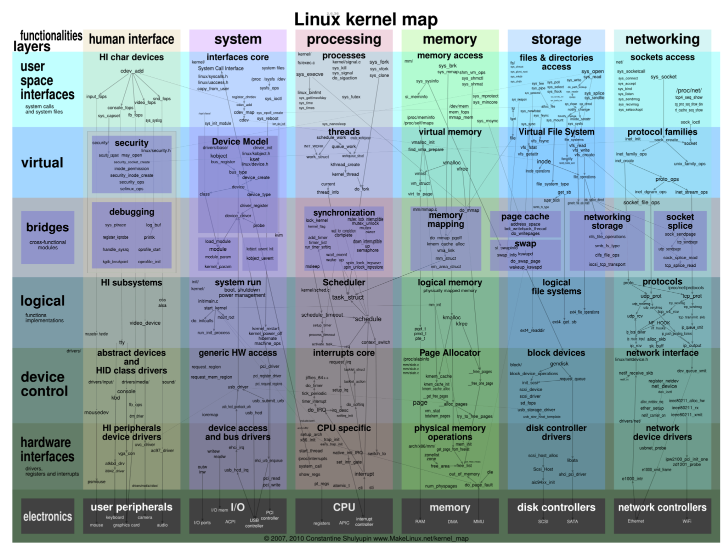
Size of TCB and Spec/Proof

- In the TCB
  - X86 hardware model
  - Hardware device/interrupt model (510 LOC)
  - System call specification (126 LOC)
  - Bootloader
  - Coq proof checker
  - Pretty-printing phase of the CompCert compiler

- Rest of the spec/proof (about 20k LOC)
  - Intermediate and auxiliary specifications and definitions
  - Coq proof scripts

Conclusion

- Compositional framework for building certified interruptible kernel with device drivers.
  - Certified abstraction layers with multiple logical CPUs.
  - An abstraction-layer-based approach for expressing interrupts.
- The first formally verified interruptible OS kernel with device drivers.
- Extensions:
  - Other drivers
  - Concurrency
  - Larger kernel



Thank You