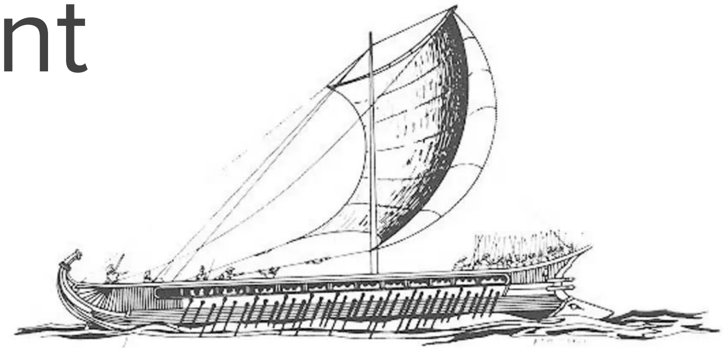
Theseus: an experiment in OS Structure and State Management



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Key Hypothesis

Fundamentally redesigning an OS to avoid *state spill* will make it easier to evolve and recover from faults.

How much can language and compilers help?

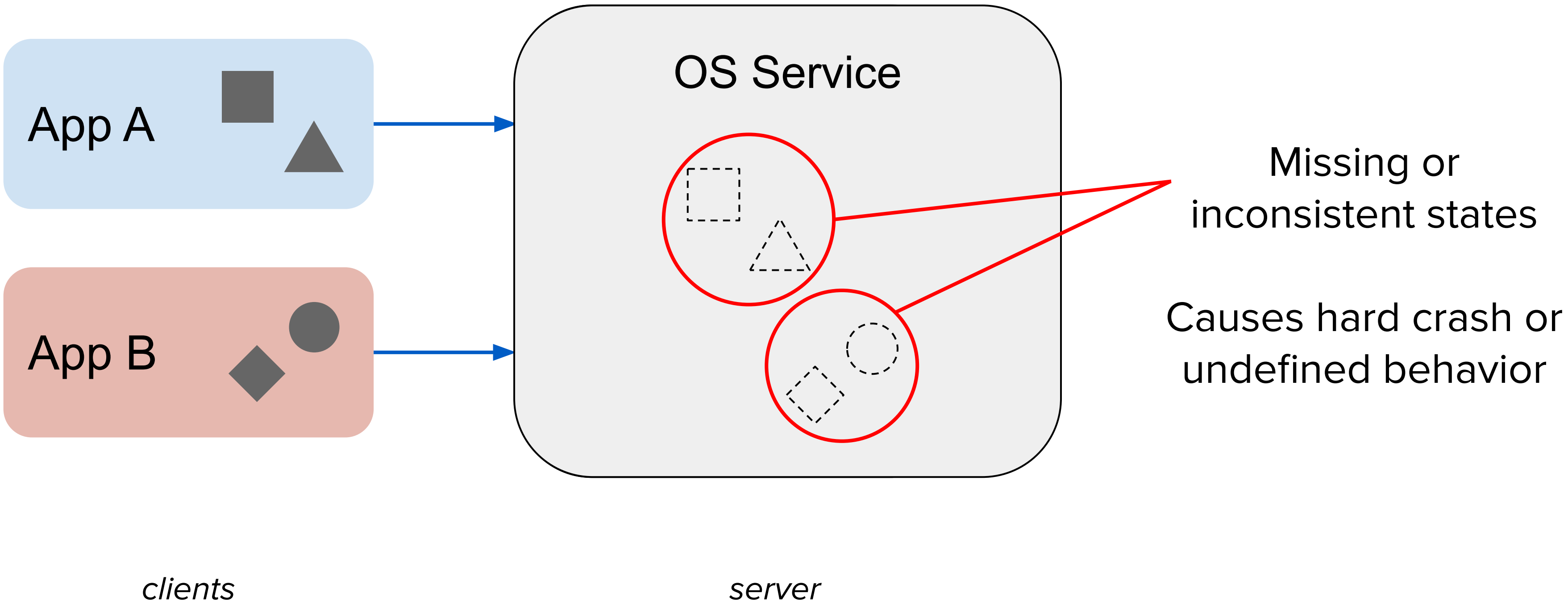
Initially motivated by study of state spill

- **State spill**: the state of a software component undergoes a lasting change a result of interacting with another component
    - Future correctness depends on those changed states

- State spill is a root cause of challenges in computing goals
    - Fault isolation, fault tolerance/recovery
    - Live update, hot swapping
    - Maintainability
    - Process migration
    - Scalability

      ...

Simple example of state spill



Motivation beyond state spill

- Modern languages can be leveraged for more than safety
  - Attracted to Rust due to ownership model & compile-time safety
  - Goal: statically ensure certain correctness invariants for OS behaviors

- Evolvability and availability are needed, even with redundancy
  - Embedded systems software must update w/o downtime or loss of context
  - Datacenter network switches still suffer outages from software failures and maintenance updates

Theseus in a nutshell

1. Establishes OS structure of many tiny components
   - *All* components must have runtime-persistent bounds
2. Adopt *intralingual* OS design to empower Rust compiler
   - Leverage language strengths to go beyond safety
   - Shift responsibility of resource bookkeeping from OS into compiler
3. Avoids state spill or mitigates its effects

- Designed with evolvability and availability in mind

- ~38K lines of Rust code from scratch, 900 lines of assembly

Theseus design principles

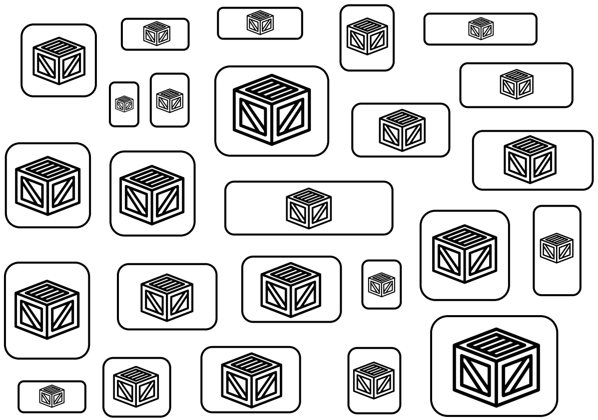
P1. Require *runtime-persistent* bounds for *all* components

P2. Maximize the power of the language and compiler

P3. Avoid state spill

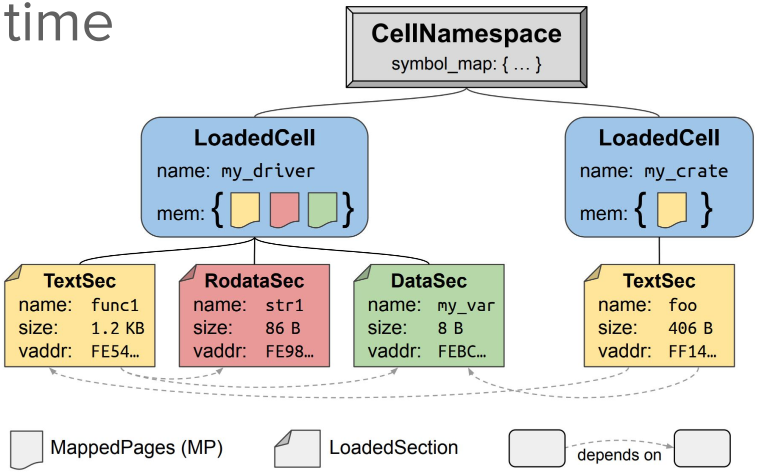
OS structure of many tiny components

- Each component is a **cell**
  - Software-defined unit of modularity
- Cells are based on **crates**
  - Rust’s project container
  - Source code + dependency manifest
  - Elementary unit of compilation



P1: Runtime-persistent cell bounds

- **All** cells are dynamically loaded at runtime
  - Not just drivers or kernel extensions
- Allows Theseus to track cell bounds
  - Location & size in memory (MP)
  - Bidirectional dependencies



- Single address space & single privilege level
  - All components across whole system are observable as cells
  - Single *cell swapping* mechanism is uniformly applicable
  - Jointly evolve cells from multiple system layers (app, kernel) safely

P2: Maximally leverage/empower compiler

- Take advantage of Rust's powerful abilities
  - Rust compiler checks many built-in safety invariants
    - e.g., memory safety for objects on stack & heap
  - Extend compiler-checked invariants to *all* resources

- *Intralingual* design requires:
  1. Matching compiler's expected execution model
  2. Implementing OS semantics fully within strong, static type system

Matching compiler's execution model

1. Single address space environment
   - Single set of visible virtual addresses
   - Bijective 1-to-1 mapping from virtual to physical address
2. Single privilege level
   - Only one world of execution (ring 0)
3. Single allocator instance
   - Rust expects one global allocator to serve all alloc requests
   - Theseus implements multiple per-core heaps
     within the single `GlobalAlloc` instance

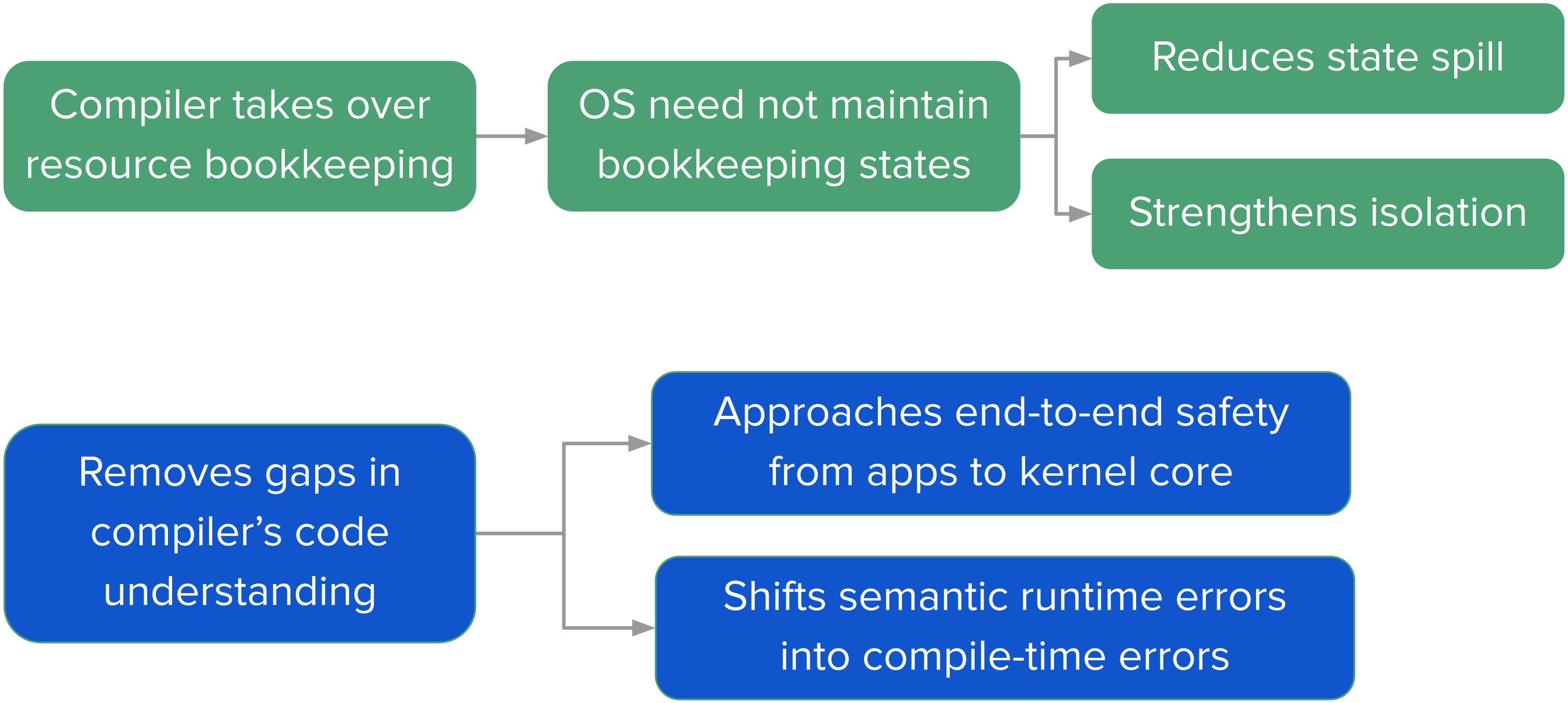
Intralingual OS implementation in brief

(0) Use & prioritize safe code as much as possible

1. Identify invariants to prevent unsafe, incorrect resource usage
    - Express semantics using existing language-level mechanisms
        - Enables compiler to subsume OS's resource-specific invariants
2. Preserve language-level context with lossless interfaces
    - e.g., type info, lifetime, ownership/borrowed status
    - Statically ensure *provenance* of language context

- Go beyond safety: prevent resource leakage
    - Theseus implements custom unwinder, which ensures cleanup

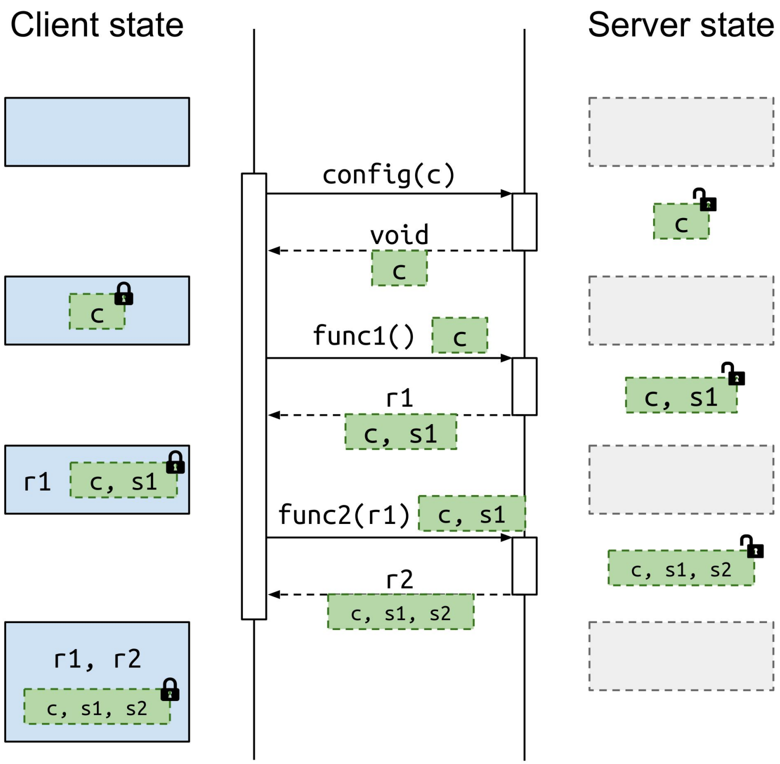
Ensuing benefits of intralingual design



P3: Addressing state spill

- Key technique: *opaque exportation*
  - Corollary is *stateless communication* (à la REST)
- Avoid known spillful abstractions, e.g., handles
- Shared states via joint ownership
- Permit *soft states*
  - Cached values that do not hinder to evolution or availability
- Accommodate hardware-required states

Opaque exportation via intralinguality



- Shift responsibility of holding progress state from server to client

- Only possible because:
  1. Server can safely relinquish its state to client, who can't arbitrarily introspect into or modify server-private state
     - Via type & memory safety
  2. System can revoke client states to reclaim them on behalf of the server
     - Via unwinder

Example: memory management

- Problems with conventional memory management:
    - Map, remap, unmap cause state spill into `mm` entity
        - Client-side *handles* (virtual addresses) to server-side VMA entries
    - Unsafety due to semantic gap between OS-level and language-level understanding of memory usage
    - Extralingual sharing: mapping multiple pages to the same frame

- Solution: the `MappedPages` abstraction

`MappedPages` code overview

```
pub struct MappedPages {
    pages:  AllocatedPages,
    frames: AllocatedFrames,
    flags:  EntryFlags,
}
```

```
pub fn map(pages: AllocatedPages,
           frames: AllocatedFrames,
           flags: EntryFlags, ...
) -> Result<MappedPages> {
    for (page, frame) in pages.iter().zip(frames.iter()) {
        let mut pg_tbl_entry = pg_tbl.walk_to(page, flags)?
            .get_pte_mut(page.pte_offset());
        pg_tbl_entry.set(frame.start_address(), flags)?;
    }
    Ok(MappedPages { pages, frames, flags })
}
```

- Virtually contiguous memory region
- Cannot create invalid or non-bijective mapping
  - `map()` accepts only owned `AllocatedPages/Frames`, *consuming* them

Ensuring safe access to memory regions

```
impl Drop for MappedPages {
    fn drop(&mut self) {
        // unmap: clear page table entry, inval TLB.
        // AllocatedPages/Frames are auto-dropped
        // and deallocated here.
    }
}
impl MappedPages {
    pub fn as_type<'m, T>(&'m self, offset: usize)
            -> Result<&'m T> {
        if offset + size_of::<T>() > self.size() {
            return Error::OutOfBounds;
        }
        let t: &'m T = unsafe {
            &*((self.pages.start_address() + offset) };
        Ok(t)
    }
}
```

- Guaranteed mapped while held
  - Auto-unmapped *only* upon drop
  - Prevents use after free, double free
- Can only *borrow* memory region
  - Overlay sized type atop regions
  - Forbids taking ownership of overlaid struct, a **lossy** action
  - Others not shown: `as_slice()`, `as_type_mut()`, `as_func()`

Safely using `MappedPages` for MMIO

```
struct HpetRegisters {
    pub capabilities_and_id: ReadOnly<u64>,
    _padding:                [u64, ...],
    pub main_counter:        Volatile<u64>,
    ...
}

fn main() -> Result<()> {
    let frames = get_hpet_frames()?;
    let pages = allocate_pages(frames.count())?;
    let mp_pgs = map(pages, frames, flags, pg_tbl)?;
    let hpet: &HpetRegisters = mp_pgs.as_type(0)?;
    let ticks = hpet_regs.main_counter.read();
    print!("HPET ticks: {}", ticks);
    // `mp_pgs` auto-dropped here
}
```

- Owned directly by app/task
    - No state spill into `mm` subsystem
- Unwinder prevents leakage
    - Ensures `mp_pgs` is unmapped, even upon panic

`MappedPages` compiler-checked invariants

1. Virtual-to-physical mapping must be bijective (1 to 1)
   - Prevents extralingual sharing
2. Memory is not accessible beyond region bounds
3. Memory region must be unmapped exactly once
   - After no more references to it exist
   - Must not be accessible after being unmapped
4. Memory can only be mutated or executed if mapped as such
   - Avoids page protection violations

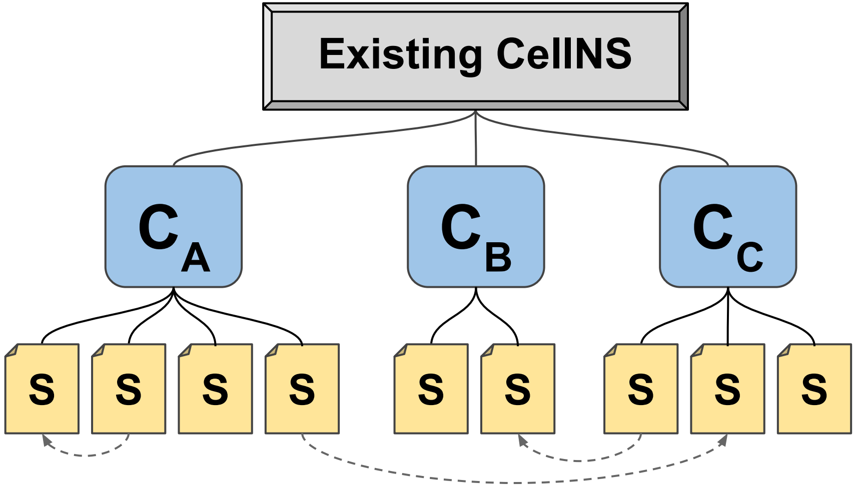
MappedPages statically prevents invalid page faults

Compiler-checked Task invariants

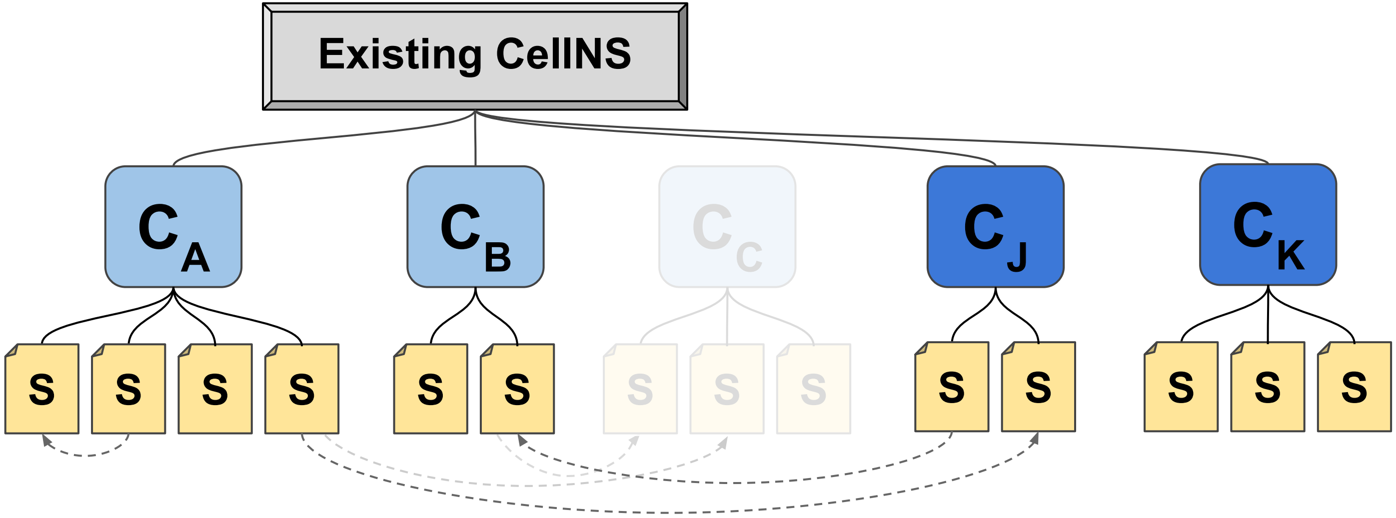
1. Spawning a new task must not violate safety
2. Accessing task states must always be safe and deadlock-free
3. Task states must be fully released in all execution paths
4. All memory reachable from a task must outlive that task

see paper for details

Realizing live evolution via cell swapping



Live evolution via cell swapping



i. Load all new cells into empty CellNamespace
ii. Verify dependencies
iii. Redirect (re-link) dependent old cells to use new cells
iv. Remove old cells, clean up

Theseus facilitates evolutionary mechanisms

- Runtime-persistent bounds simplify cell swapping
  - Dynamic loader ensures non-overlapping memory bounds
  - No size or location restrictions, no interleaving ➜ cleanly removable cells
- Spill-free design of cells results in:
  - Less (faster) dependency rewriting and state transfer
  - More safe update points
- Cell metadata accelerates cell swapping
  - Dependency verification = quick search of symbol map
  - Only scan stacks of tasks whose entry functions can reach old crates

Realizing availability via fault recovery

- Many classes of faults prevented by Rust safety & intralinguality
  - Focus on transient *hardware-induced* faults beneath the language level

- Cascading approach to fault recovery

Stage 1:	**Tolerate fault:**	clean up task via unwinding
Stage 2:	**Restart task:**	respawn new instance
Stage 3:	**Reload cells:**	replace corrupted cells

↓ increasingly intrusive

- Recovery mechanisms have few dependencies
  - Works in core OS contexts, such as CPU exception handlers
  - Microkernels need userspace, context switches, interrupts, IPC

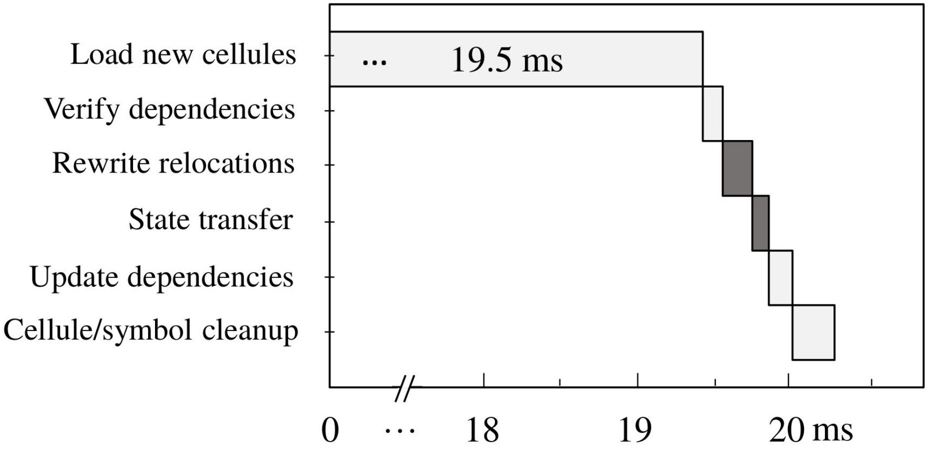
Brief evaluation overview

- Live evolution case studies
- Fault recovery experiments
  - Injecting faults into Theseus
  - Comparison with MINIX 3 microkernel
- Cost of intralingual and spill-free design
- Microbenchmark comparison with Linux
  - Negligible overhead of runtime-persistent bounds (dynamic linking)
  - IPC fastpath is competitive with microkernel and safe-language OSes

Live Evolution: sync ➜ async “IPC”

- Theseus advances evolution beyond monolithic/microkernel OSes
  - Safe, joint evolution of user-kernel interfaces and functionality
  - Evolution of core components that must exist in microkernel
- Do microkernels need to change? Change histories say *yes*
  - IPC is noteworthy change

Theseus suffers no state loss evolving sync ➜ async ITC



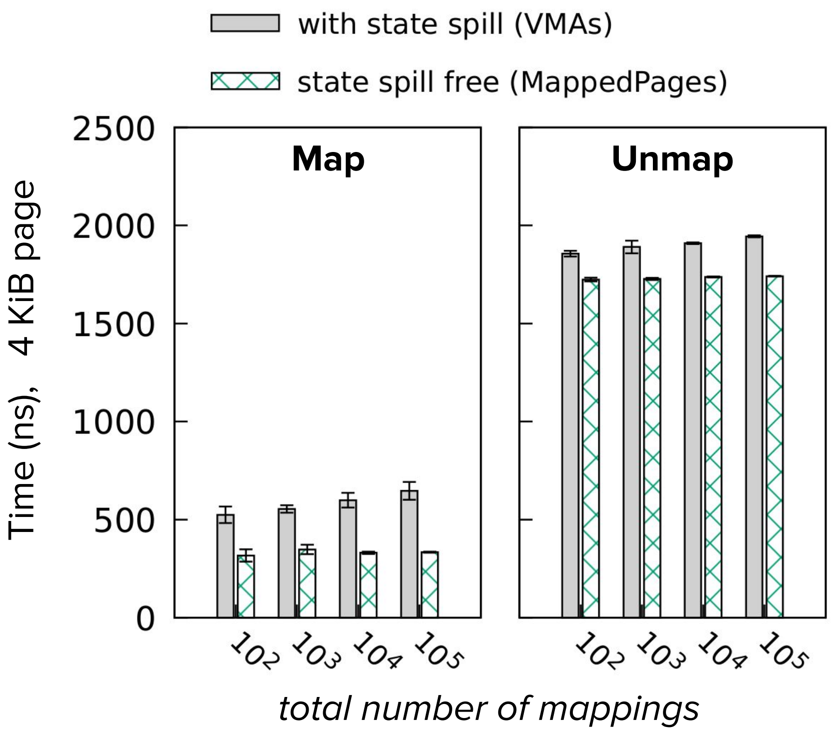
General fault recovery: 69% success

- Injected 800K faults, 665 manifested
  - Workloads include graphical rendering, task spawning, FS access, ITC channels
  - Targeted the working set of task stack, heap, cell sections in memory
- Most failures due to lack of asynchronous unwinding
  - Point of failure (instr ptr) isn't covered by compiler's unwinding table

Successful Recovery	**461**
Restart task	50
Reload cell	411
Failed Recovery	**204**
Incomplete unwinding	94
Hung task	30
Failed cell replacement	18
Unwinder failure	62

Cost of intralinguality & state spill freedom

`MappedPages` performs better



Safe heap: up to 22% overhead

due to allocation bookkeeping

Heap impl.	*threadtest*	*shbench*
unsafe	20.27 ± 0.009	3.99 ± 0.001
partially safe	20.52 ± 0.010	4.54 ± 0.002
safe	24.82 ± 0.006	4.89 ± 0.002

times in seconds (s)

Limitations at a glance

- Unsafety is a necessary evil ➜ detect *infectious* unsafe code
- Reliance on safe language
  - Must trust Rust compiler and `core/alloc` libraries
- Intralinguality not always possible
  - Nondeterministic runtime conditions, incorporating legacy code
- Tension between state spill freedom and legacy compatibility
  - Make decision on per-subsystem basis, e.g., prefer legacy FS

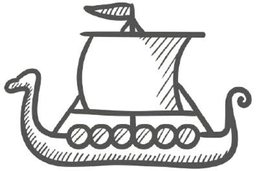
Conclusion: Theseus design recap

1. Structure of many tiny cells
   - Dynamic loading/linking ➜ runtime-persistent bounds for all
2. Empower the language through intralinguality
   - Beyond safety: subsume OS correctness invariants into compiler checks
   - Shift resource bookkeeping duties into compiler, prevent leakage
3. Avoid state spill

➜ Designed to facilitate evolvability and availability

Thanks -- contact us for more!

github.com/theseus-os/Theseus



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