SKI: Exposing Kernel Concurrency Bugs through Systematic Schedule Exploration

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Kernel concurrency bugs

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The bug is a race ... particular machi... within **10 minut**... **timing such that** ... machine is in trouble and needs to be rebooted.

Three of the five 3.4.9 machines [...] **locked up.** I've tried reproducing the issue, but so far I've been unsuccessful [...]

Linux kernel mailing list (5/1/2013)

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Approaches to explore interleavings

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This talk

Approaches to explore interleavings

- Stress testing approach
  - Hope to find the interleaving
- Systematic approach
  - Take full control of the interleavings
  - ~~Existing tools focus on user mode applications~~

Focus on operating system kernels

android

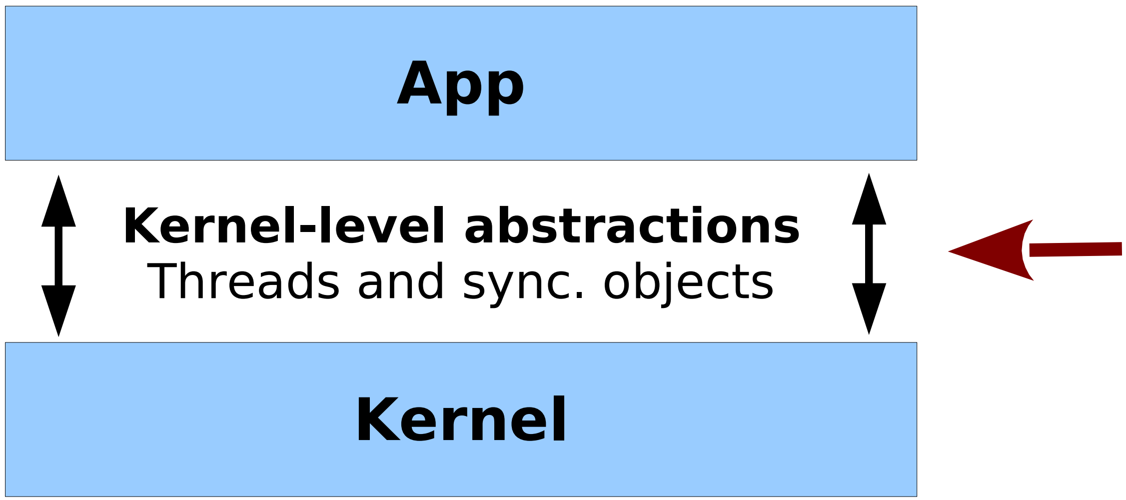
This talk

SKI

Finding kernel concurrency bugs

- **Testing applications versus kernels**
- Our approach
- Implementation
- Evaluation

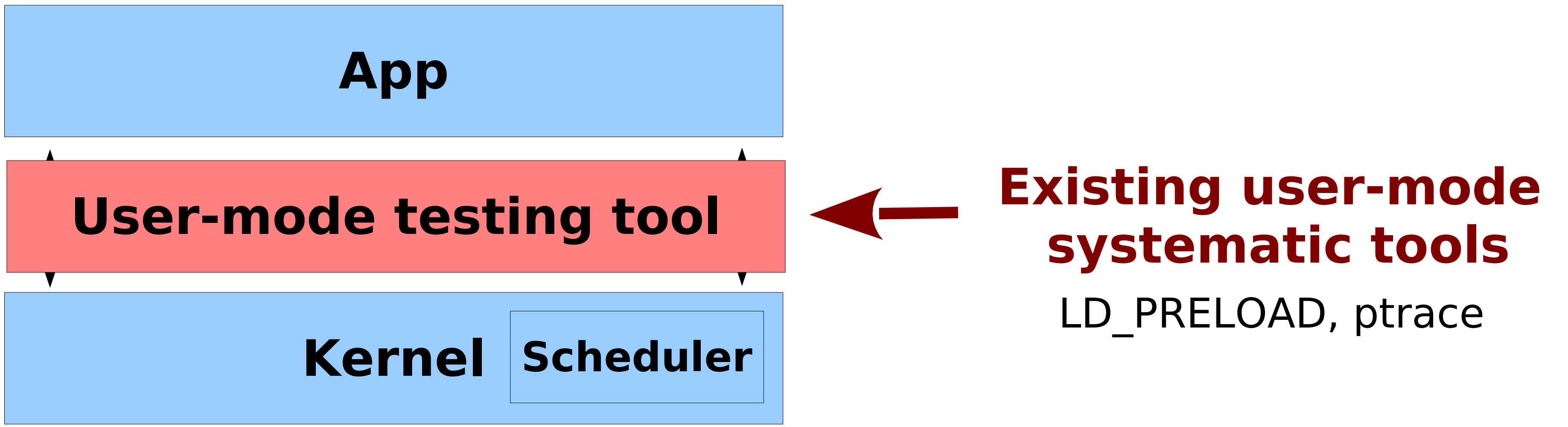
Existing user-mode tools



Existing user-mode systematic tools

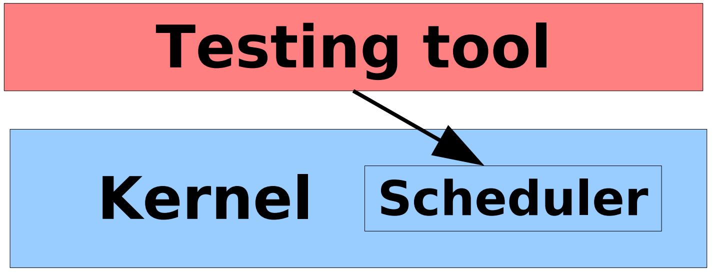
LD_PRELOAD, ptrace

Existing user-mode tools



Kernel-mode challenges

- Kernel doesn't have a good instrumentation interface



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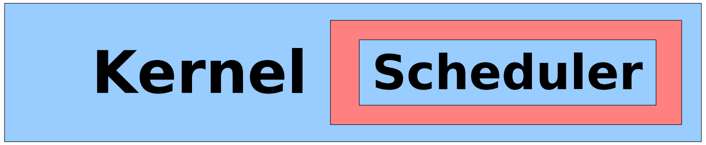

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  - But kernel modifications:

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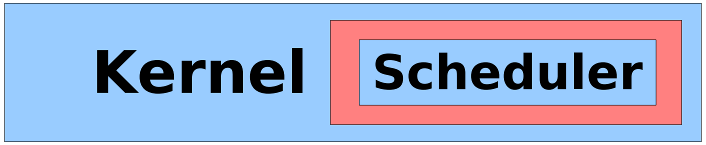

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    - Are non-trivial
    - Hinder portability

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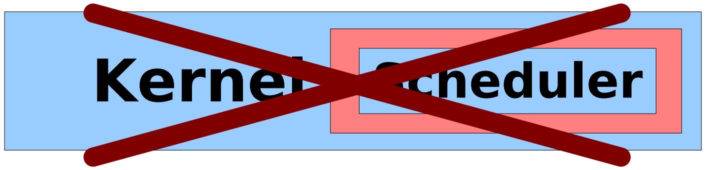

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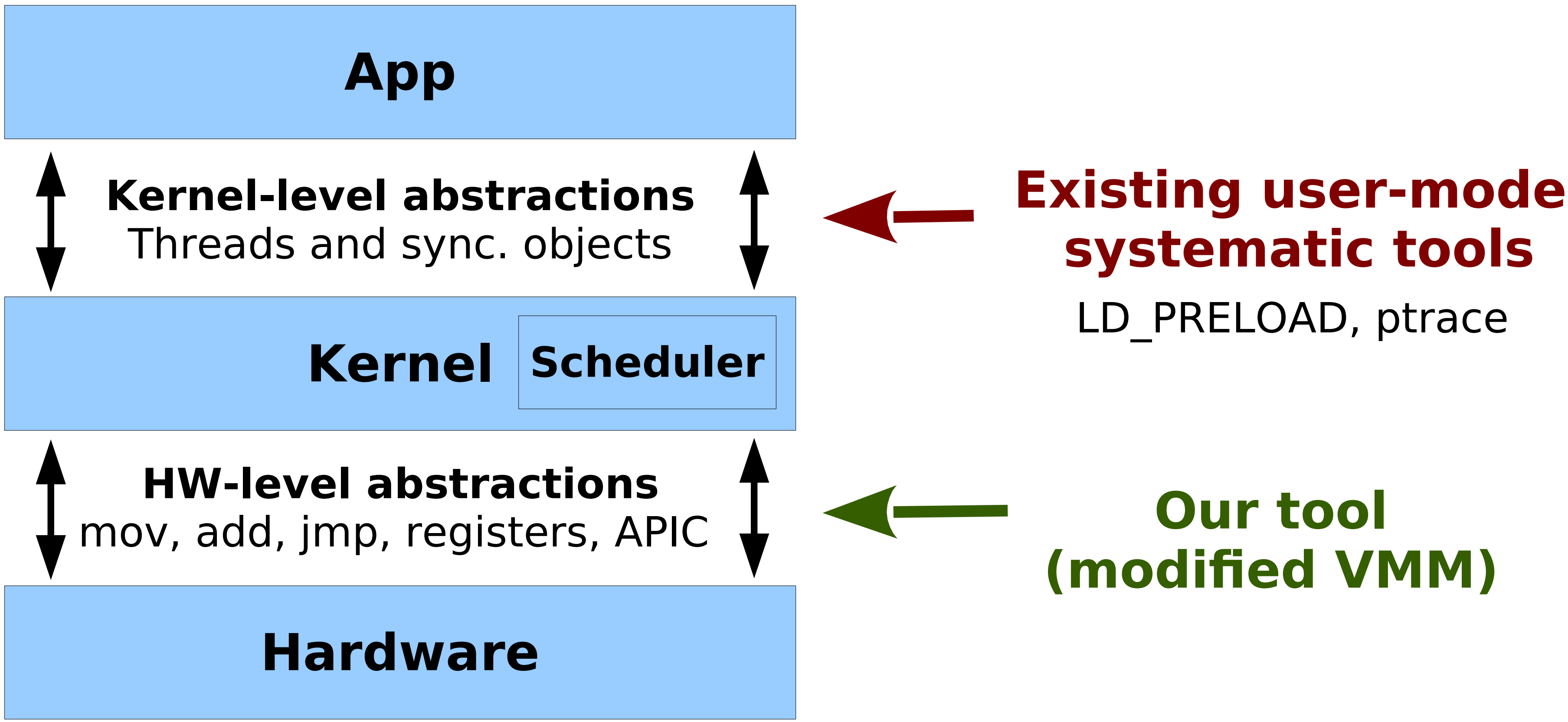
Avoid kernel modifications

User-mode *versus* kernel-mode



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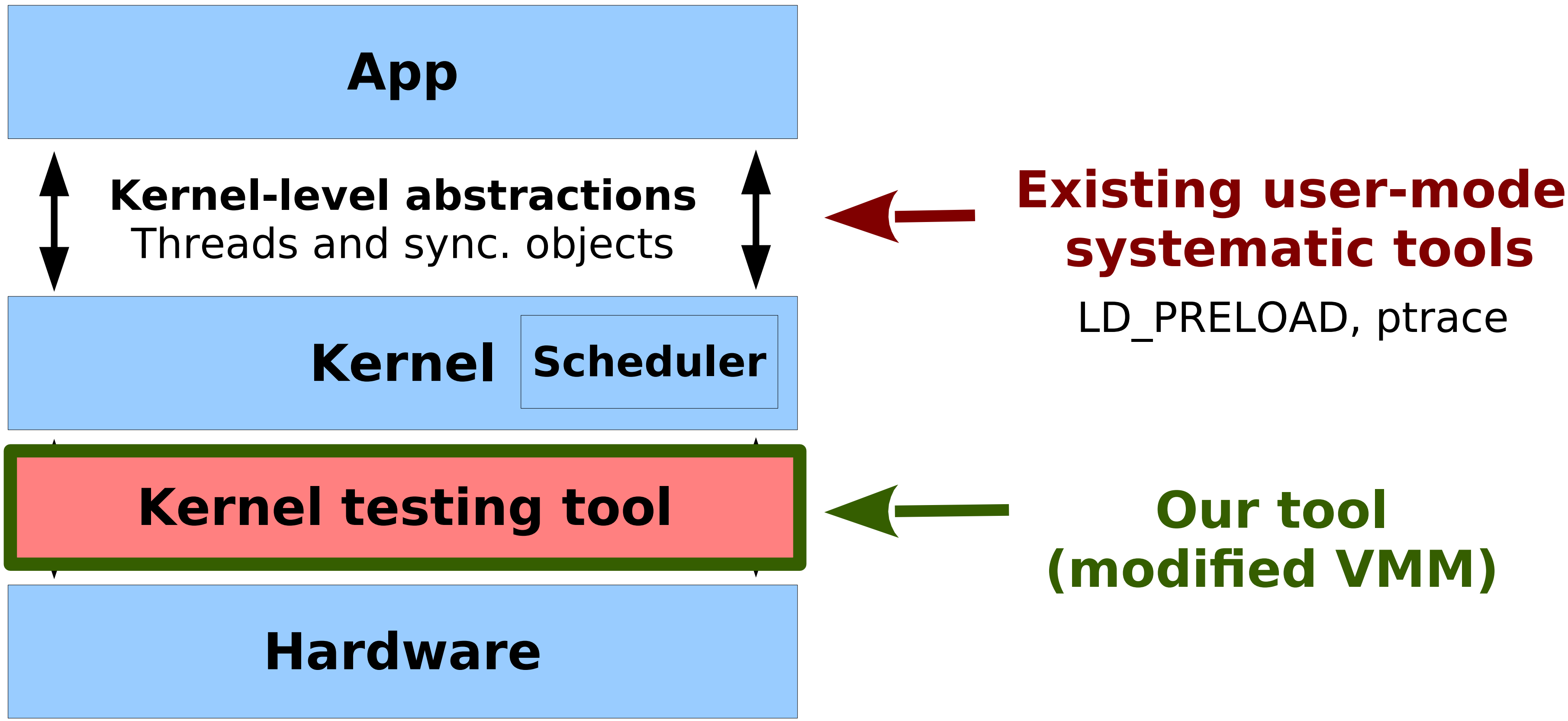

SKI

Finding kernel concurrency bugs

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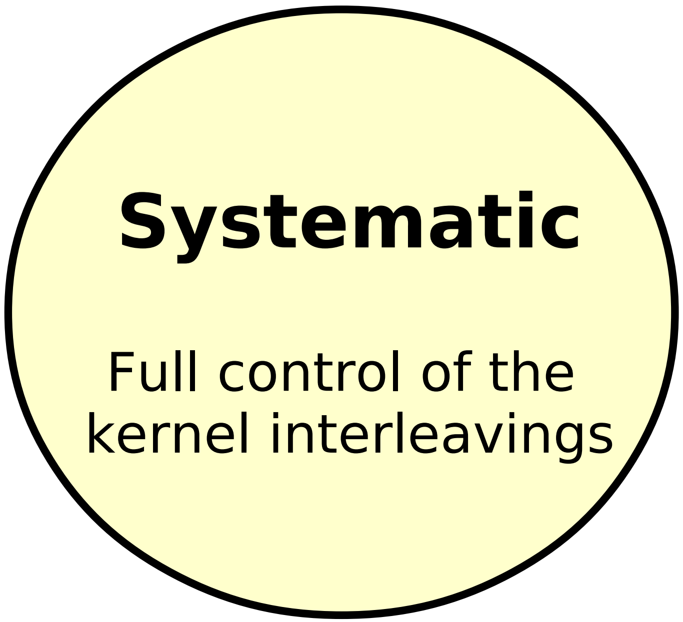


SKI

Finding kernel concurrency bugs

Systematic

Full control of the kernel interleavings

+

Practical

No modifications to the kernel

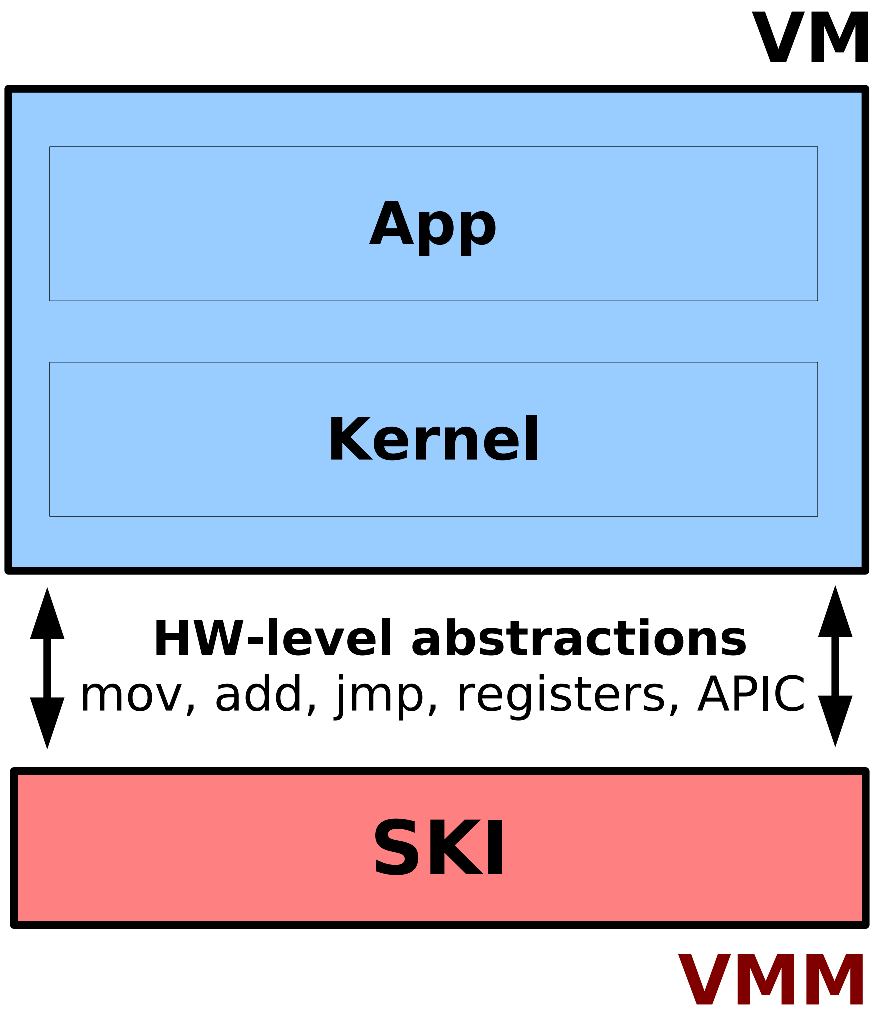
Fast

SKI

Finding kernel concurrency bugs

- Challenges testing the kernel code
- **SKI's approach**
- Implementation
- Evaluation

SKI's approach



Challenges

1. How to control the schedules?
2. Which contexts are schedulable?
3. Which schedules to choose?

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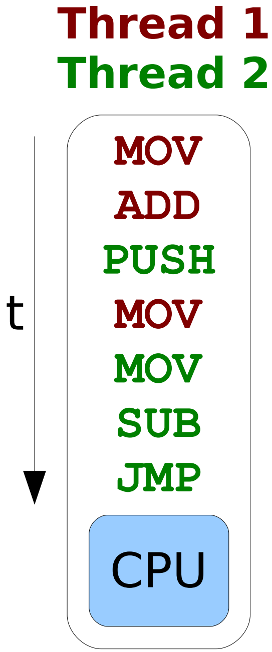

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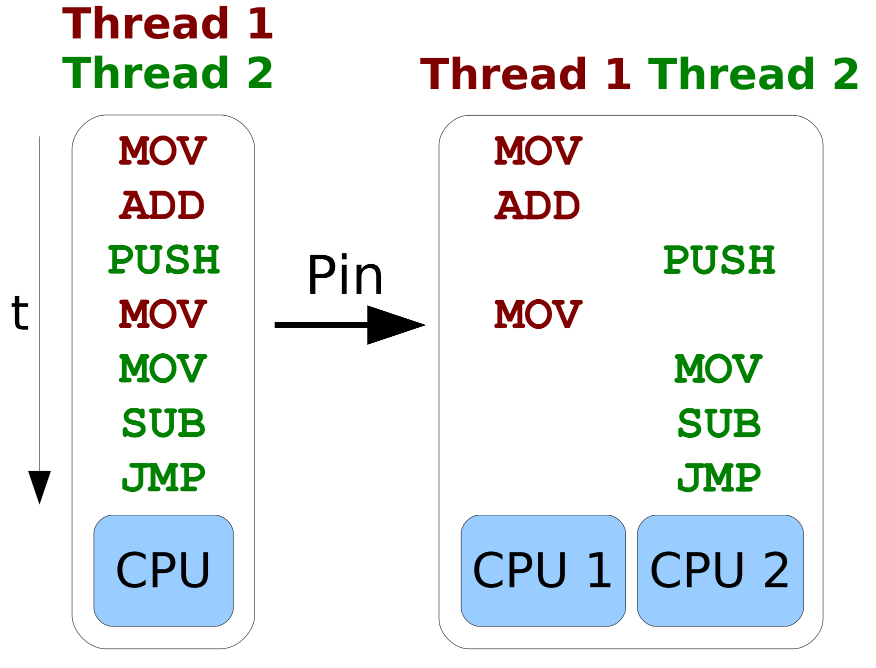
- Pin each tested thread to a different CPU (thread affinity)



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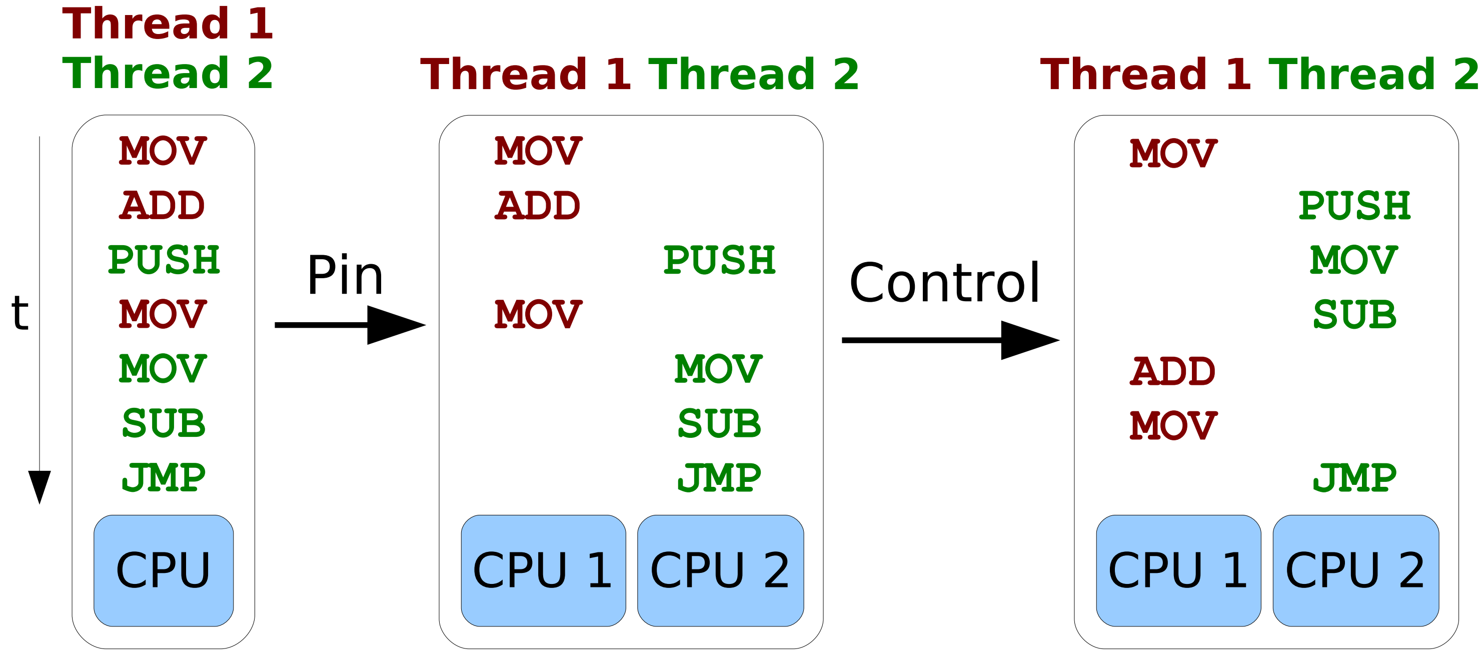

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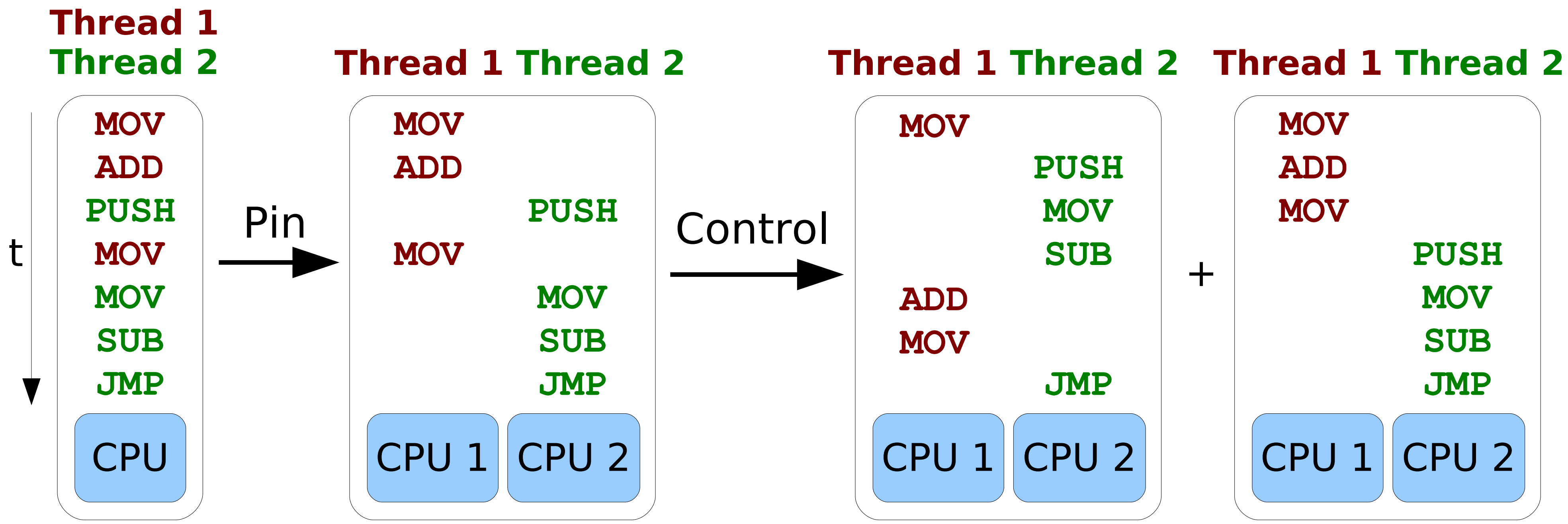

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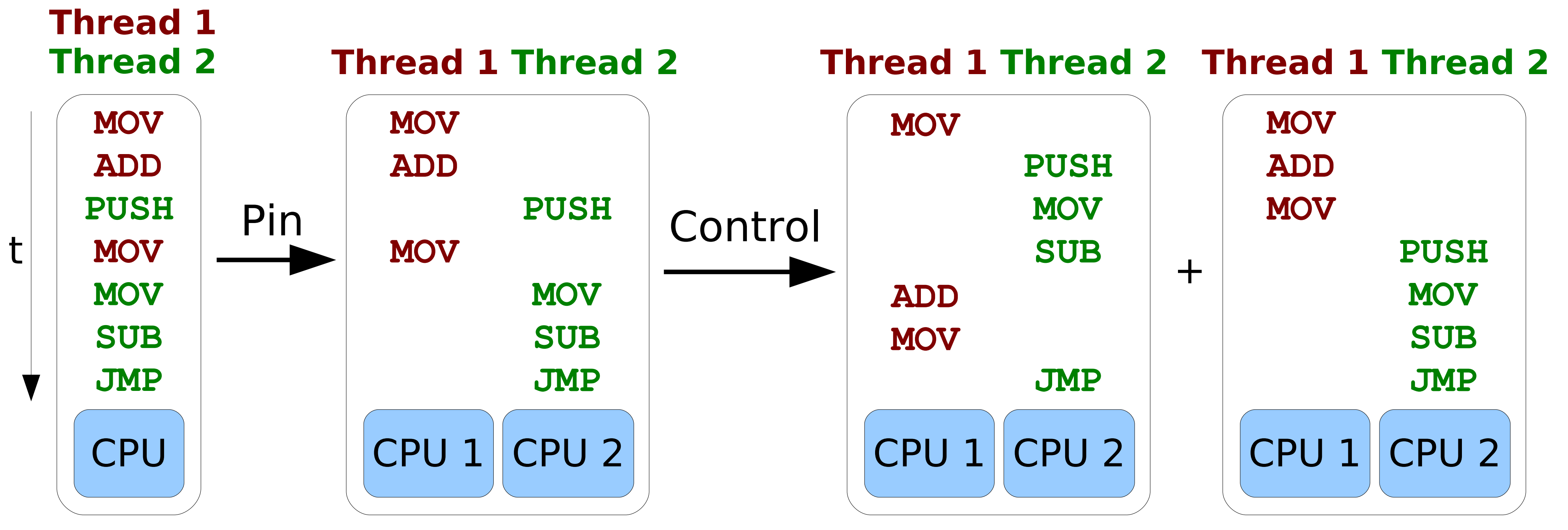

Leverage thread affinity and control CPUs

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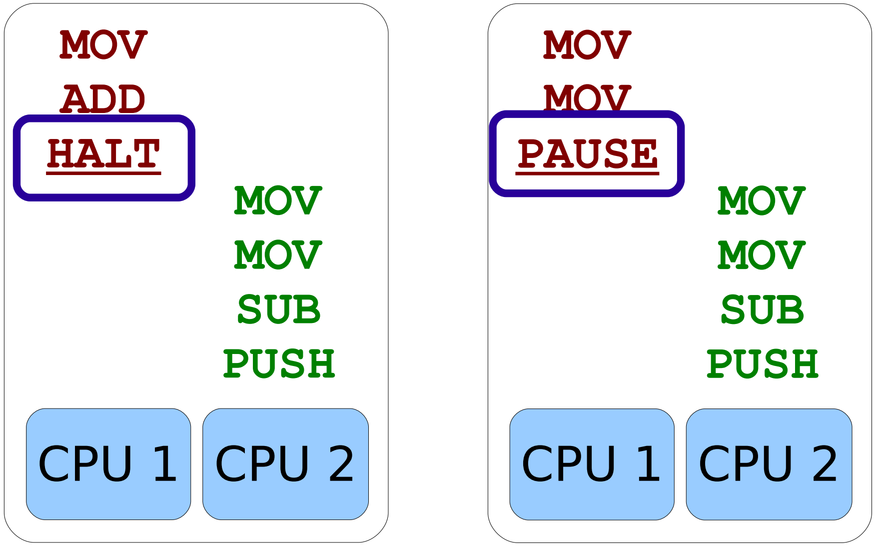

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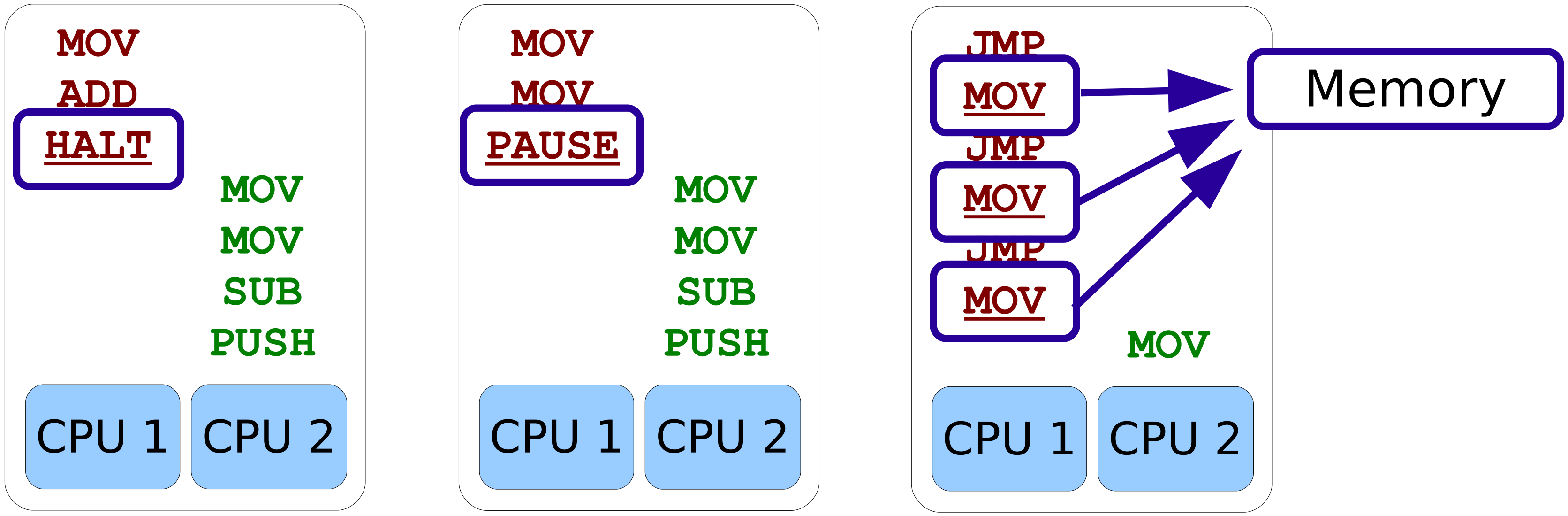

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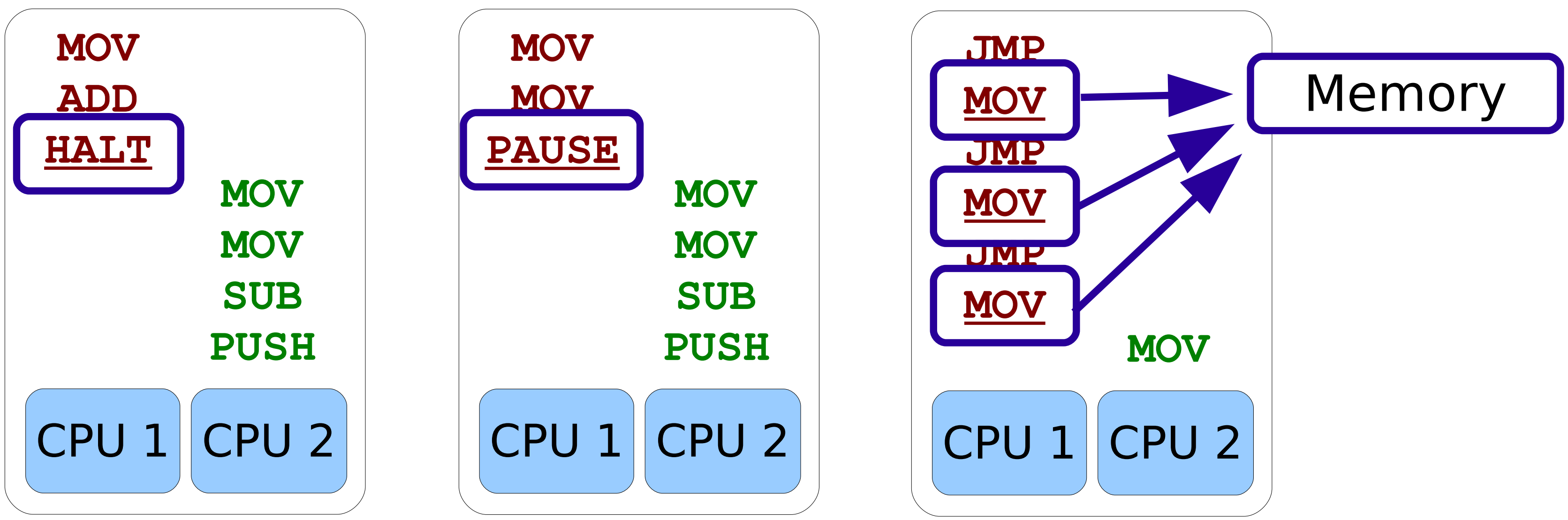

Rely on VMM introspection

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Generalize user-mode systematic testing algorithms

SKI

Finding kernel concurrency bugs

- Challenges testing kernel code
- SKI's approach
- **Implementation**
- Evaluation

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- Implemented SKI by modifying QEMU (VMM)
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    - e.g., file system tests
- Implemented several optimizations

Detecting and diagnosing bugs with SKI

- SKI supports different types of bug detectors
  - Crash and assertion violations
  - Data races
  - Semantic bugs (e.g. disk corruption)

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  - Data races
  - Semantic bugs (e.g. disk corruption)
- SKI produces detailed execution traces

SKI

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1. Regression testing

2. Finding previously unknown bugs

1. Regression testing: setup

- Searched for previously reported bugs
  - In kernel bugzilla, mailing lists, git logs
  - Well documented reports and diverse set of bugs
- Created SKI test suites for these bugs
  - By adapting the stress tests in the bug reports

1. Regression testing: results

Bug	Kernel	Component	Detector
A	Linux 2.6.28	Anonymous pipes	Crash
B	Linux 3.2	Inotify + FAT32	Crash
C	Linux 3.6.1	Proc + Ext4	Semantic
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Diverse properties

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SKI is portable

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SKI can expose bugs in seconds

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B	Linux 3.2	Inotify + FAT32	Crash	53	169,300	200,000 (4h)
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Some stress tests were ineffective

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2. Finding previously unknown bugs

- Created a SKI test suit for file systems
  - Adapted the existing *fsstress* test suit
  - Tested several file systems
- Bug detectors
  - Crashes, warnings, data races, semantic errors (*fsck*)
- Tested recent versions of Linux

2. Finding previously unknown bugs

Bug	Linux	FS	Detector / Failure	Status
1	3.11.1	Btrfs	Crash (Null-pointer)	Fixed
2	3.11.1	Btrfs	Crash (Null-pointer) + Warning	Fixed
3	3.11.1	Btrfs	Warning	Fixed
4	3.11.1	Btrfs	Fsck (References not found)	Reported
5	3.11.1+p	Btrfs	Crash (Null-pointer)	Fixed
6	3.12.2	Btrfs	Warning	Fixed
7	3.13.5	Logfs	Crash (Null-pointer)	Reported
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Official Linux releases

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Requested by developers

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Important file systems

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Data loss

Current limitations and future work

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- Bugs in kernel scheduler code
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    → Represent a small set of bugs
- Bugs in device drivers
  - SKI supports a large set of devices but not all

    → Implement SKI with binary instrumentation techniques
- Bugs that depend on weak memory models
  - SKI currently implements a strong memory model

    → Generalize SKI to also expose these bugs

Conclusion

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SKI is Systematic

Full control of the kernel interleavings

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SKI is Practical

No modifications to the kernel

Fast

Conclusion

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SKI is Effective

Finds and reproduces real-world kernel concurrency bugs