Proofcraft

seL4® Multikernel Roadmap and Concurrency Verification

Corey Lewis @ Proofcraft

The world's most highly assured operating system kernel*

The world's most highly assured operating system kernel*

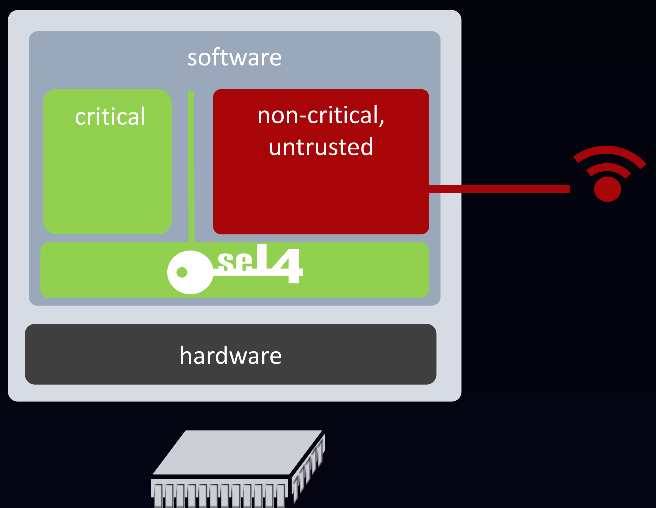
* only when running on a single core

The world's most highly assured operating system kernel*

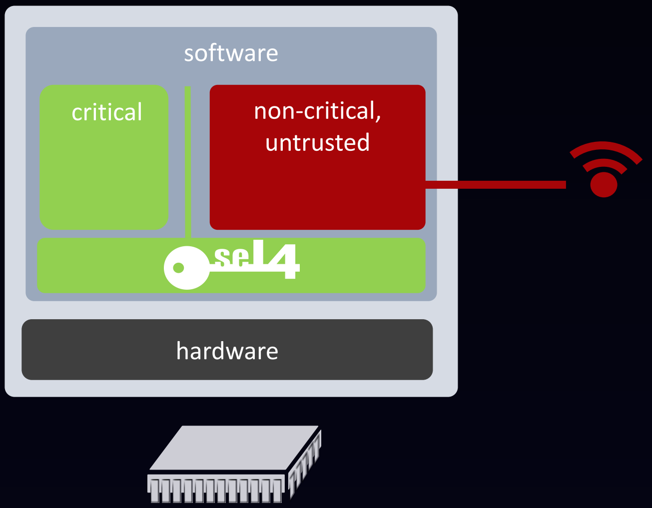
* when running sequentially, without interference

```
void kernel_call () {
        ...
        ...
        ...
}
```

✓erified

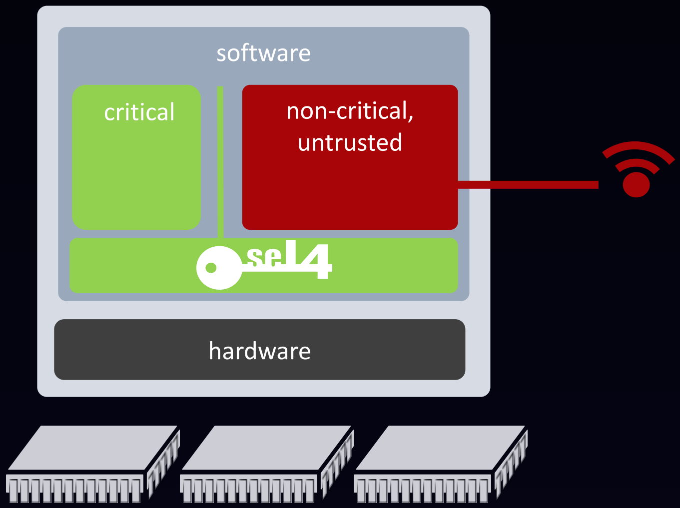


What do we want?



What do we want?

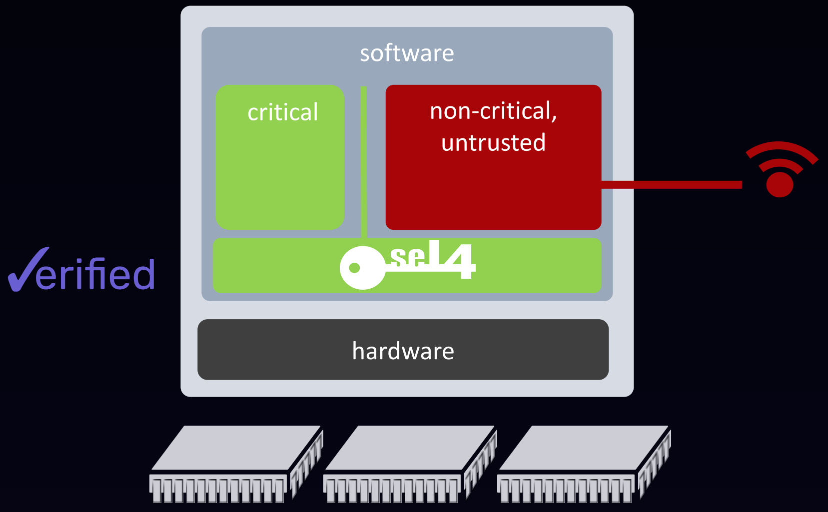
Better performance,
by using more cores



What do we want?

Better performance,
by using more cores

Still high assurance



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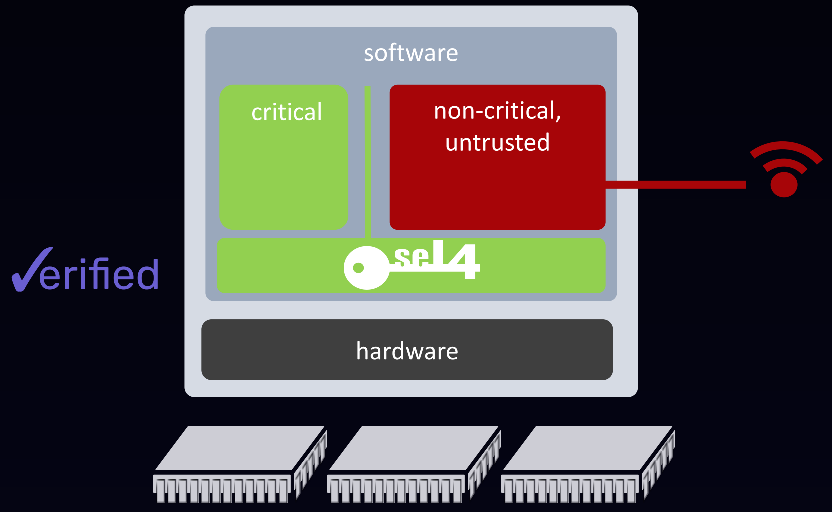
Better performance, by using more cores → Concurrency

Still high assurance → Formal Verification



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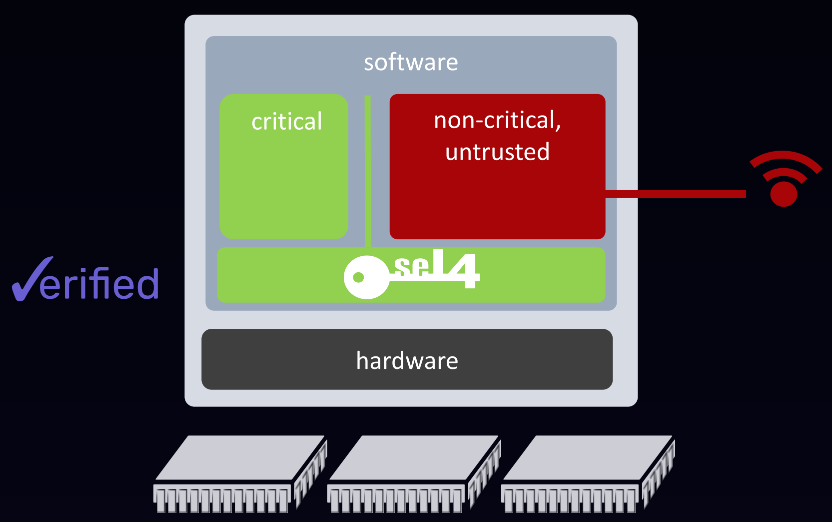
Better performance, by using more cores → Concurrency

Still high assurance → Formal Verification

Concurrency + Formal Verification → Very hard!



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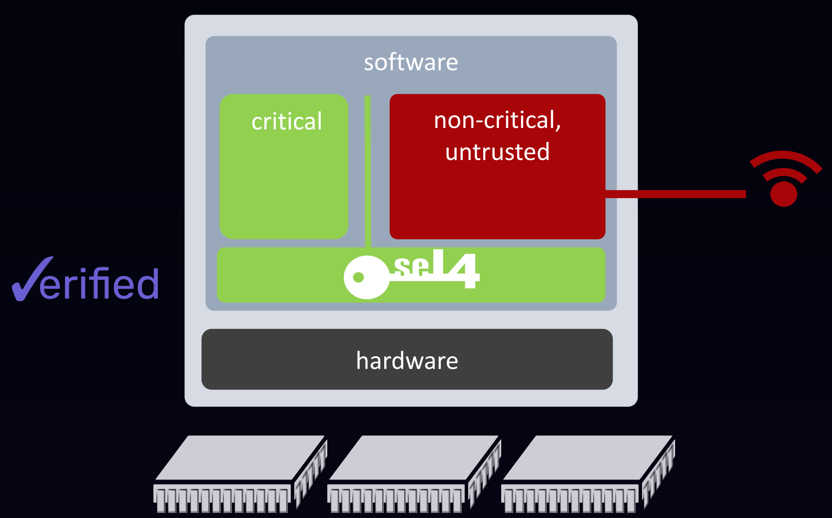
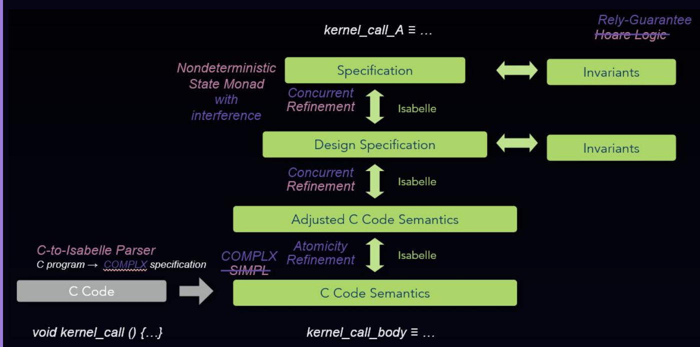
Goal:
Allow use of multiple cores as soon as possible,
with incrementally stronger and stronger assurance



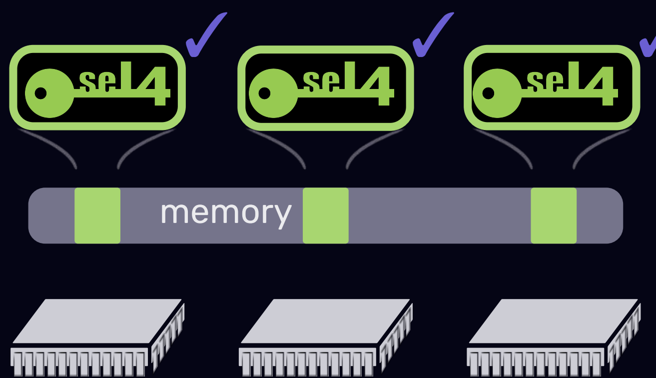
Overview

Goal:
Allow use of multiple cores as soon as possible,
With incrementally stronger and stronger assurance

What's hard?
What have we got so far?



Towards a verified static multikernel seL4



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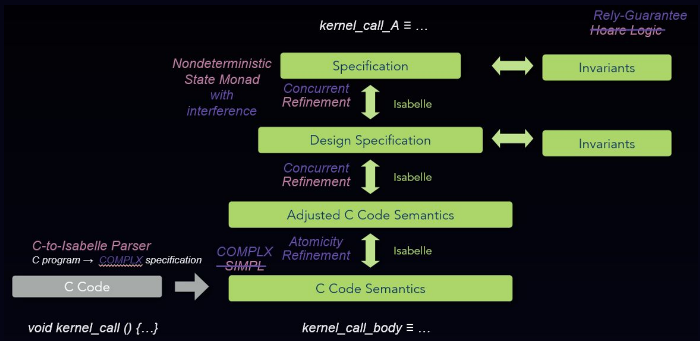

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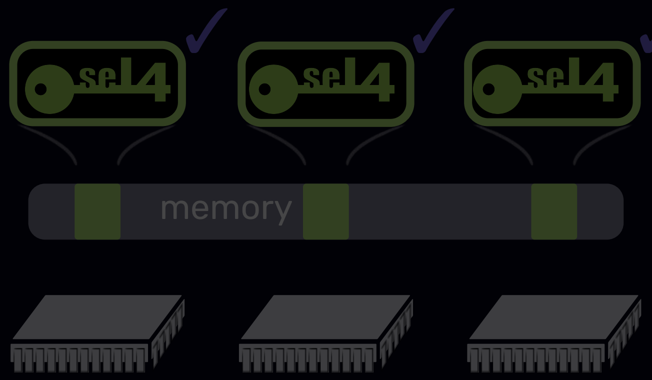

What’s hard?

Concurrency

Formal Verification

Very hard!

Isn’t that solved?

There exist approaches for concurrency verification
that work for small / self-contained algorithms

But:

What's hard?

Concurrency

Formal Verification

Very hard!

Isn't that solved?

There exist approaches for concurrency verification
that work for small / self-contained algorithms

But:

seL4 is neither small nor high-level nor modular
(because it's a microkernel and it is fast)

What's hard?

Plus:

seL4's existing verification framework is complex
(because it's doing formal proof of low-level complex code)

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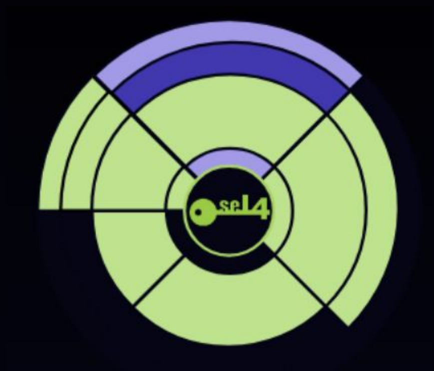

- > 1 million lines of proof
  - Developed over 15 years
- Three levels of specifications
  - Two very different specification languages
  - Needs to capture a lot of detail
- Many different configurations
  - Multiple architectures, multiple features, MCS

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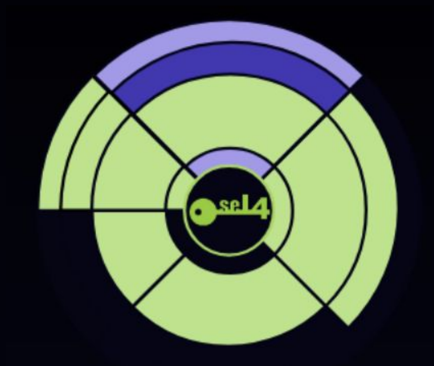

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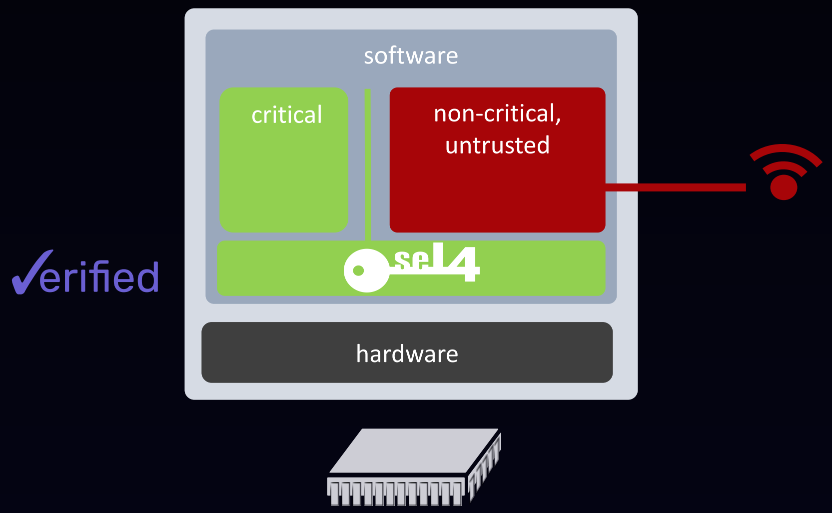
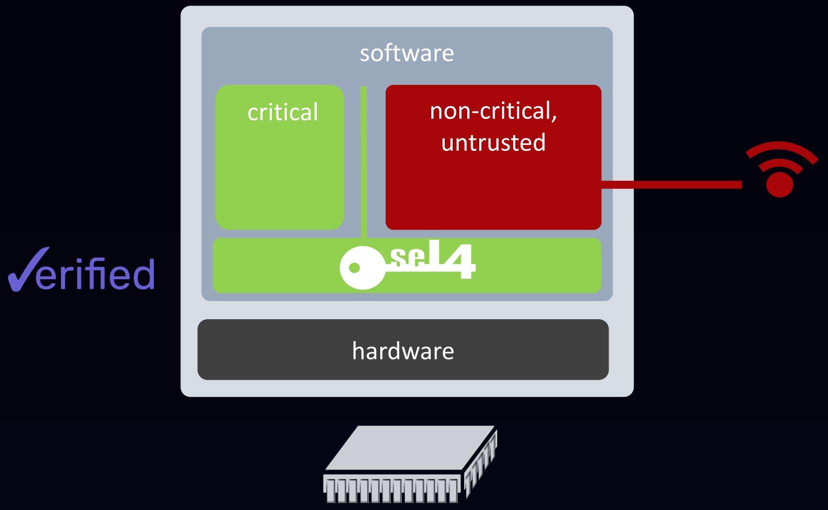
We want to maximise reuse of existing proofs

The unicore situation



The unicore situation

Verified = the C code is correct (w.r.t its specification)
(+security, binary, etc. Ignored here for simplicity)



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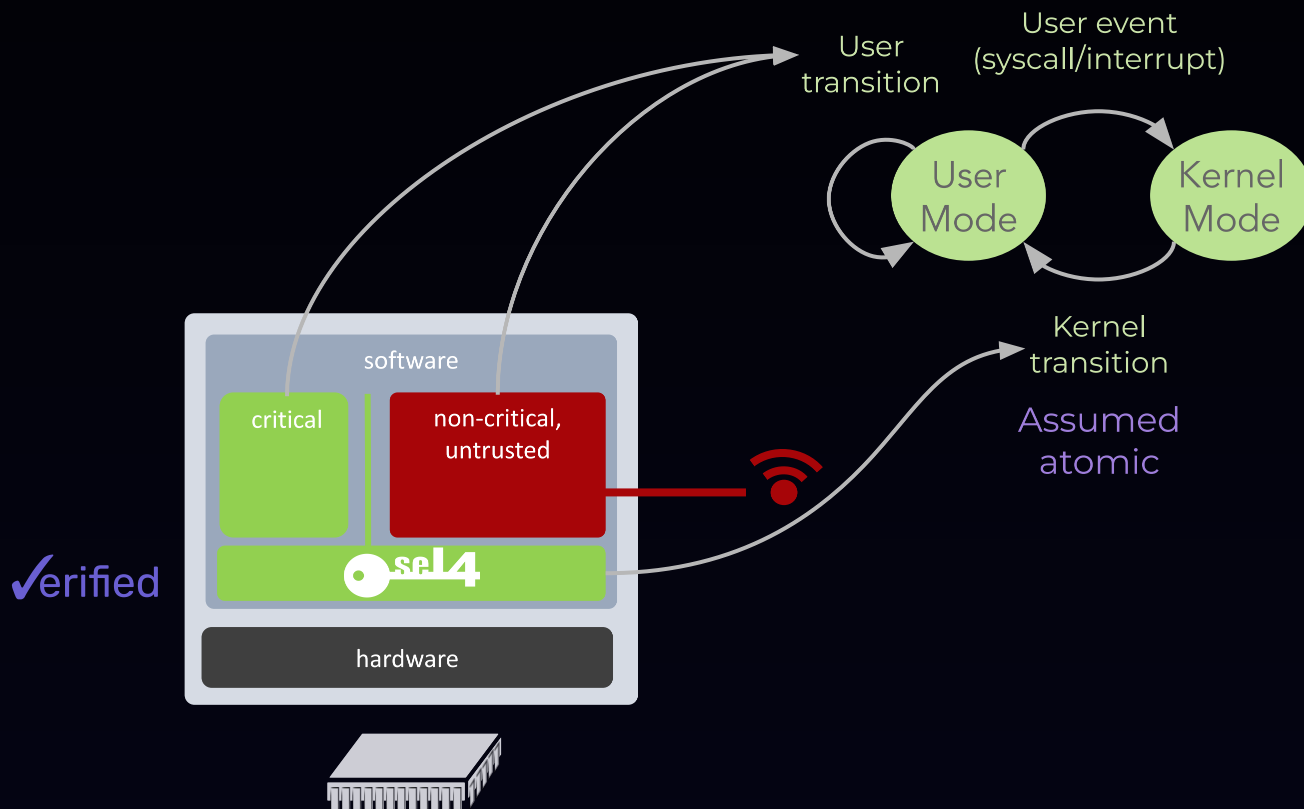

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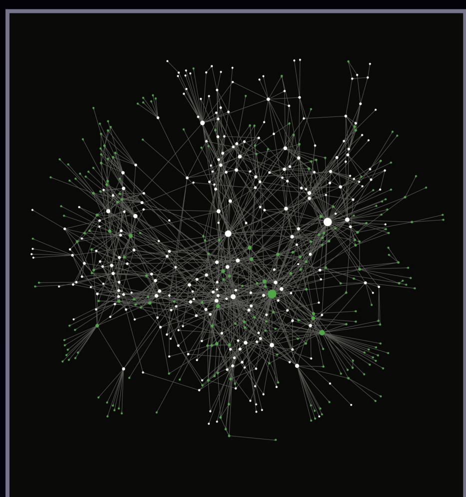
~10,000 LOC
>500 functions



void kernel_call () {
…
…
…
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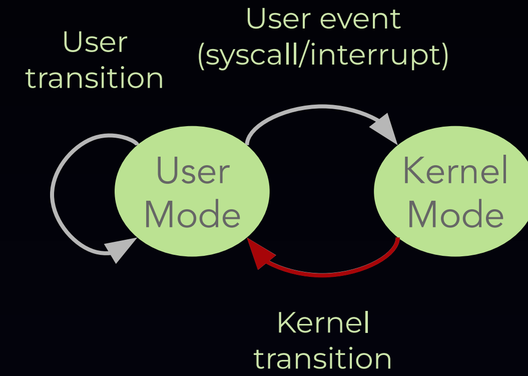
C Code



Assumed atomic

The unicore situation

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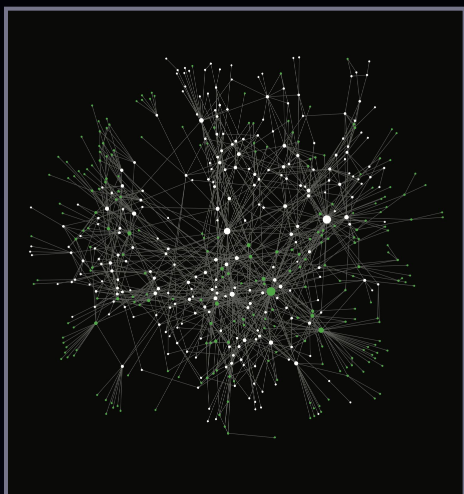

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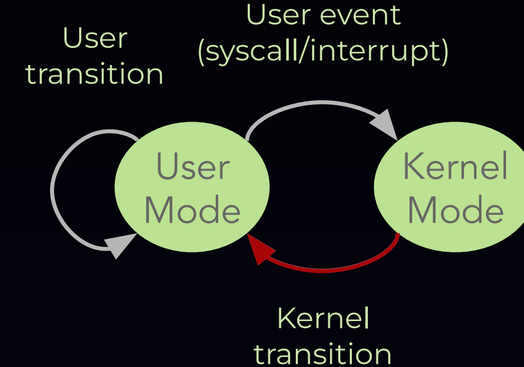
Functional Correctness

Specification

↕

C Code



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The multicore situation

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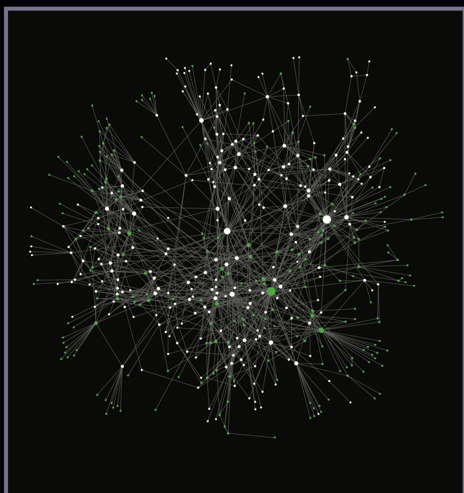

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Functional Correctness

Specification

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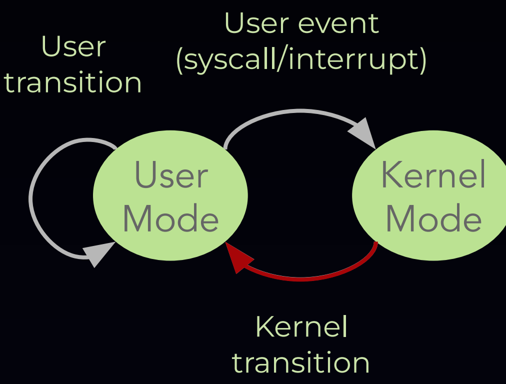

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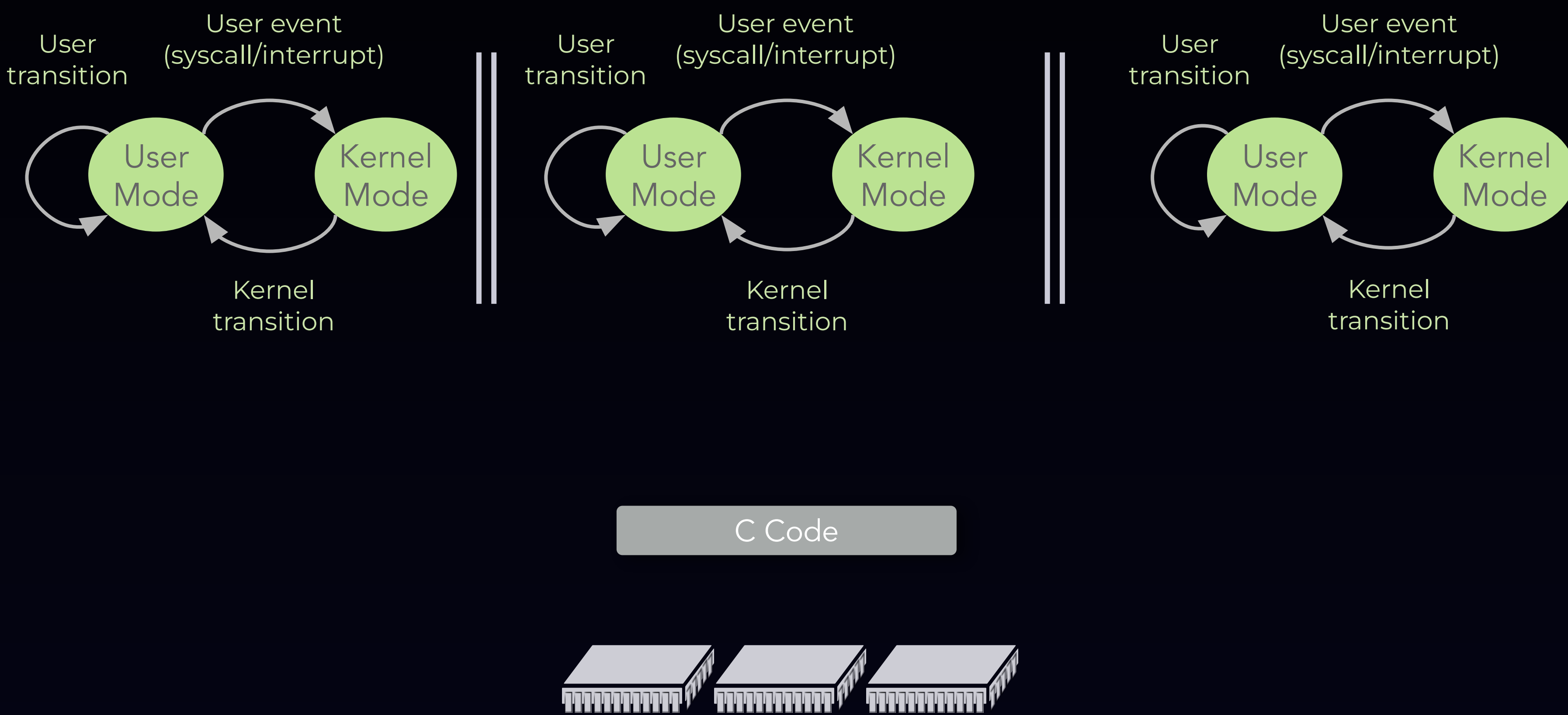

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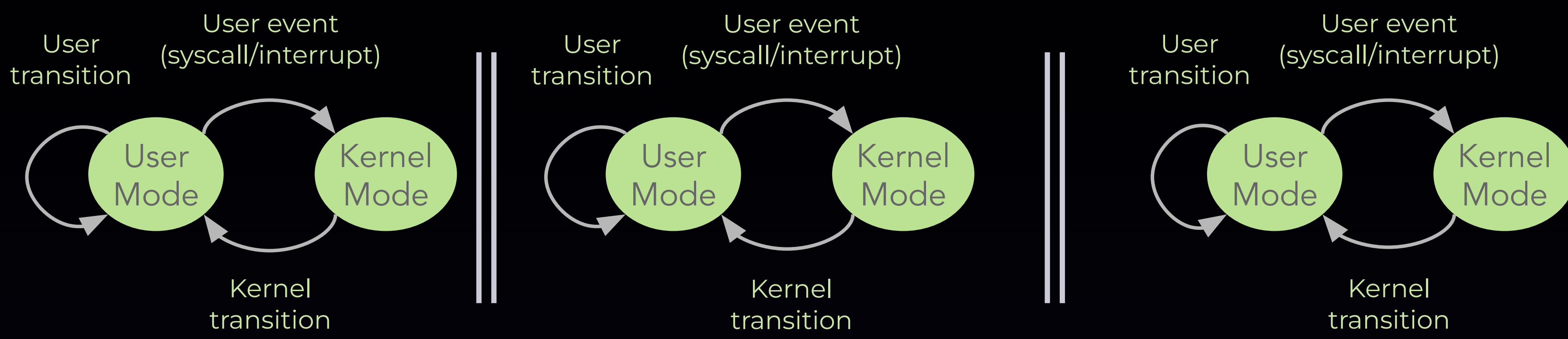
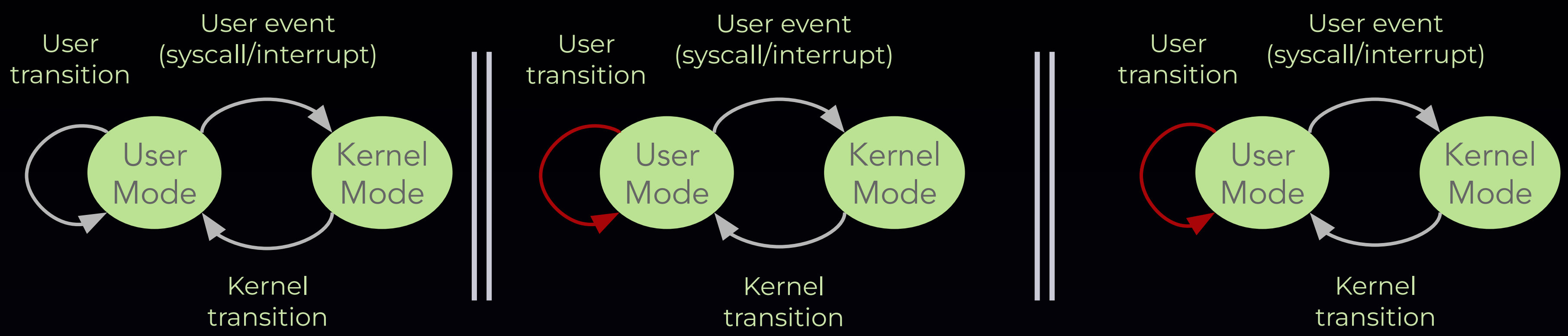


Introduces three types of concurrency

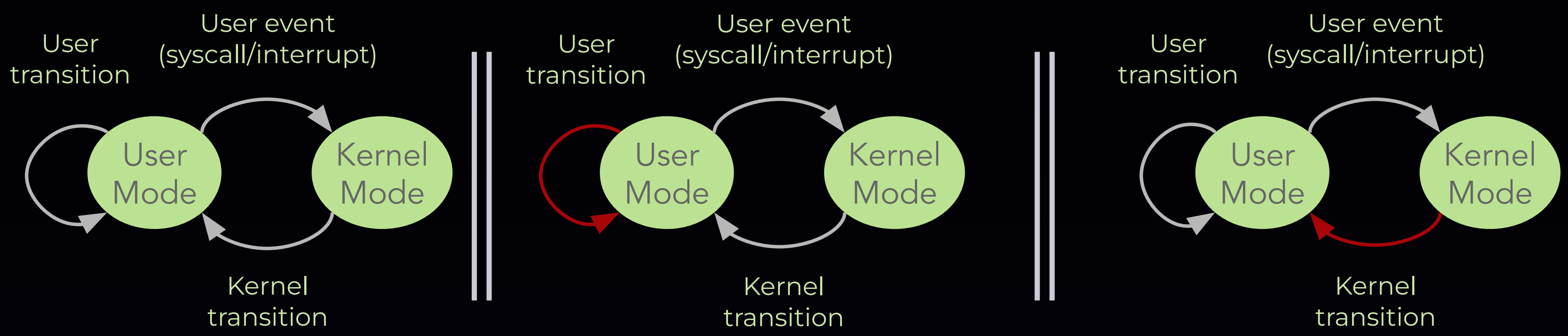
The multicore situation



Introduces three types of concurrency

1. User and User
   - Part of overall system design
   - Out of scope of kernel verification
   - Must reason about this for whole-system proofs

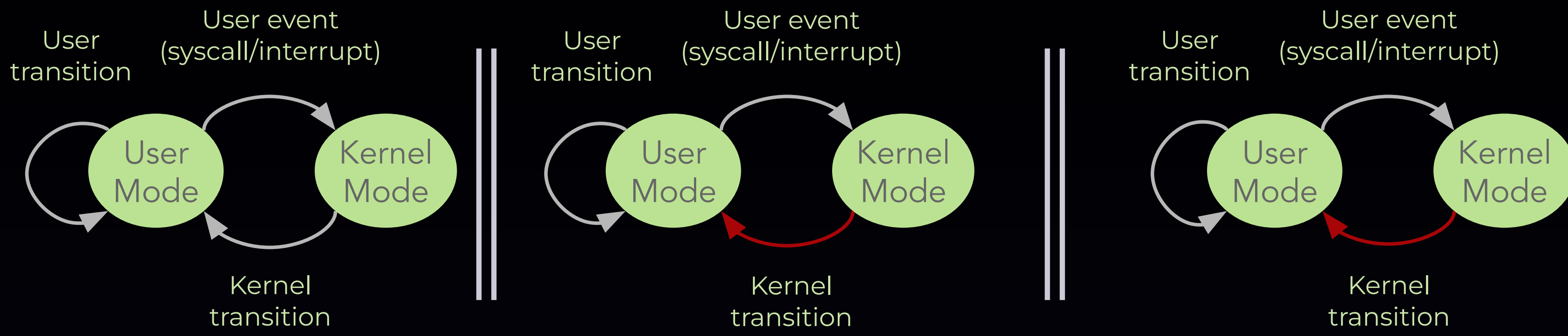
The multicore situation



Introduces three types of concurrency

2. User and Kernel
   - Must prove that the kernel does not depend on what the user has access to

The multicore situation



Introduces three types of concurrency

3. Kernel and Kernel
   - Must prove that the kernel itself correctly handles this
   - SMP seL4 does this with locks, the static multikernel uses separation of resources

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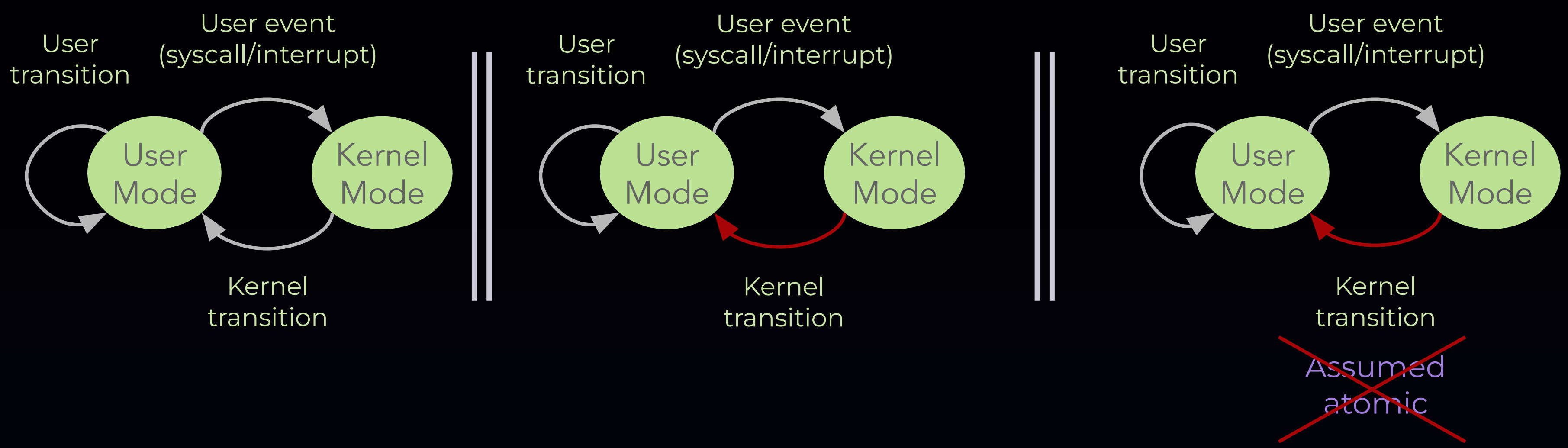

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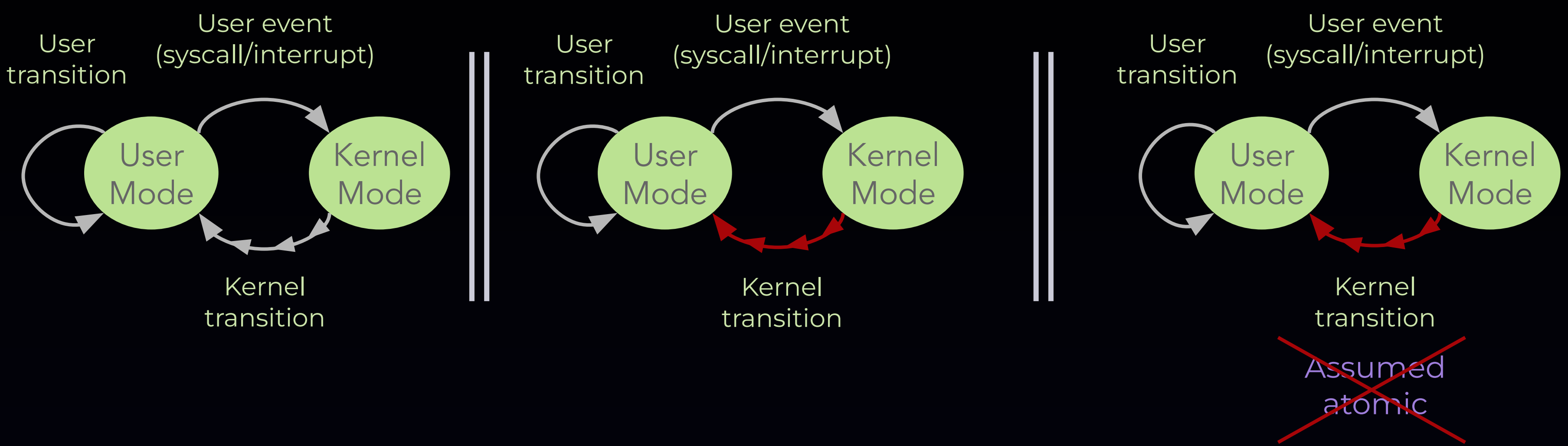

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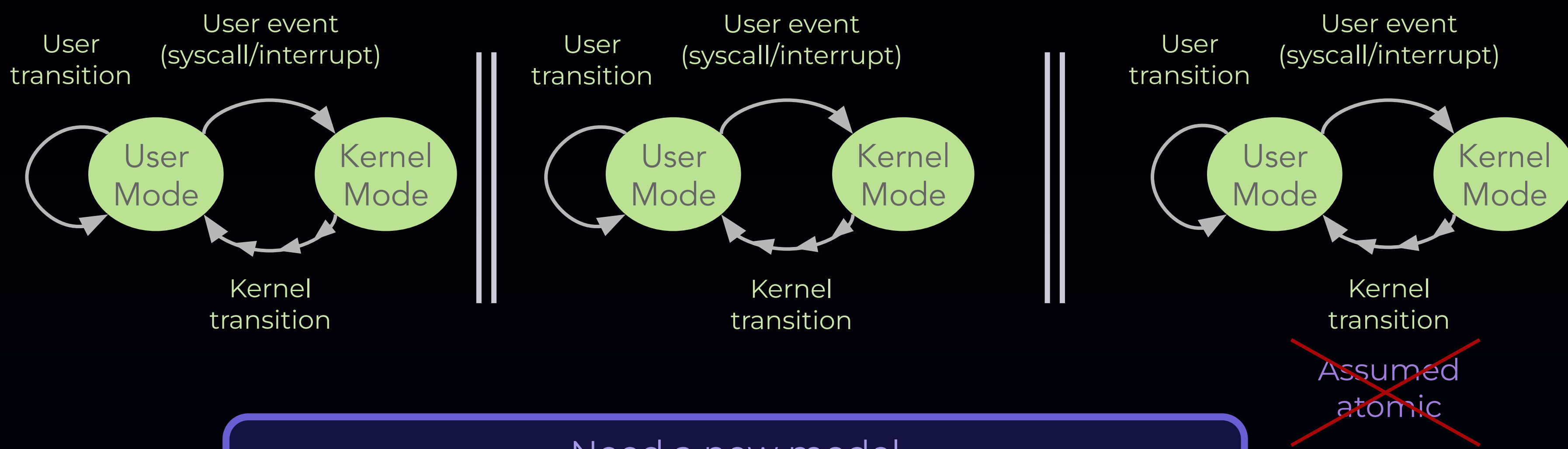
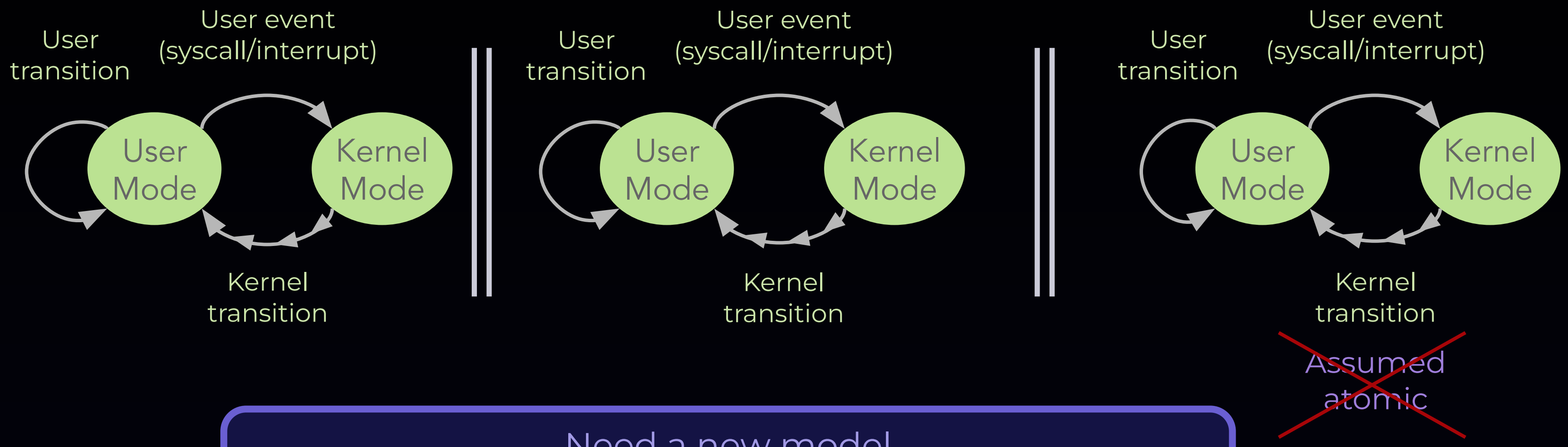


Need a new model
and verification framework

The multicore situation



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We want to maximise reuse of existing sequential proofs
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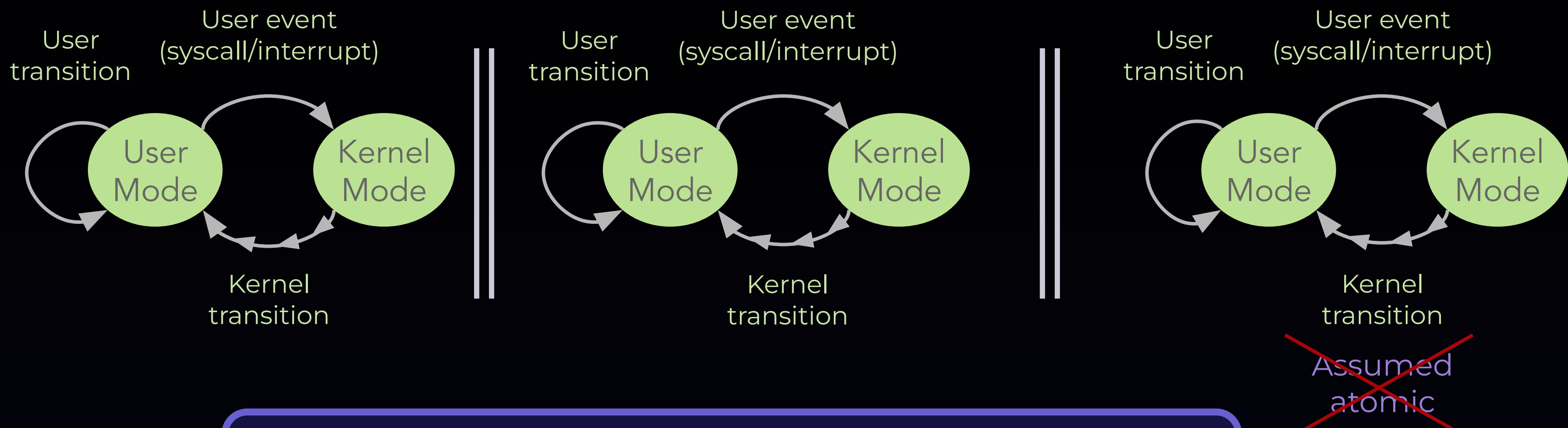

Need a new model
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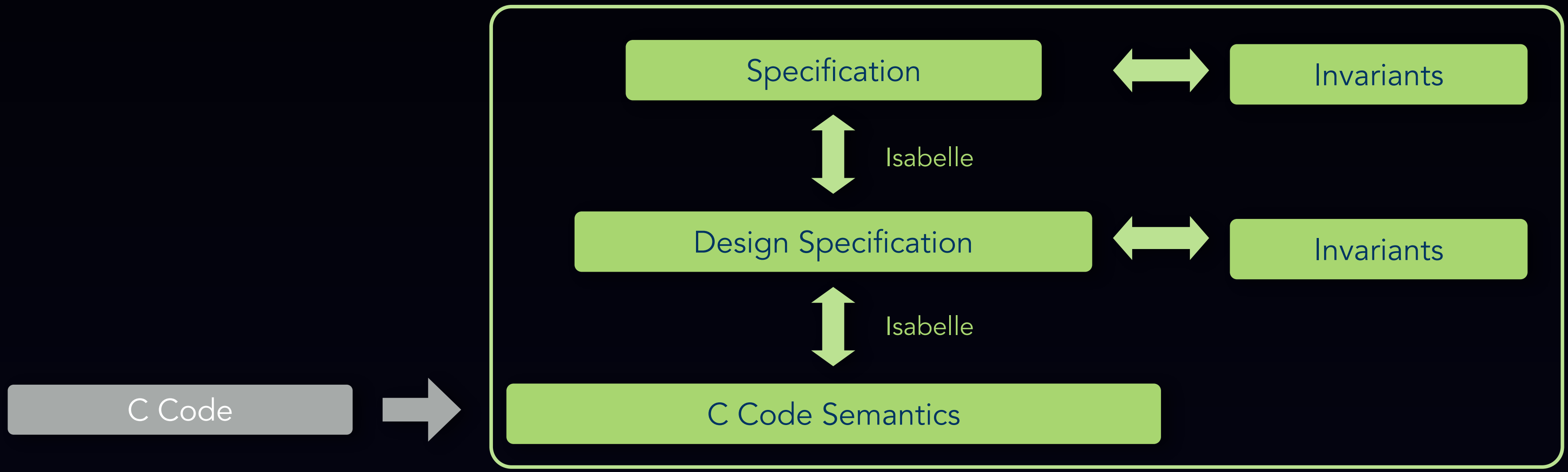
We have developed a proof-of-concept framework
for concurrent reasoning for seL4 with maximum reuse

The existing sequential framework (for unicore)



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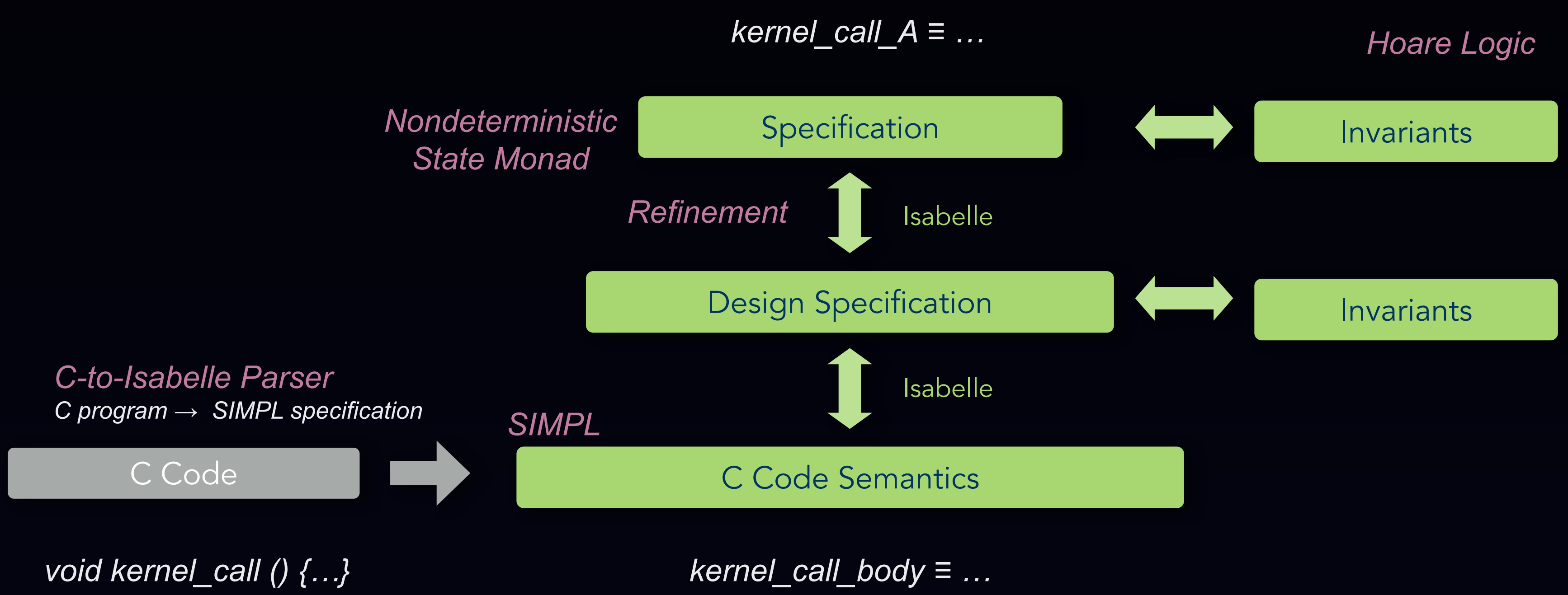
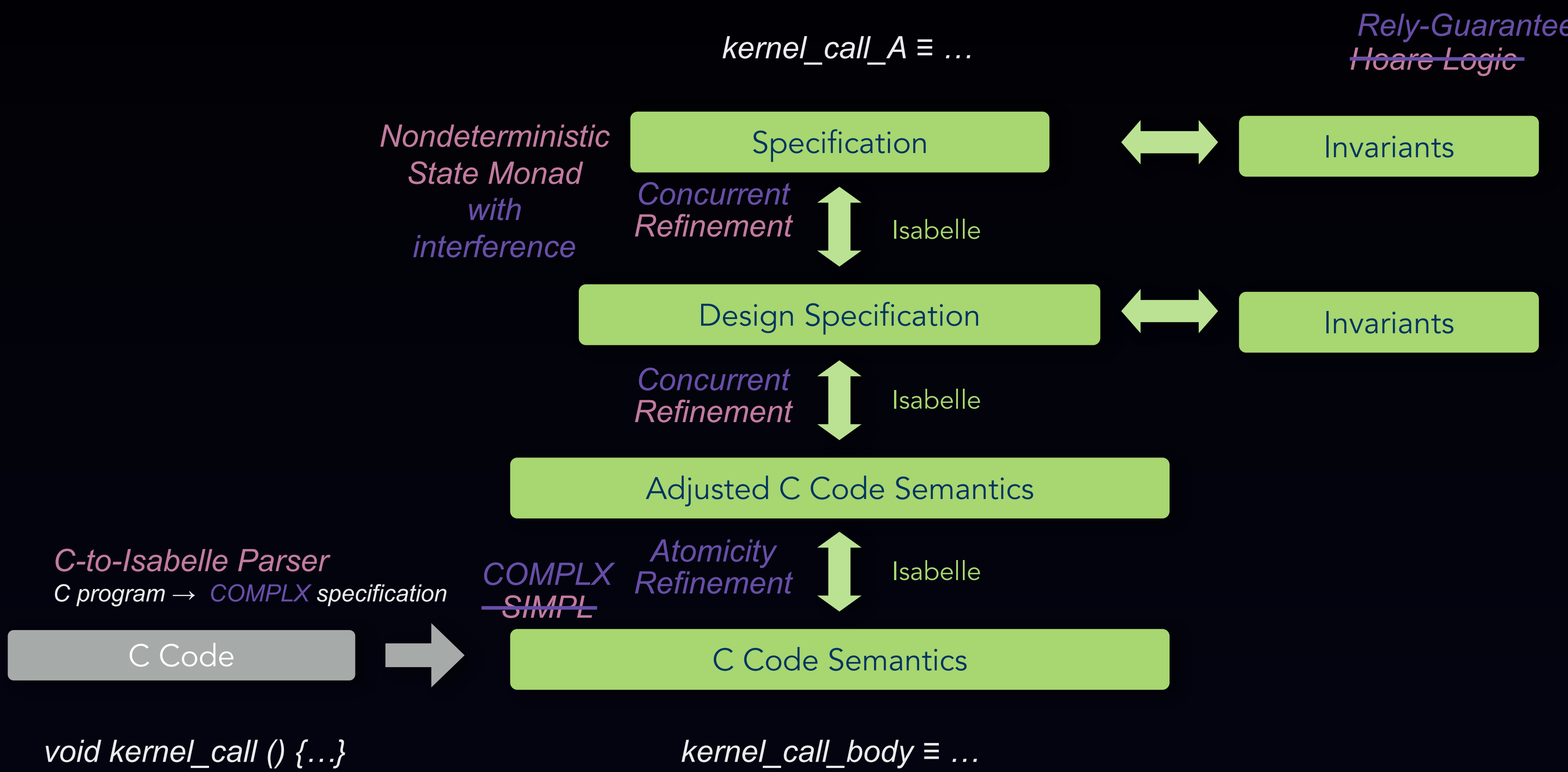
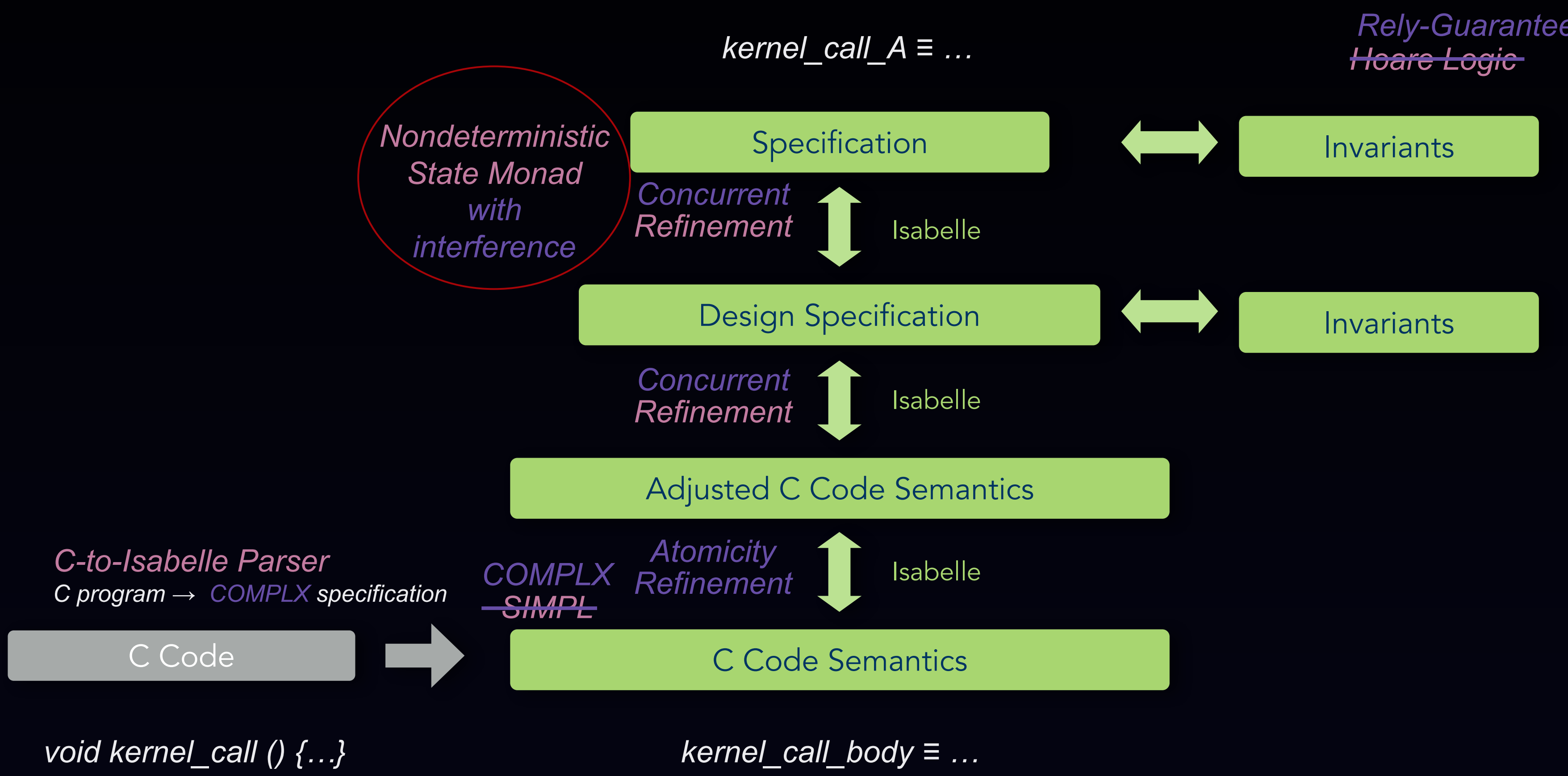


Proof-of-concept concurrent framework



Small dive: interference monad (to maximize reuse)



Small dive:

Sequential: Nondeterministic State Monad

$$\text{state} \longrightarrow (\text{result}, \text{state})\ \text{set}$$

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"do_fault_transfer badge sender receiver buf ≡ do
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Nondeterministic State Monad
With concurrency?

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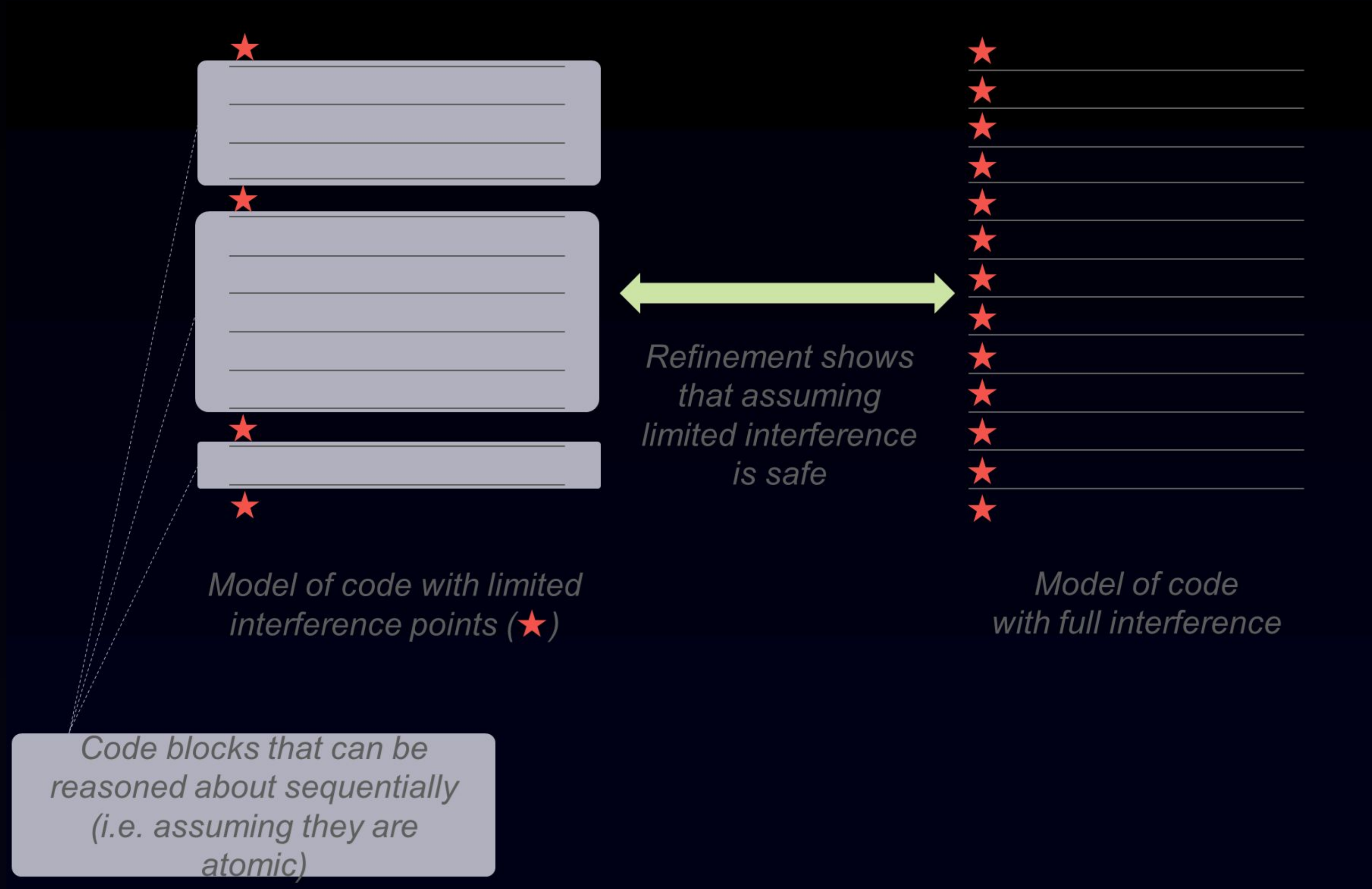
Limited interference



Small dive:

Concurrent: Interference Trace Monad

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Concurrent: Interference Trace Monad

$$state \longrightarrow (trace, (result, state))\ set$$

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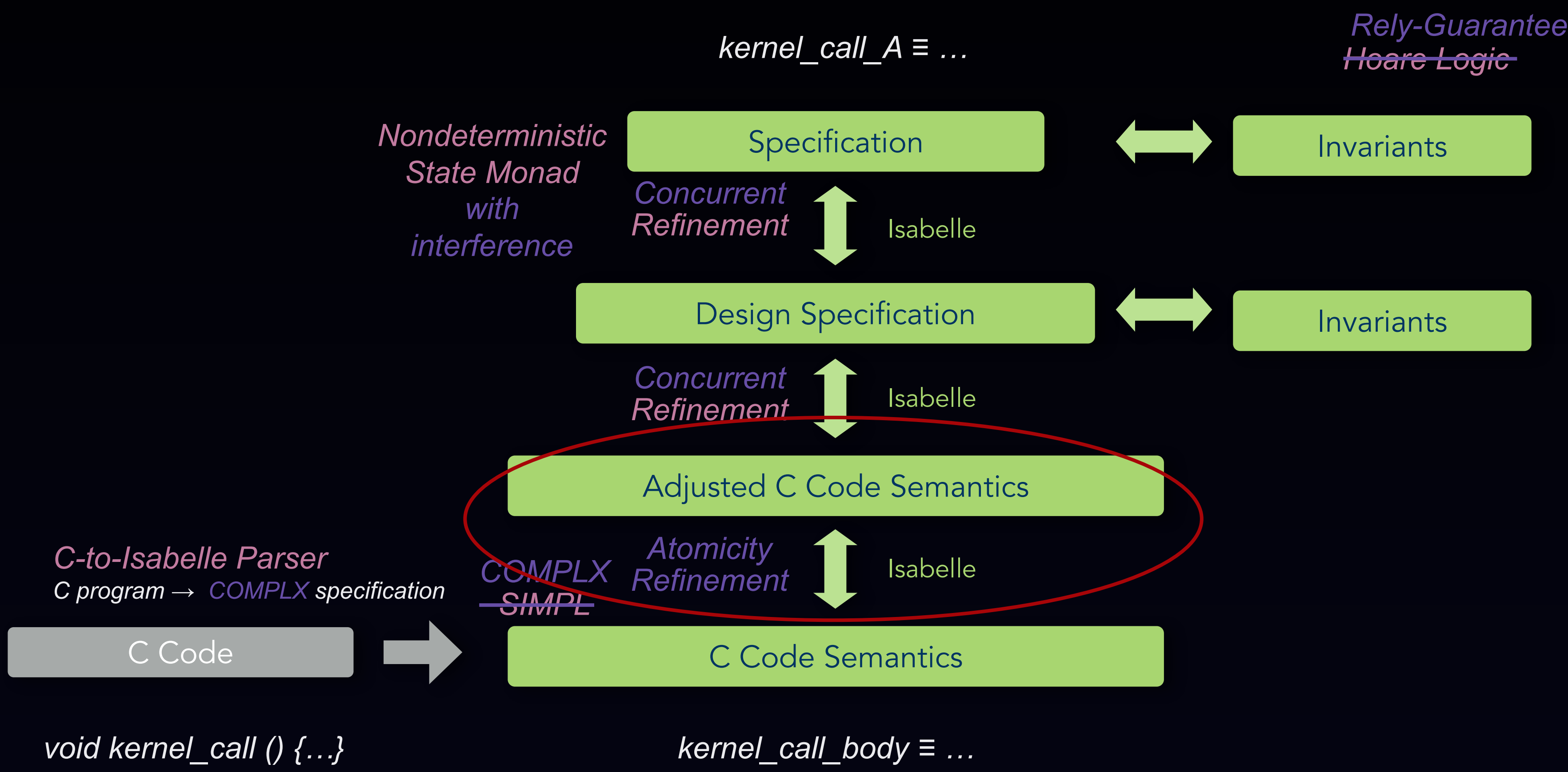
Proof-of-concept concurrent framework



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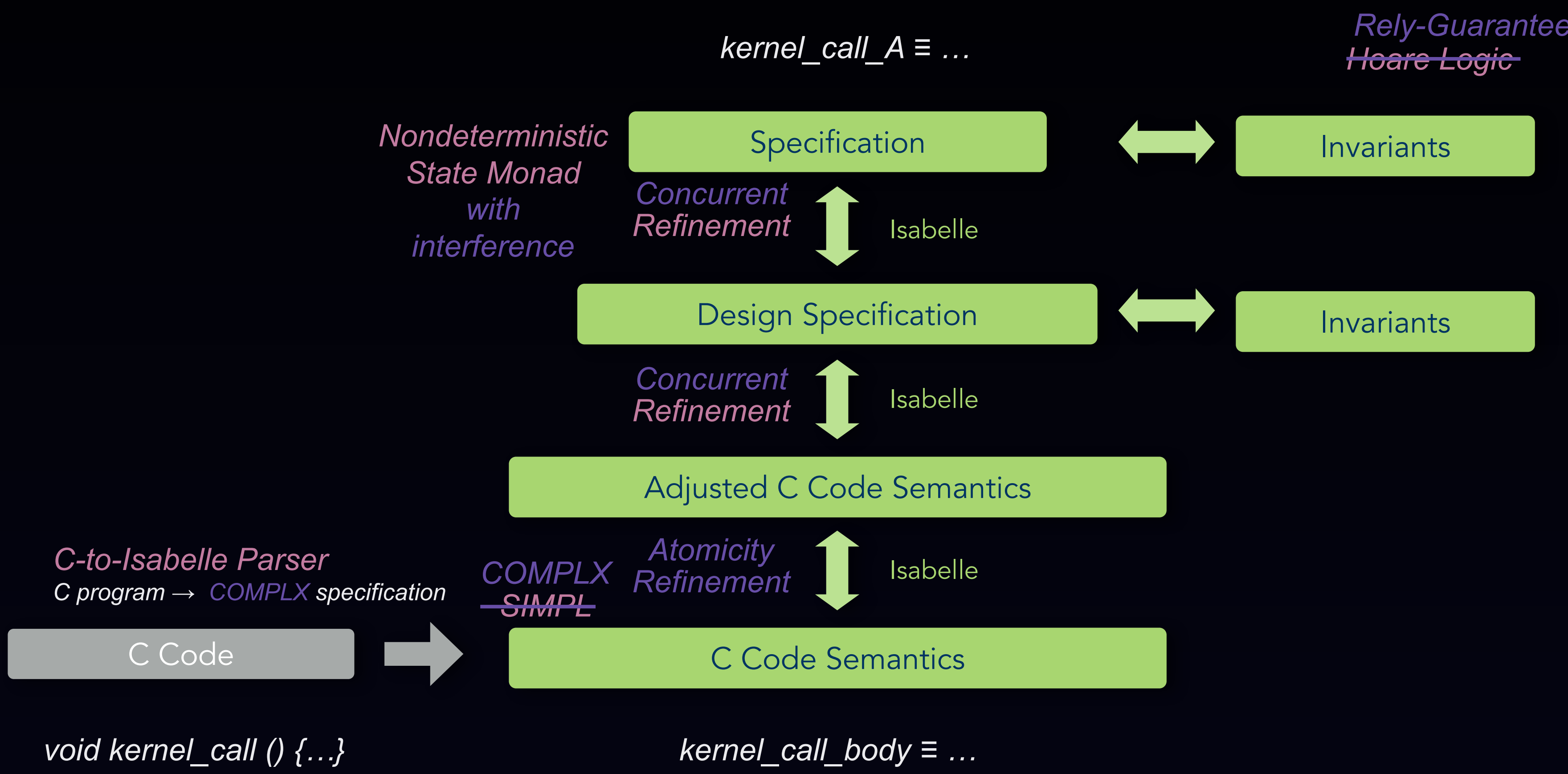

Proof-of-concept concurrent framework

Rely-Guarantee
~~oare Logic~~

riants

Now how do we apply this to update all of the seL4 proofs?

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Adjusted C Code Semantics

C-to-Isabelle Parser
C program → COMPLX specification

COMPLX
~~*SIMPL*~~

Atomicity Refinement

Isabelle

C Code

C Code Semantics

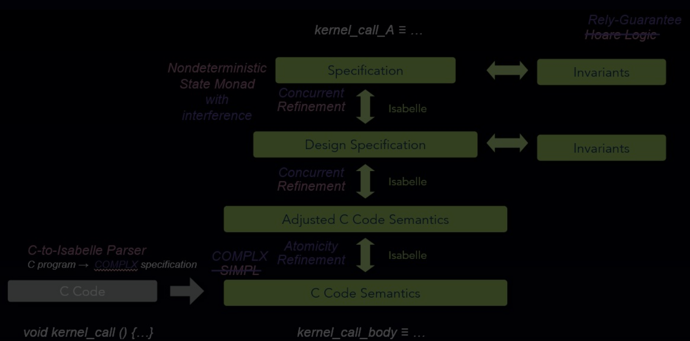
void kernel_call () {…}

kernel_call_body ≡ …

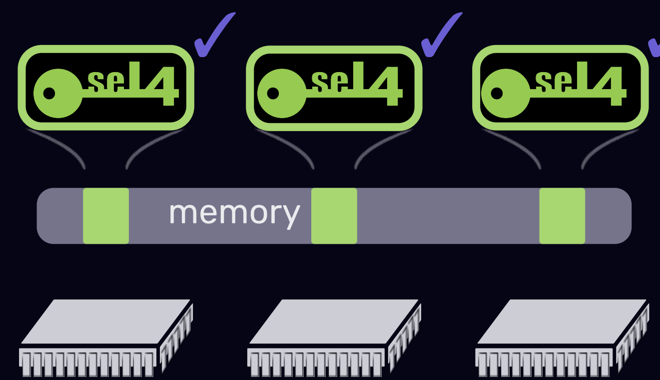
Overview

<u>Goal</u>:
Allow use of multiple cores as soon as possible,
With incrementally stronger and stronger assurance

What's hard?
What have we got so far?



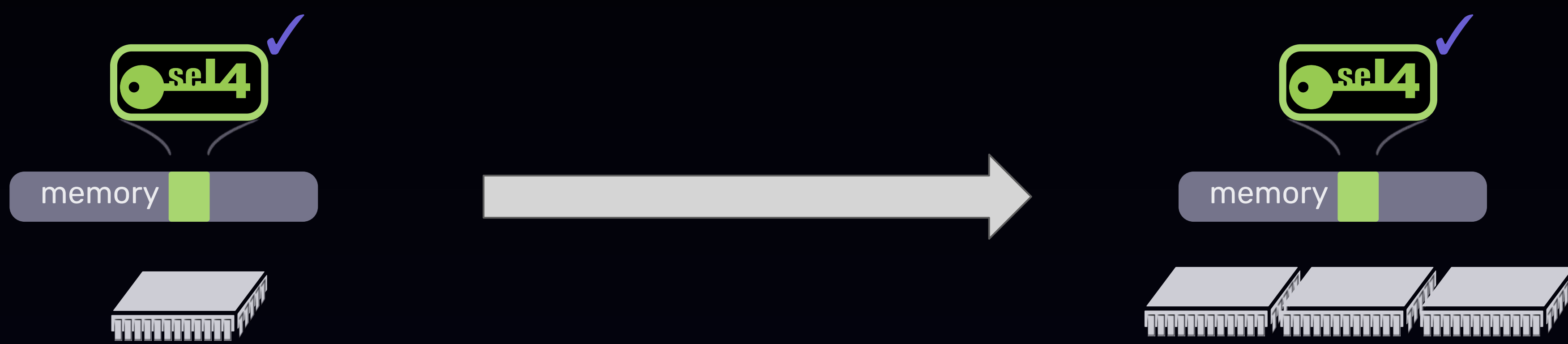
Towards a verified static multikernel seL4



Progressive roadmap

Single core

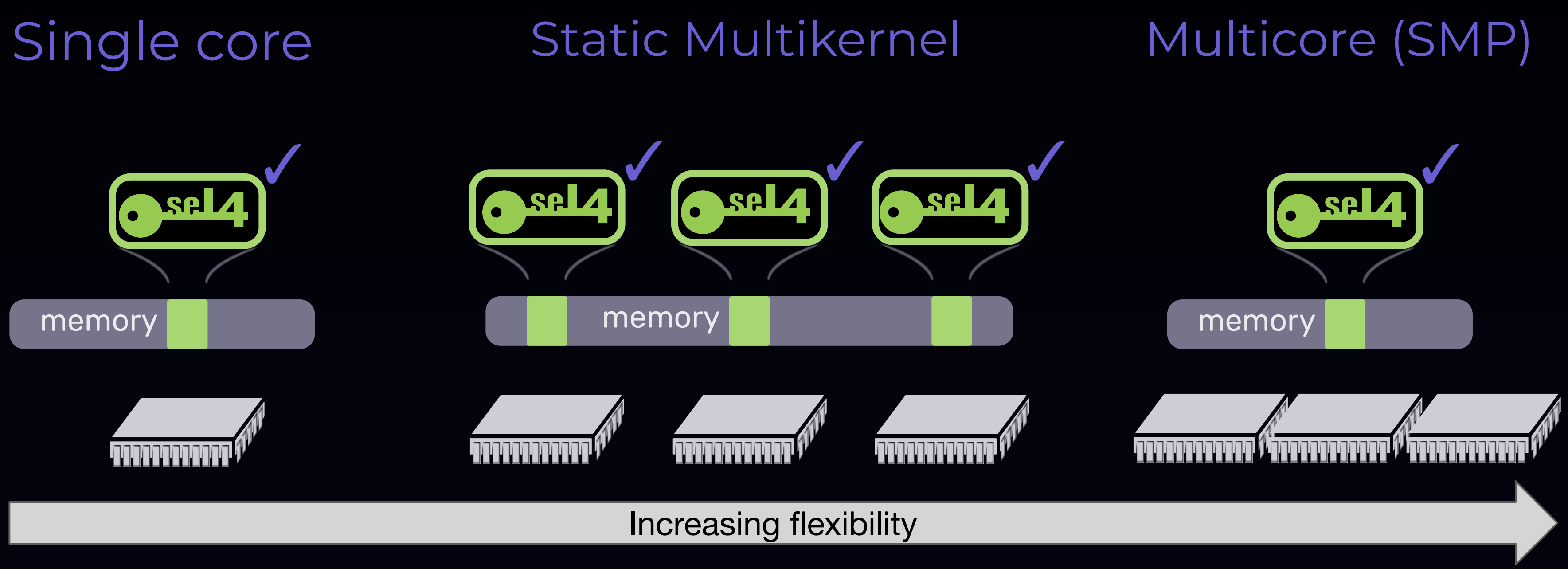
Multicore (SMP)



Need full concurrency on Day 1

No assurance until done

Progressive roadmap: via static multikernel



One seL4 per core

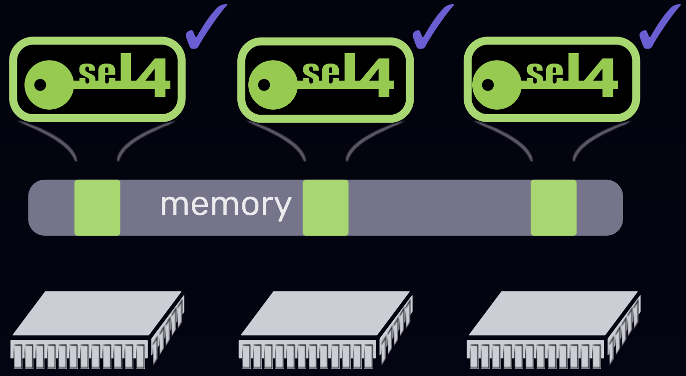
Progressively building stronger assurance from Day 1

Static multikernel configuration of seL4

- Each core runs a copy of the kernel
  - Each copy has separate resources and data structures
  - No kernel-kernel interactions

- User code communicates via shared memory and inter-processor interrupts
  - seL4 API remains nearly identical

- Static partition of memory simplifies verification
  - Still provides increased utility and performance



Multikernel seL4 verification roadmap

Assurance

Multikernel seL4 verification roadmap

Verify sequentially

- Verify code changes sequentially
  - Add IPI API

Sequentially correct

Assurance

Multikernel seL4 verification roadmap

✔ Verify sequentially

- Verify code changes sequentially
  - Add IPI API

Sequentially correct

Assurance

Multikernel seL4 verification roadmap

✔ Verify sequentially

List obligations

- Identify required proof obligations
  - e.g. separation of resources between kernel instances

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

. . .

Assurance

Multikernel seL4 verification roadmap

✔ Verify sequentially

List obligations — Prove obligations

- Prove required obligations in isolation
  - Proofs would still be sequential

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores
…

Assurance

Multikernel seL4 verification roadmap

✔ Verify sequentially

List obligations — Prove obligations

Parametrise specifications

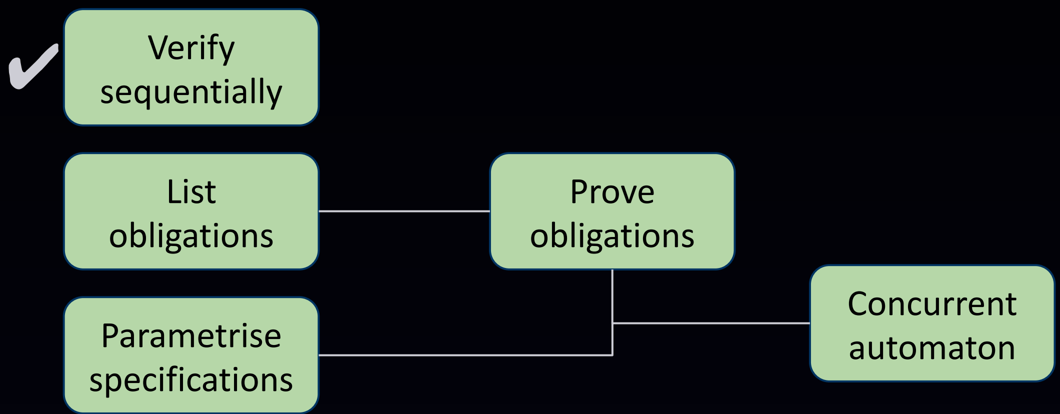
- Parametrise specifications to allow multiple instances of the kernel
  - Parameters such as physical memory location

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

…

Assurance

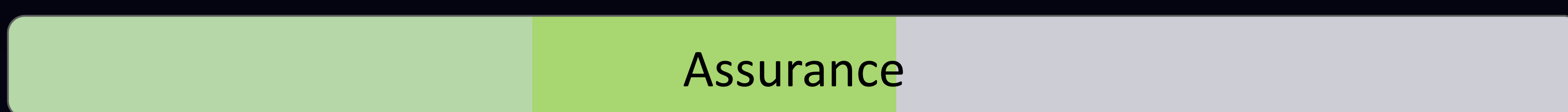
Multikernel seL4 verification roadmap



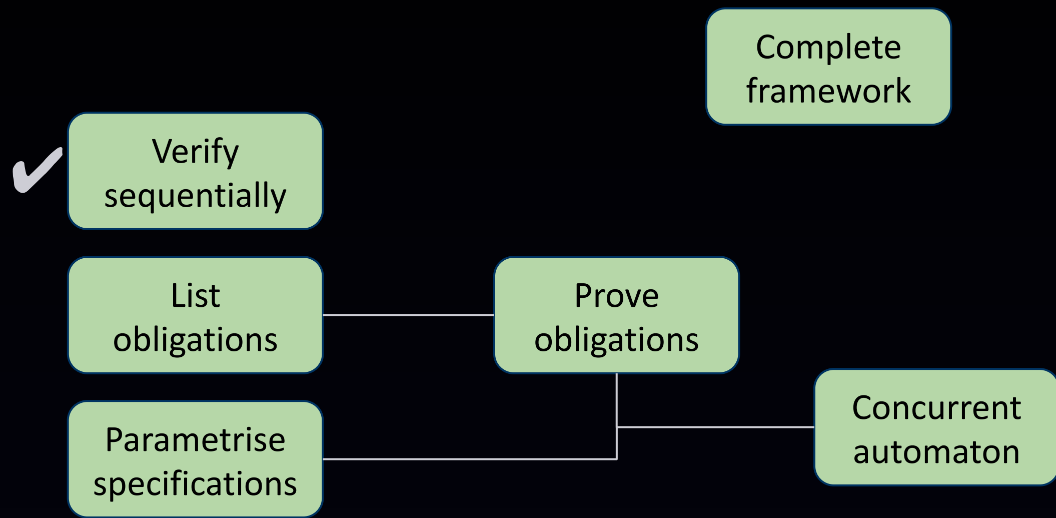
- Add coarse-grained concurrency to the automaton
  - Transitions are still atomic, some obligations will be validated

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

…
More proof obligations?



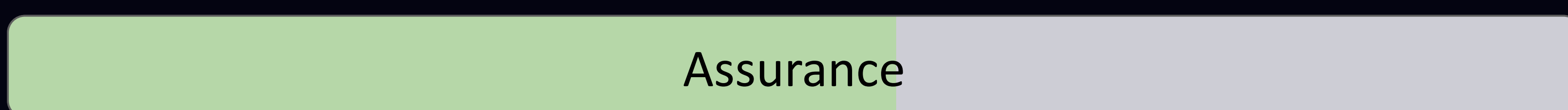
Multikernel seL4 verification roadmap



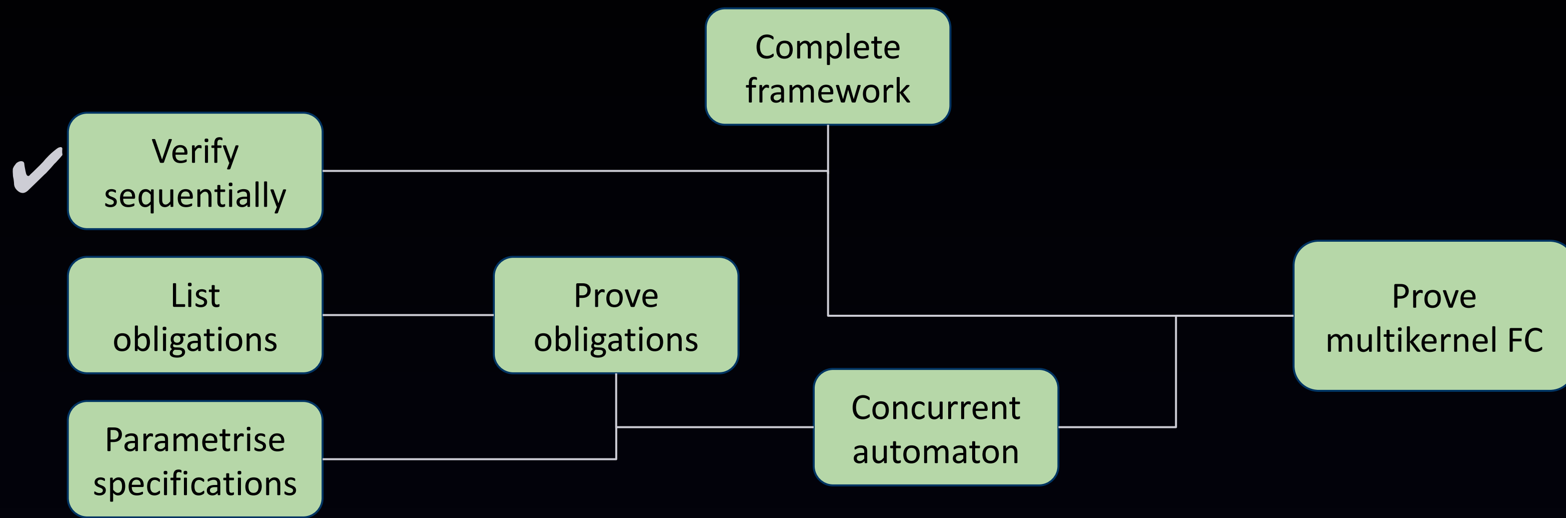
- Exercise and complete concurrency framework
  - Monad rulesets, haskell translator, atomicity refinement, C-Parser, …

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

…
More proof obligations?



Multikernel seL4 verification roadmap



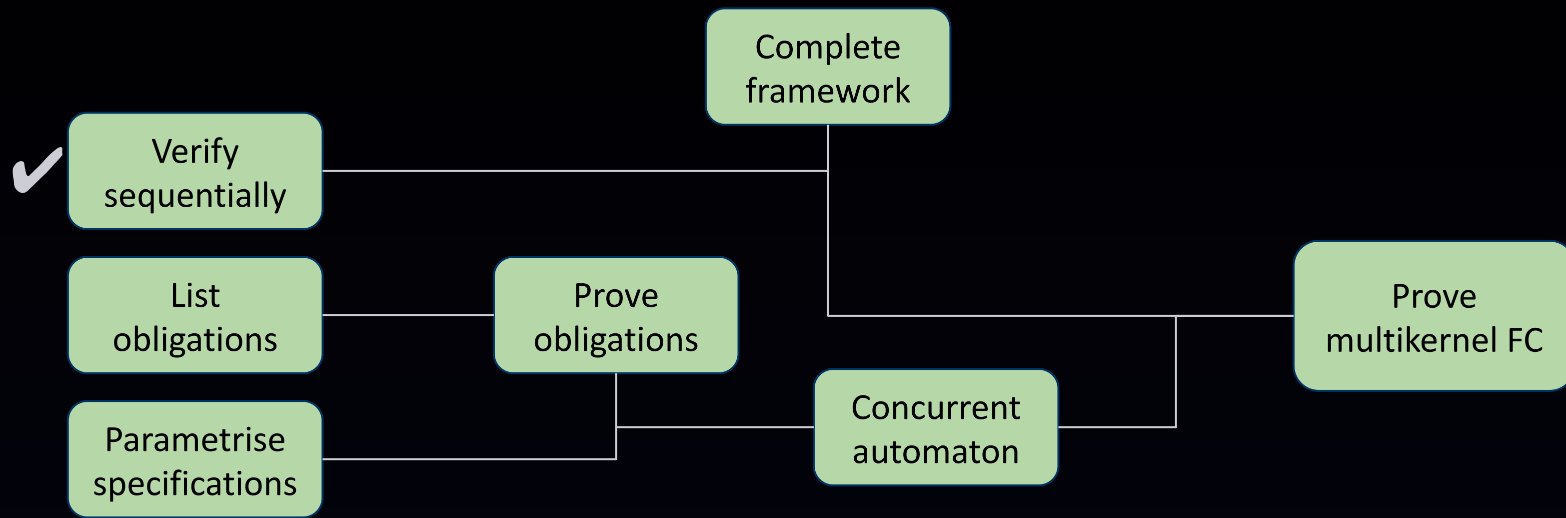
- Prove functional correctness for multikernel
  - This is where full concurrency is introduced

Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

…
More proof obligations?

Assurance

Multikernel seL4 verification roadmap



- Prove functional correctness for multikernel
  - This is where full concurrency is introduced

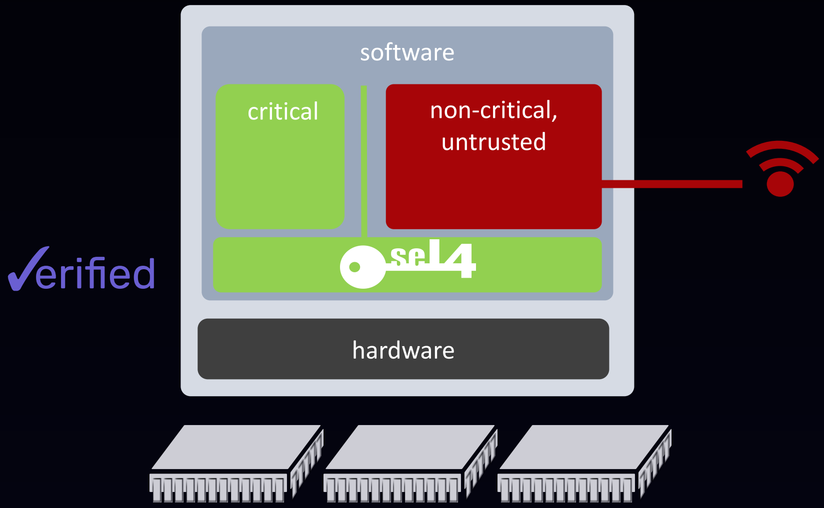
Sequentially correct
Separation of resources maintained
Isolation of kernels on different cores

…
More proof obligations?
Functional correctness!

Assurance

What do we want?

Goal:
Allow use of multiple cores as soon as possible,
with incrementally stronger and stronger assurance



Assurance

Thank you

Proofcraft
Corey Lewis
Principal Proof Engineer