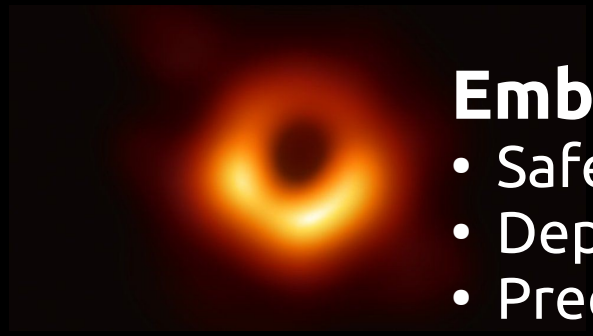
Component-based OS Design for *Dependable* Cyber-Physical Systems

Gabriel Parmer, Runyu Pan, Yuxin Ren, Phani Kishore Gadepalli, Wenyuan Shao

The George Washington University
gparmer@gwu.edu

Gravitational Pull in CPSes



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- Safety
- Dependability
- Predictability

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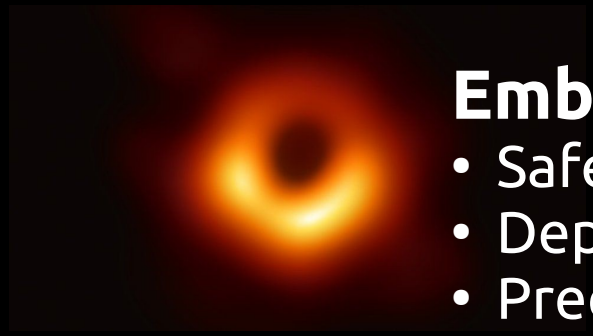

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- Functionality
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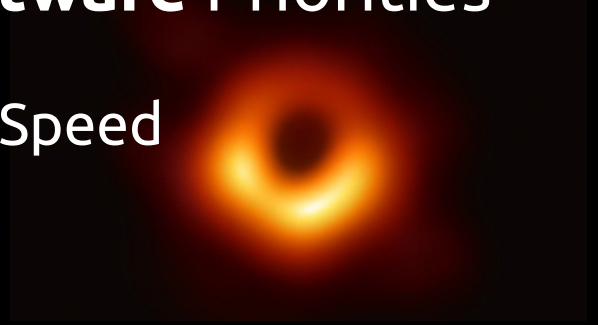
- Throughput
- Security



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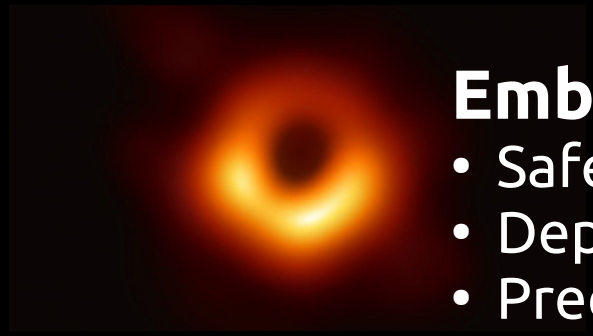

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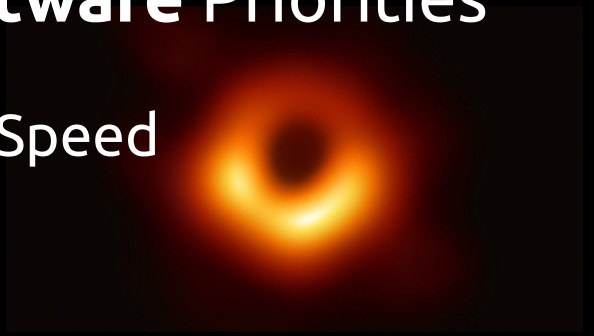

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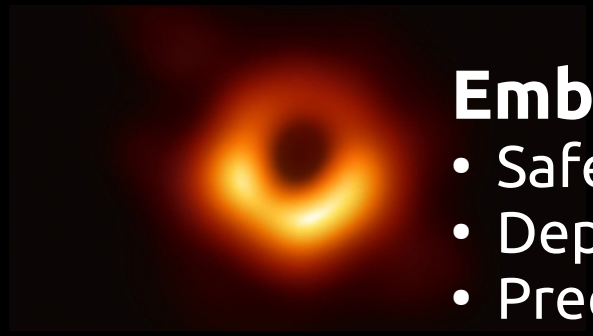

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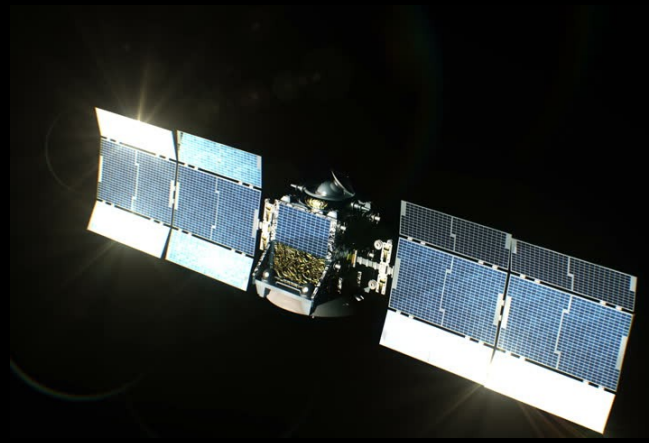

Cyber-Physical Systems

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- Functionality
- Development Speed
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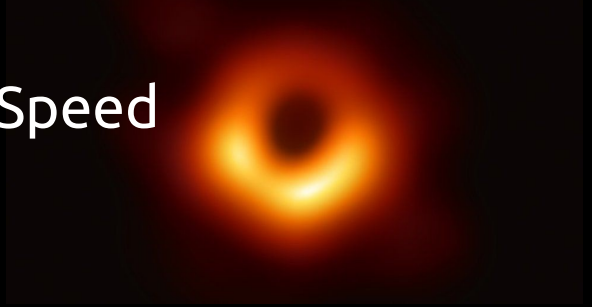
- Security



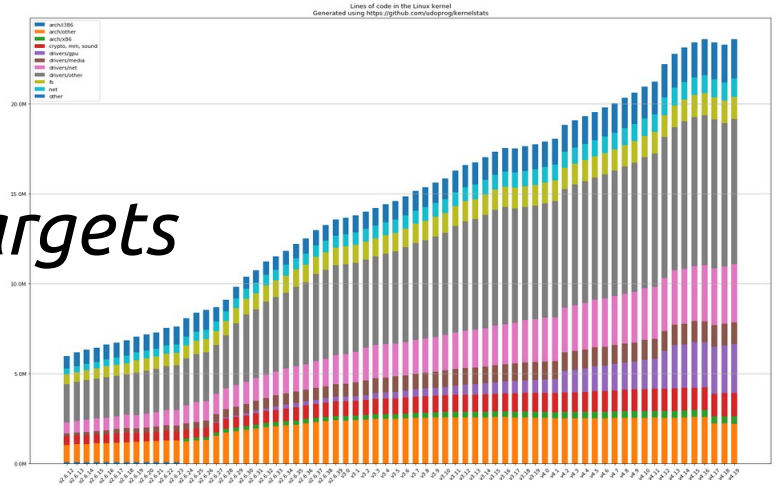
POSIX++

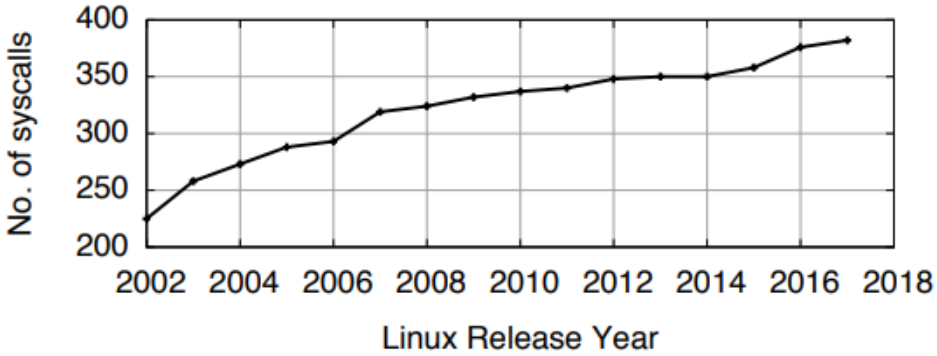
- Enduring foundation
  - Pervasive for high-functionality libraries/apps
  - Extended in many directions

- Dominates high-functionality SW development
  - *Move fast and break things*

Beyond POSIX

- Lot of *warts*
  - fork, signals, allocation, copies…
- Practical systems: *fast moving targets*
  - ...or vulnerable
- *Insufficient*
  - Linux-specific extensions commonplace
- Implied *complexity*
  - Little ability to scale down





RTOSes

- Simple(-ish) implementations
  - Some support for more complicated standards

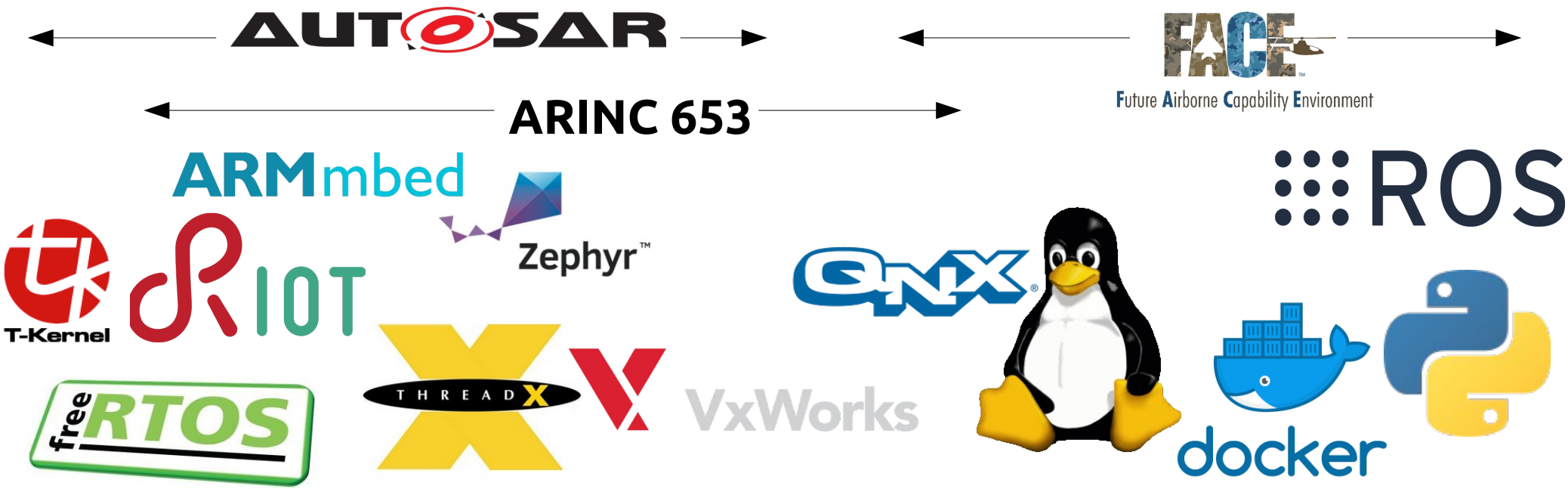
- Standards:

ARINC 653 AUTOSAR FACE™ Future Airborne Capability Environment

Beyond RTOSes

- Limited software availability
- Inefficient use of multi-core
- Large ecosystem
  - With difficult code reuse story
- Silos

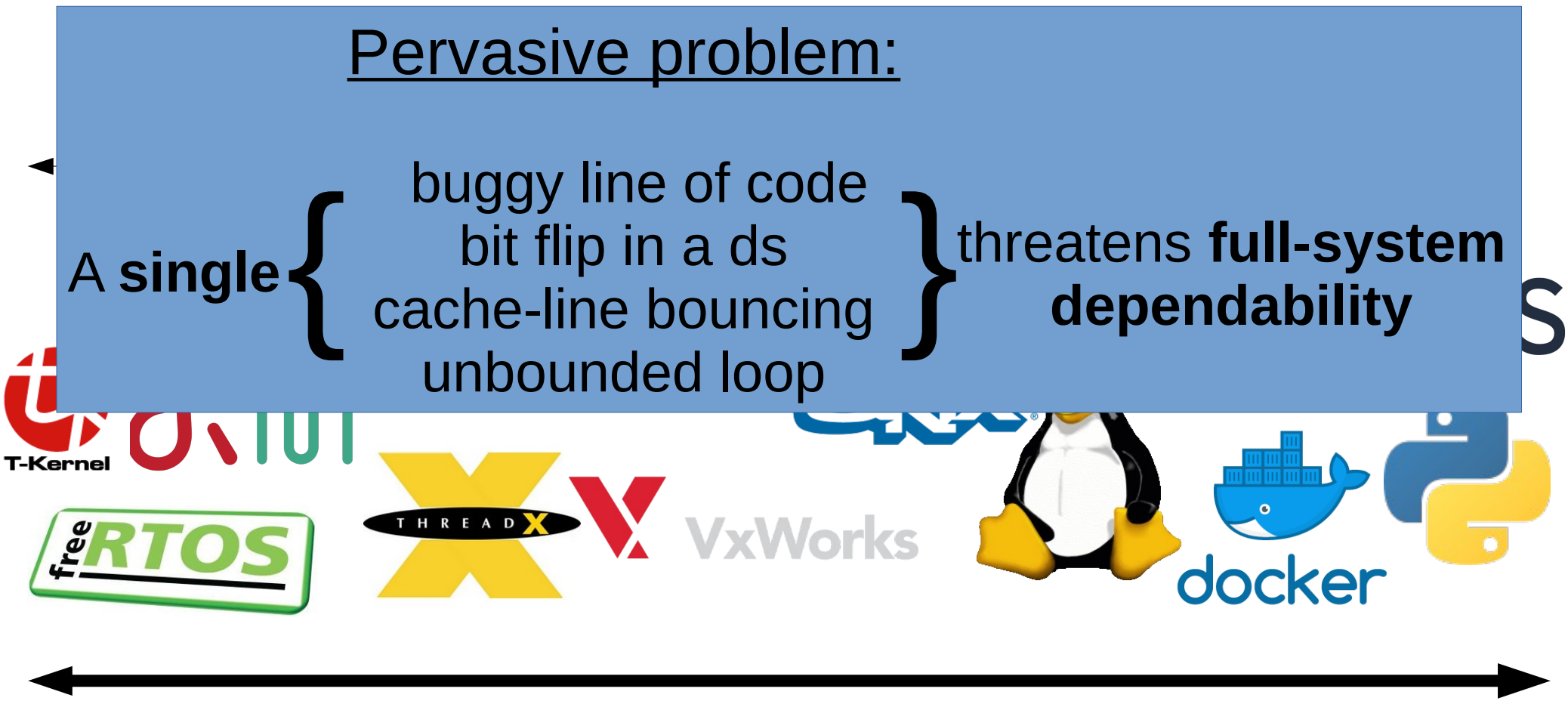
Choose your system



High Assurance
Predictable
Simple

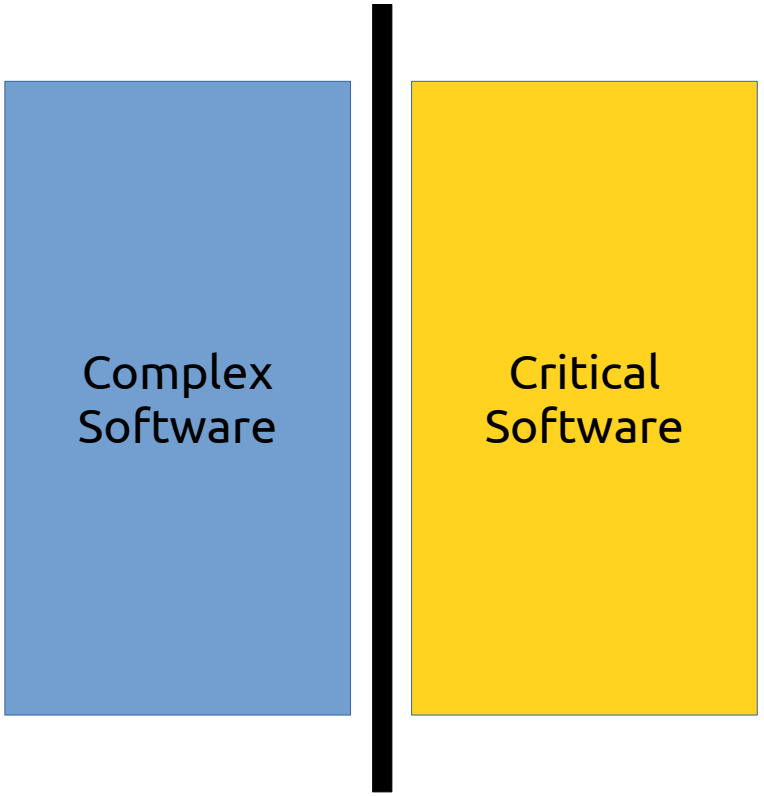
Lower Assurance
Tenuous WCET bounds
Complex

Choose your system



Isolation:
Still the remedy for complexity

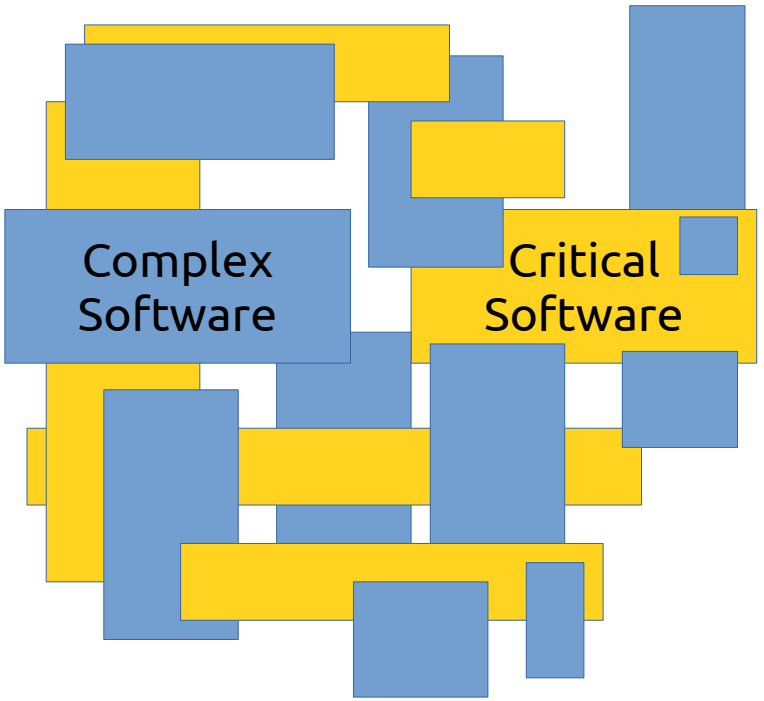
- Temporal Isolation
  - Core partitioning, Threading
  - TDMA, Rate-limiting Servers
- Spatial Isolation
  - HW Memory Access Cntl
- Abstract Resource Isolation
  - Access control



XtratuM ARINC 653 PikeOS

Isolation: Only a Partial Solution

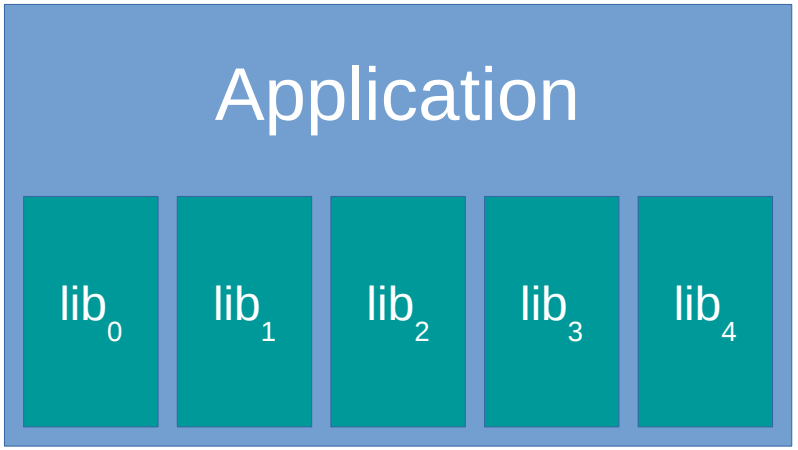
- Temporal Isolation
  - Shared resources
  - Shared HW
- Spatial Isolation
  - Shared Services
- Abstract Resource Isolation
  - Discretionary Access Cntl



Modern “Standardization”

Productivity via package/dependency mgrs

- OS Distributions
  - apt, rpm/yum, brew, …
- Language ecosystems
  - npm, pip, **cargo**, …



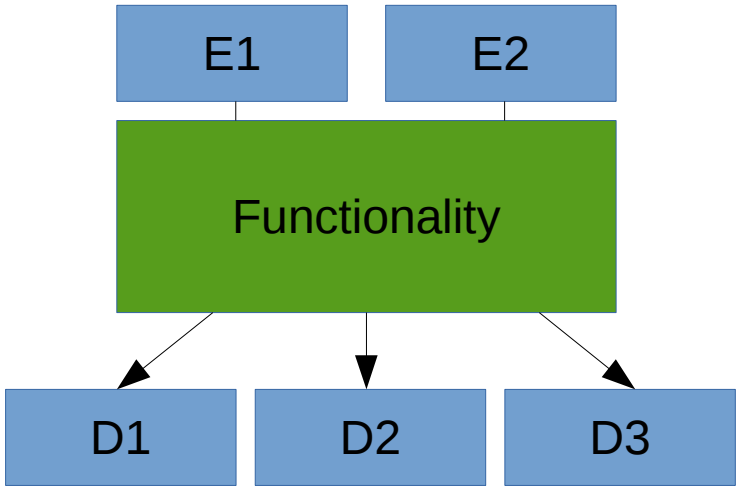

```
[package]
name = "mkimg"
version = "0.1.0"
authors = ["Gabe Parmer
           <gparmer@gwu.edu>"]

[dependencies]
xmas-elf = "0.6.0"
toml = "0.4"
serde = "1.0"
serde_derive = "1.0"
pipers = "1.0.0"
tar = "0.4"
```

Goal:
Functionality + Dependability + Productivity

Component-based system design

- Code, data
- Export APIs (`E1 = {fn, ...}`)
- Explicit dependencies
- Unit of reuse & isolation



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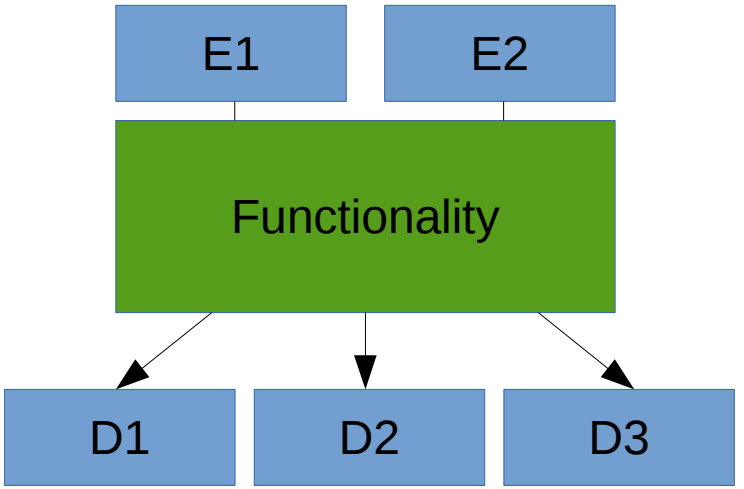
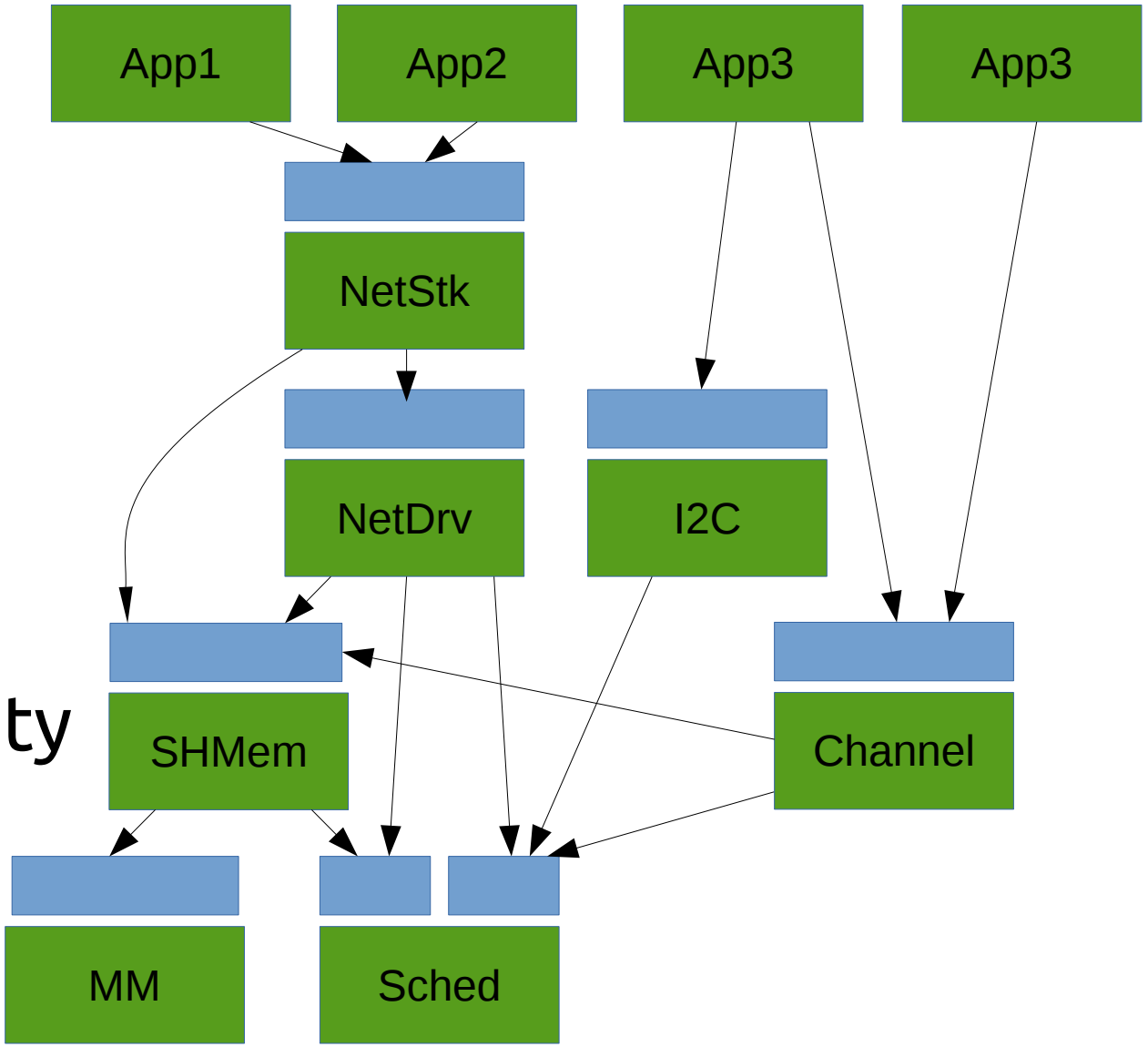


- *Minimize* functionality for the *necessary APIs*
- Strong, *fine-grained isolation*
- Libraries of *shared functionality*

Goal:
Functionality + Dependability + Productivity

- Components *compose* system
- Limit *scope* of
  - compromise
  - fault
  - unpredictability



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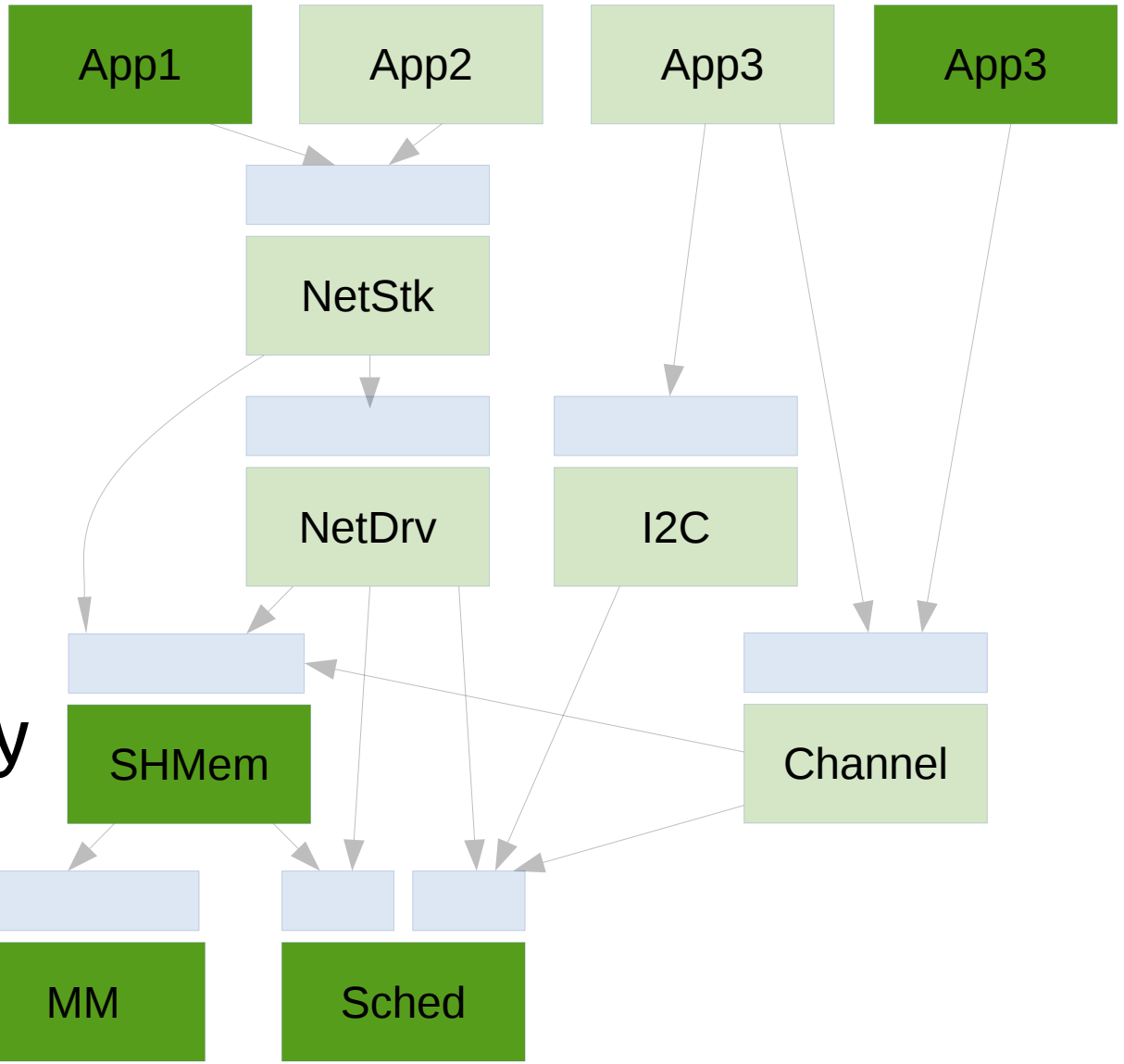


Cross Cutting Concerns

Adversarial economics of *existing systems*

Security

- A *single line of code* → full system compromise

Predictability

- A *single unbounded loop* → unpredictable exec

Dependability

- A *single fault/bit flip* → full system failure

Scalability

- A *single bouncing cache-line* → ~~scalability~~

Requirements for CPSOSes

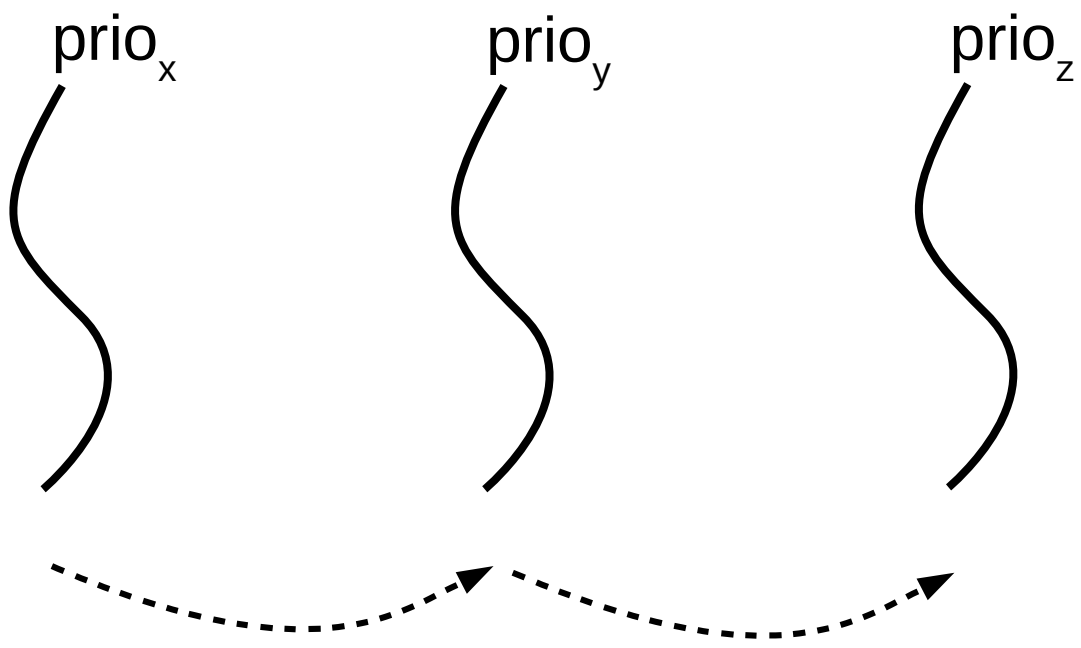
- **Efficient Isolation**
  - Constrain scope of impact of any one line/byte
  - Spatial, temporal, I/O
- **Policy customization***
  - Various assurance-levels, functional requirements
  - Multiple policies co-exist w/ *designed* interference
- **Composability WRT cross-cutting concerns**
  - Components must compose

* See Bjorn's talk: we have no opinions ;-)

Example Challenge I: *IPC*

- Communication between components
  - Efficient?
  - Predictable?
  - Policy interactions with kernel?

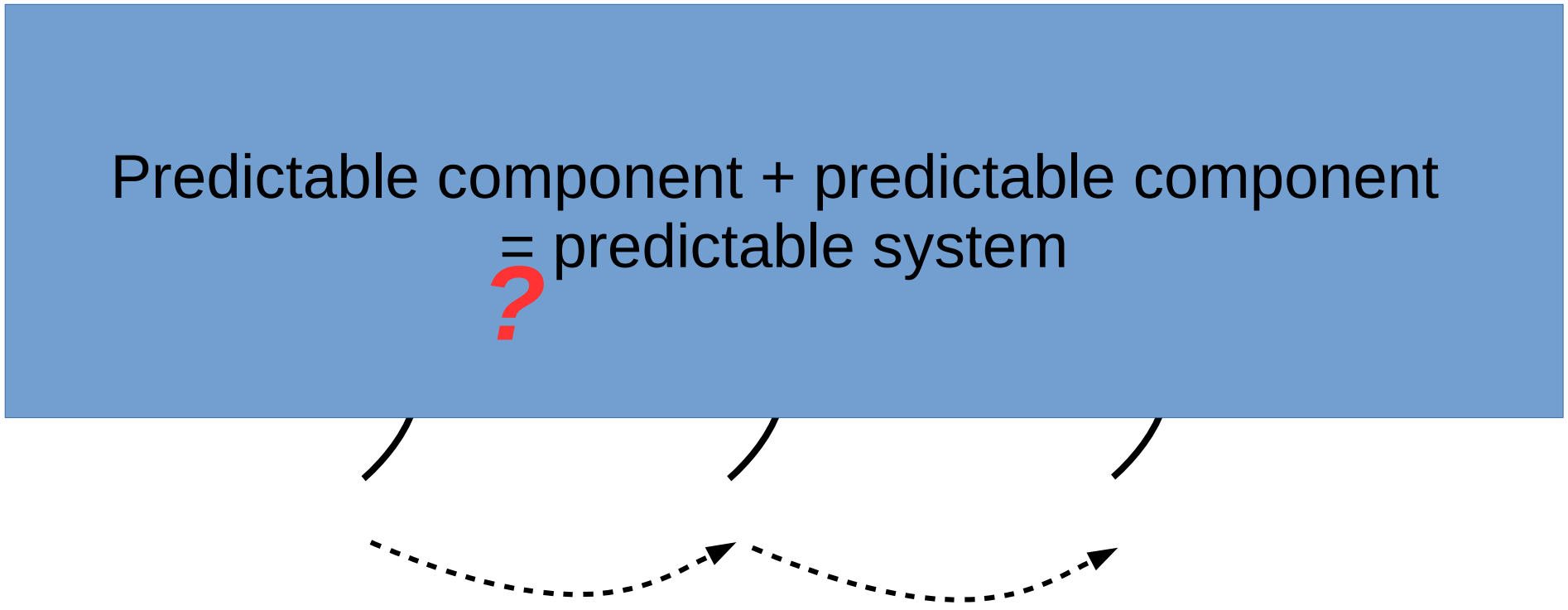
Asynchronous IPC



Scheduling analysis is dependency-aware

- Holistic scheduling
- Self-interference
- *f*(scheduling policy)

Asynchronous IPC



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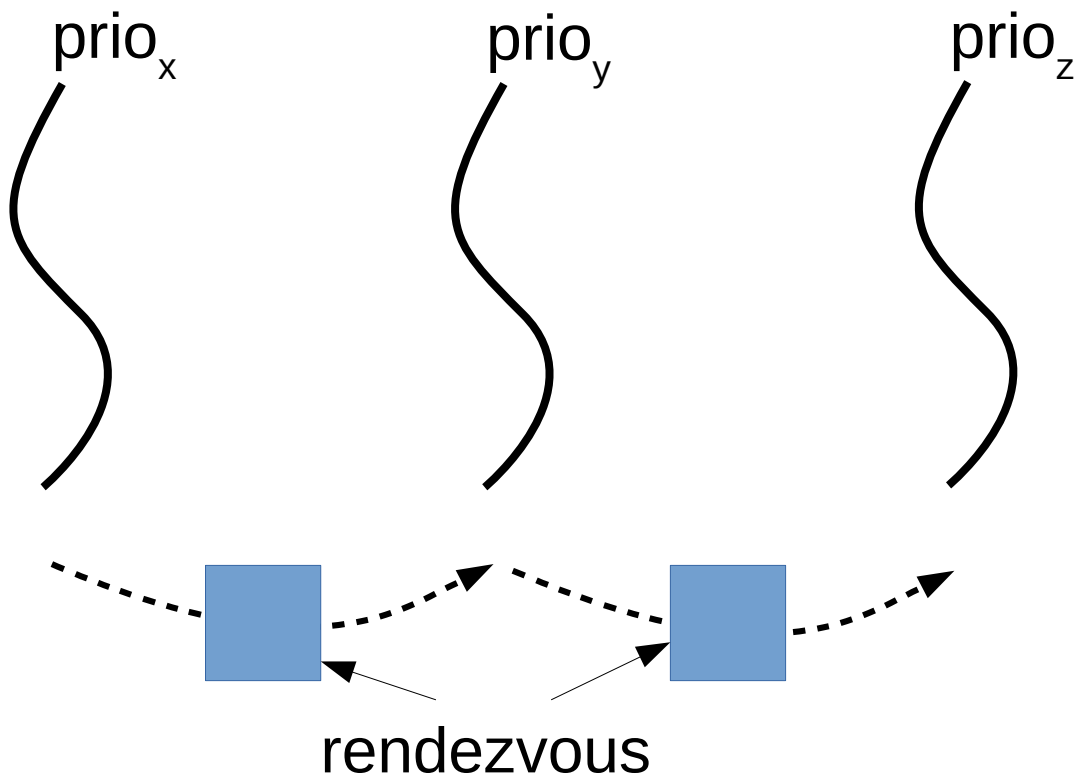
Synchronous IPC between Threads



Scheduling analysis is dependency-aware

- Resource sharing
- Requires in-kernel priority inheritance machinery

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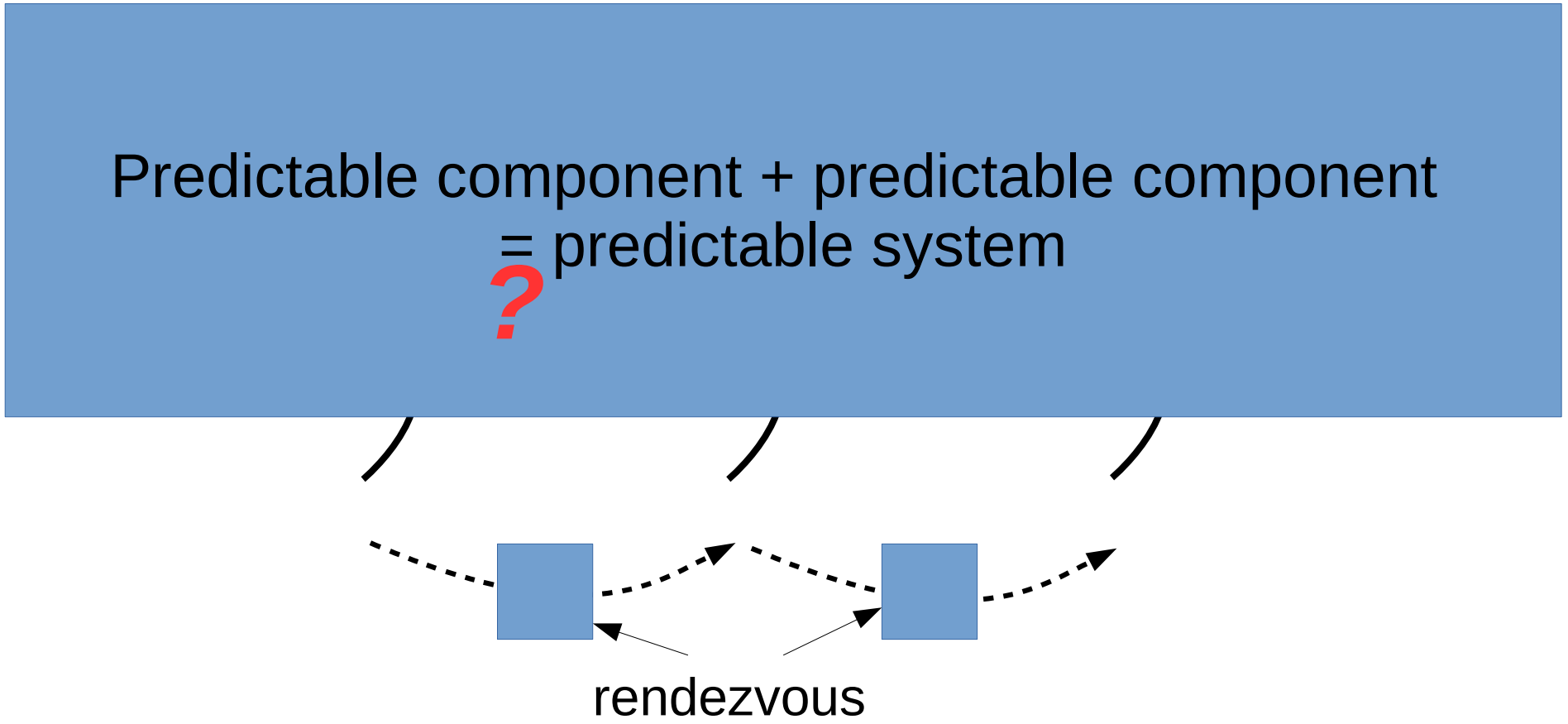
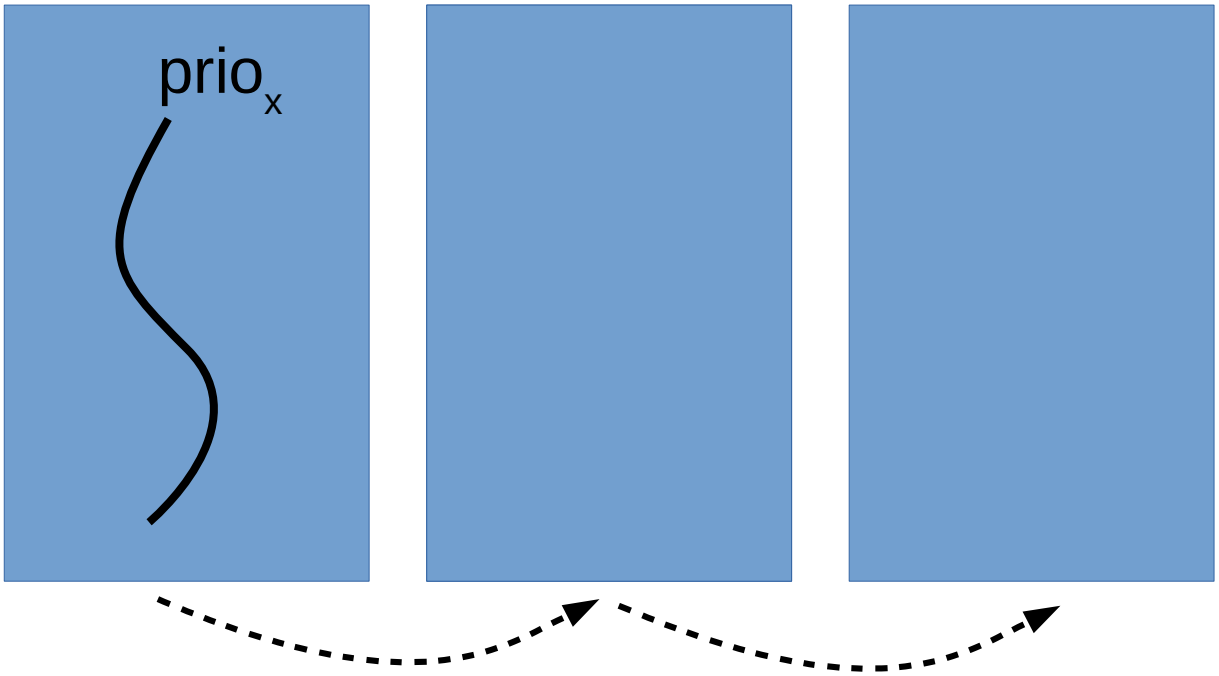


Scheduling analysis is dependency-aware

- Lock-aware scheduling
- Requires in-kernel priority inheritance machinery

Thread Migration



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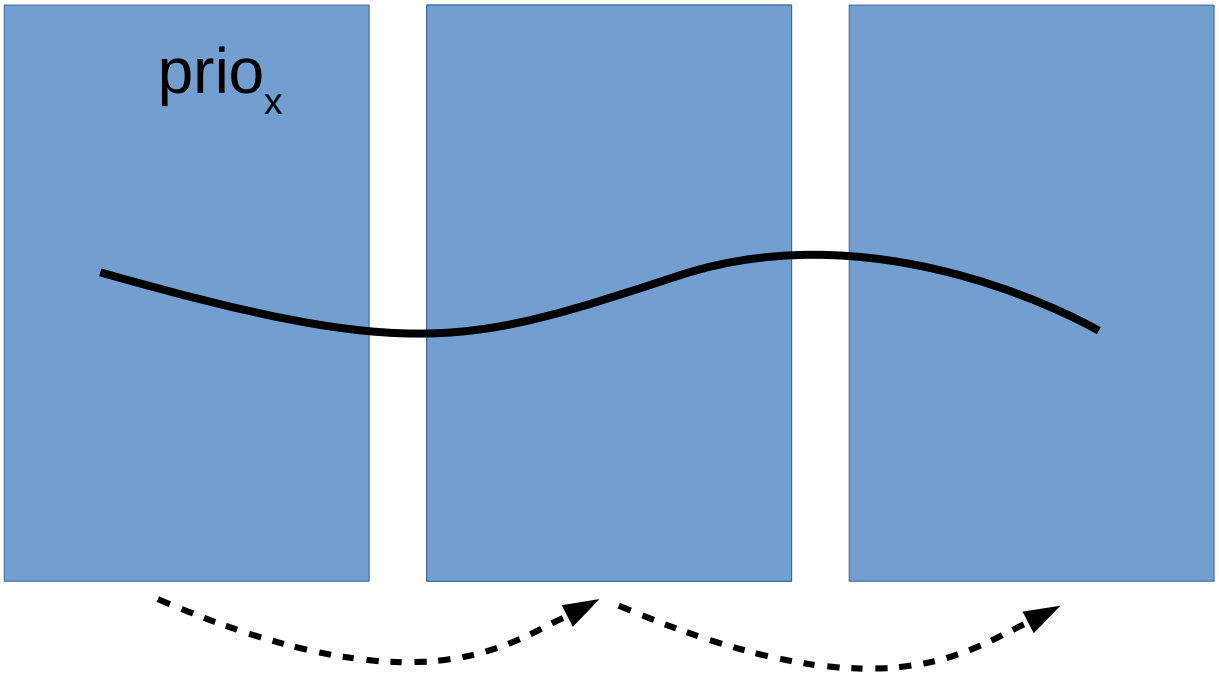
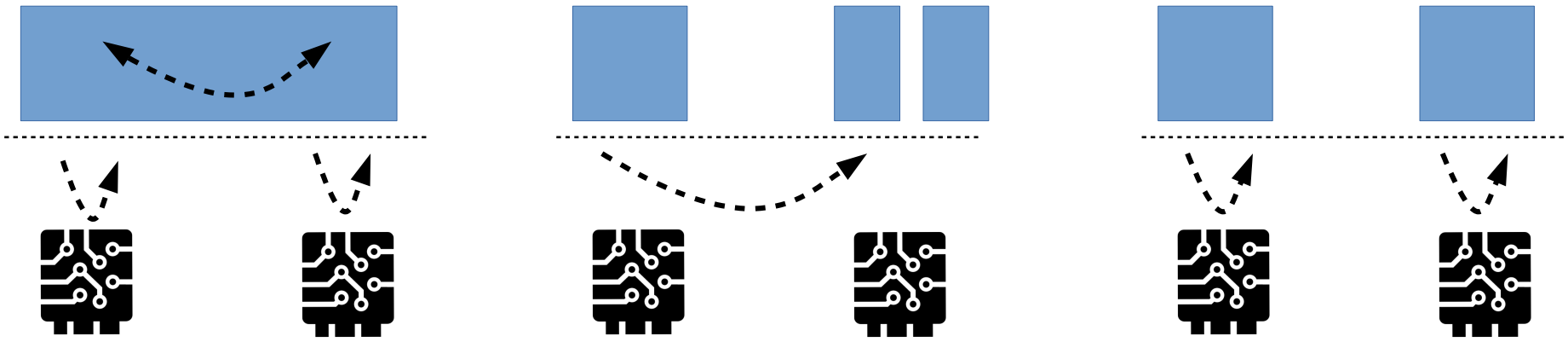


Predictable component + predictable component
= predictable system

Example Challenge II: *Kern Sync*

Can kernel APIs

- Limit the scalability of components?
- Cause interferences between components?



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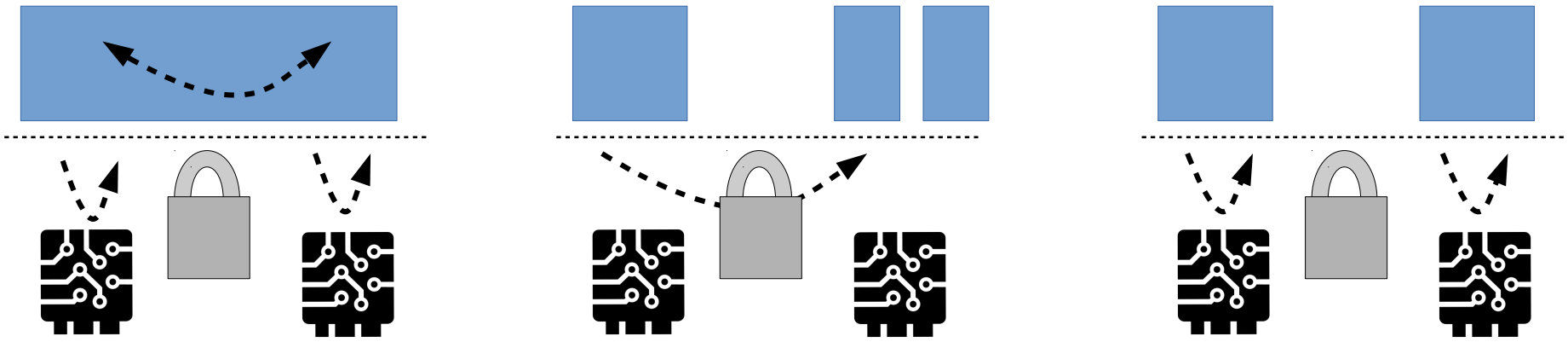

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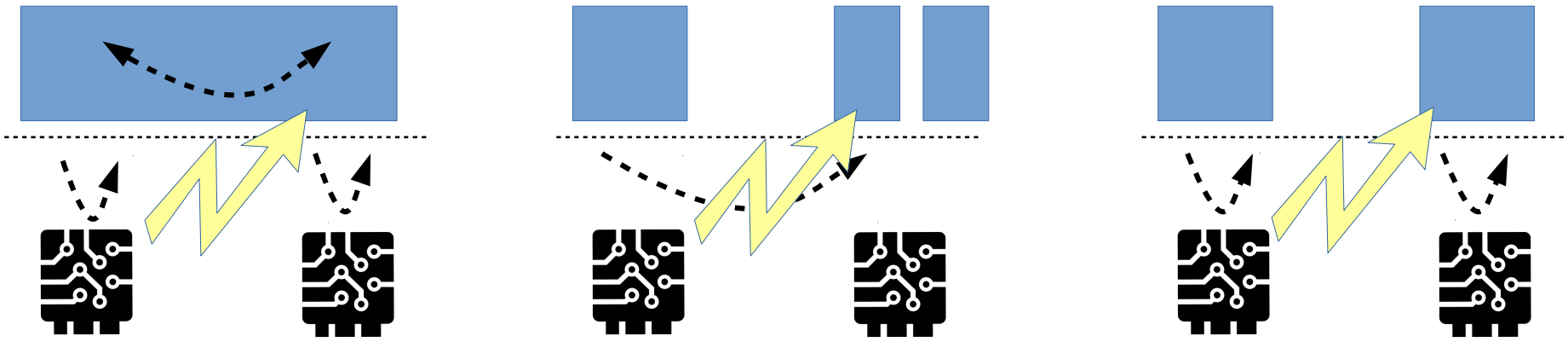
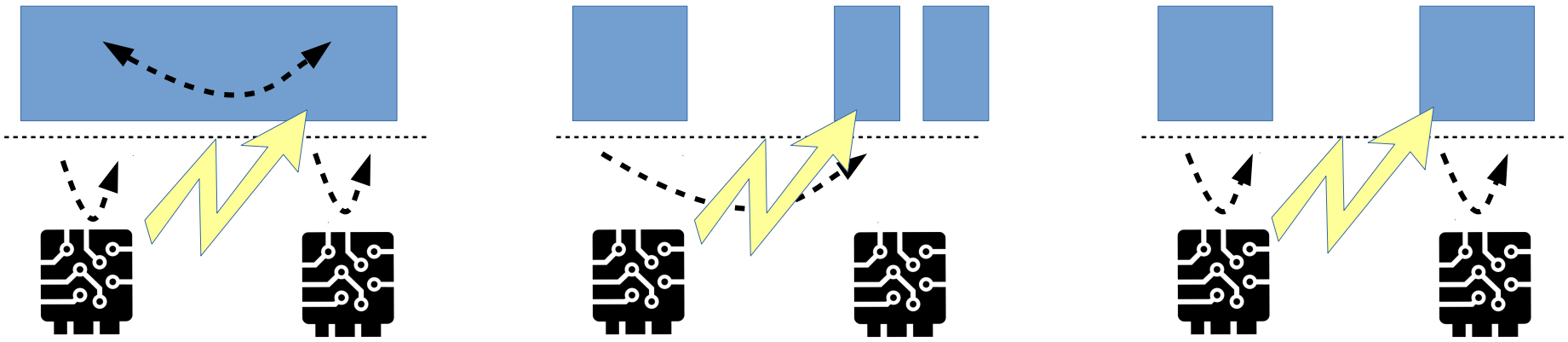


Example Challenge II: *Kern Sync*

Possible to enable *composability* WRT *predictability/scalability*?

– Kernel must be lock-**free**
– Kernel must use **controlled IPI facilities**



Guidance for µ-Kernel Design

”...a concept is tolerated inside the µ-kernel only if moving it outside the kernel, i.e. permitting competing implementations, would prevent the implementation of the system’s required functionality.

- Liedtke '95

Guidance for CPSOS Design I

Kernel mechanisms must enable the definition of resource management **policies** in user-level **components**, and the *additive construction* of high-level **behaviors** from components.

Guidance for CPSOS Design II

The kernel should include minimal but strong facilities for component-centric resource isolation, while enabling cross cutting concern-constrained composability.

The **FUTURE**

- Trust in a service should be chosen & designed
- Services/abstractions are mutually isolated
- Systems are composed of these components
- Components that are *x*, compose to be *x*

$x \in$ { security, dependability, predictability, scalability}

The Skeptic

- IPC is slow
- This cannot scale down
- You cannot support legacy
- This is too much work

? || /* */

composite.seas.gwu.edu

Functional composition

Do component *functionalities* compose?

- Interface algebras (e.g. Henzinger)
- Hierarchical scheduling compositions
- …

Questions:

- How to test this with generic compositions?
- For system-level code?