Karlsruhe Institute of Technology

Fast and Accurate Functional Simulation for Dynamic Full System Analysis

GI Fachgruppentreffen Betriebssysteme (BS) 2018

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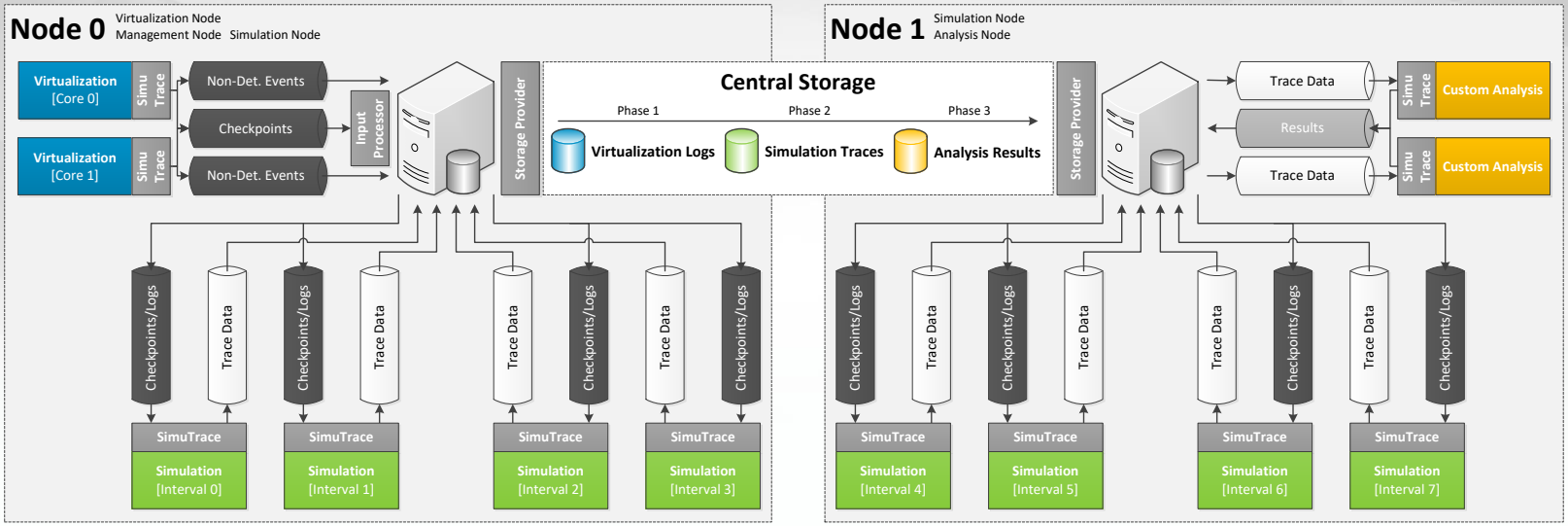


Motivation

- Study properties of redundant memory contents [Miller13]
  - Origin? Lifetime? Sharing possible?
  - Analyze memory contents after each modification
  - But: Analysis should not affect workload

- Analyze memory access patterns on system interfaces [Jurczyk13, Wilhelm15]
  - Detect vulnerabilities in Windows 8 and Xen (CVE-2015-8550)
  - Trace individual memory reads and writes

We want detailed runtime information

Motivation

- Functional full system simulation
  - Allows collecting required data
  - Simulation on instruction-level
  - Includes operating system and drivers

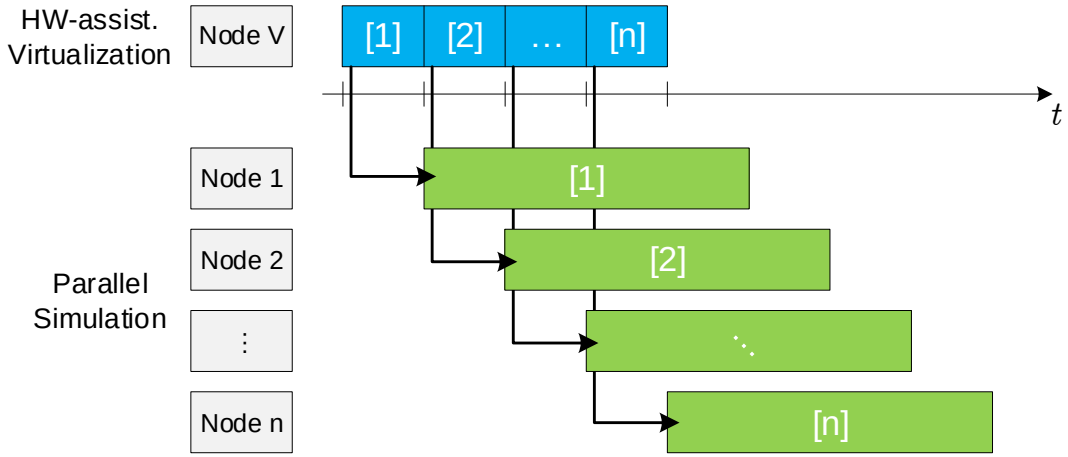
- But: It is slow

Virtualization	Simulation	
KVM	QEMU	Simics
~ 1x	~ 100x	~ 1000x

Average slowdowns for: kernel build, SPECint_base06, LAMMPS

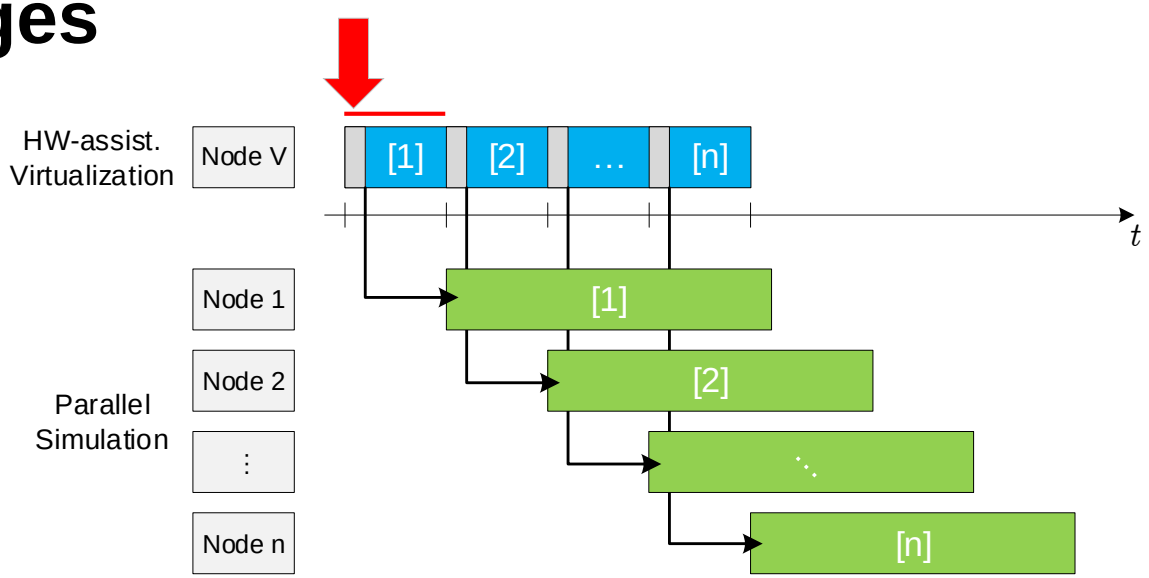
• Not practical for long-running workloads
• Loss of interactivity (users and remote hosts)

SimuBoost



- Use virtualization and split execution into intervals
  - Checkpoints at interval boundaries bootstrap simulations
  - Speed difference drives parallelization
  - Hardware acceleration provides full interactivity
- Does not trade accuracy for speed
- Scales with run time of workload

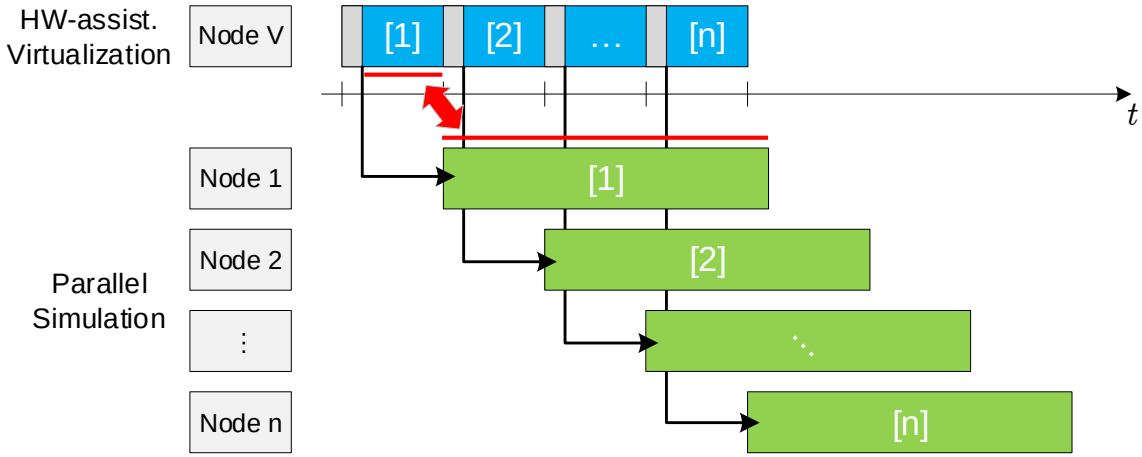
Challenges



- **Downtime** to capture consistent state
  - Keep below 100ms to preserve interactivity [RbMiller68]
- **Run time overhead** to asynchronously save data
  - Keep low to minimize probe effect

Lightweight Checkpointing

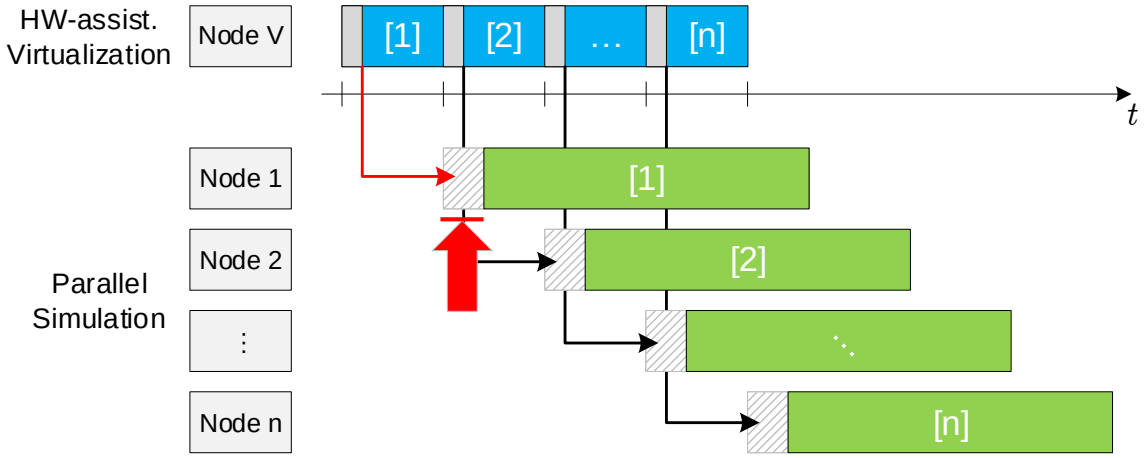
Challenges



- **Replay** of events
  - Must have instruction-level precision
- **Run time overhead** to capture non-deterministic events
  - Keep low to minimize probe effect

Lightweight Checkpointing	Deterministic Replay

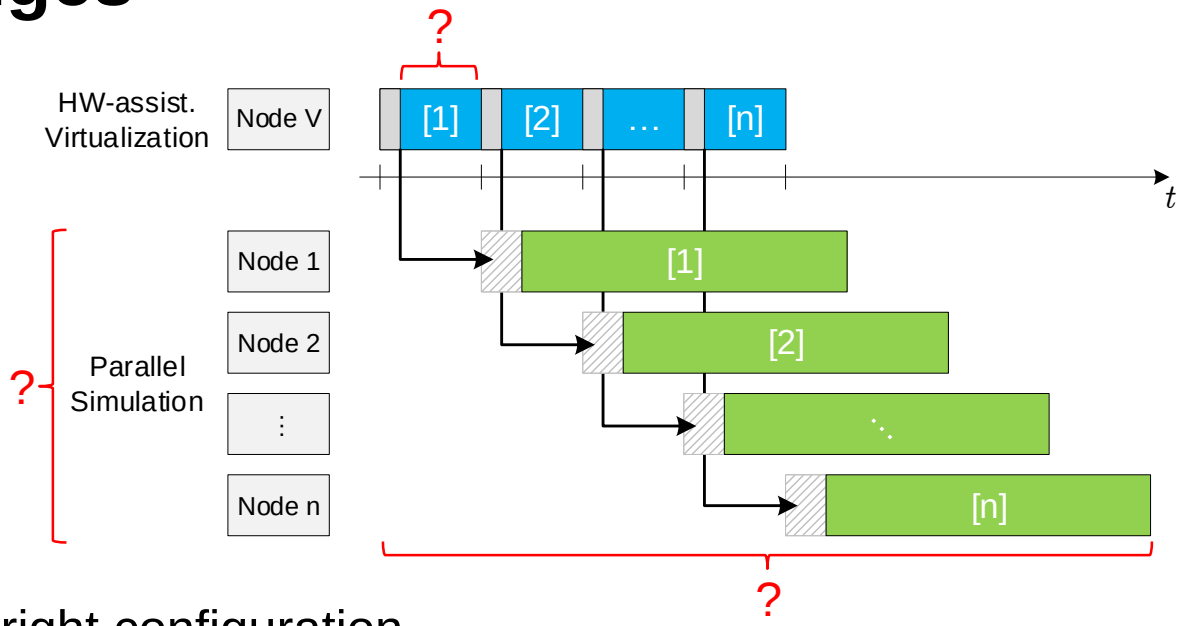
Challenges



- Startup time: **Transfer time** + **Checkpoint loading time**
  - Keep low to maximize speedup
- Network **bandwidth** to migrate checkpoints
  - Keep low to allow commodity network infrastructure (Gigabit Ethernet)

Lightweight Checkpointing	Deterministic Replay	Fast Simulation Startup

Challenges



- Choose right configuration
  - Interval length & number of simulation nodes
- Estimate performance
  - Parallel simulation time & speedup

Lightweight Checkpointing	Deterministic Replay	Fast Simulation Startup	Performance Model

Checkpointing

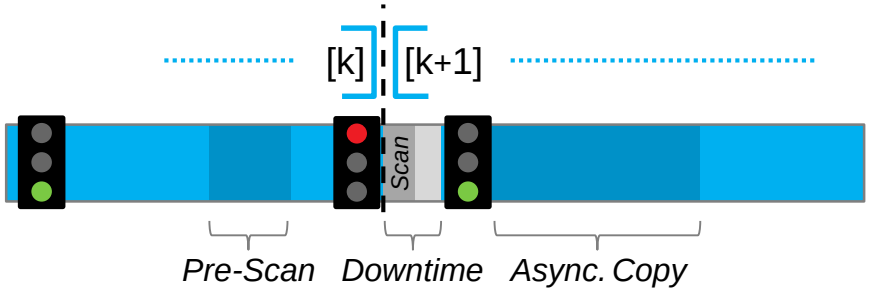
- Problem: Cannot save full guest memory on each checkpoint

- Observation: Only some data modified per interval

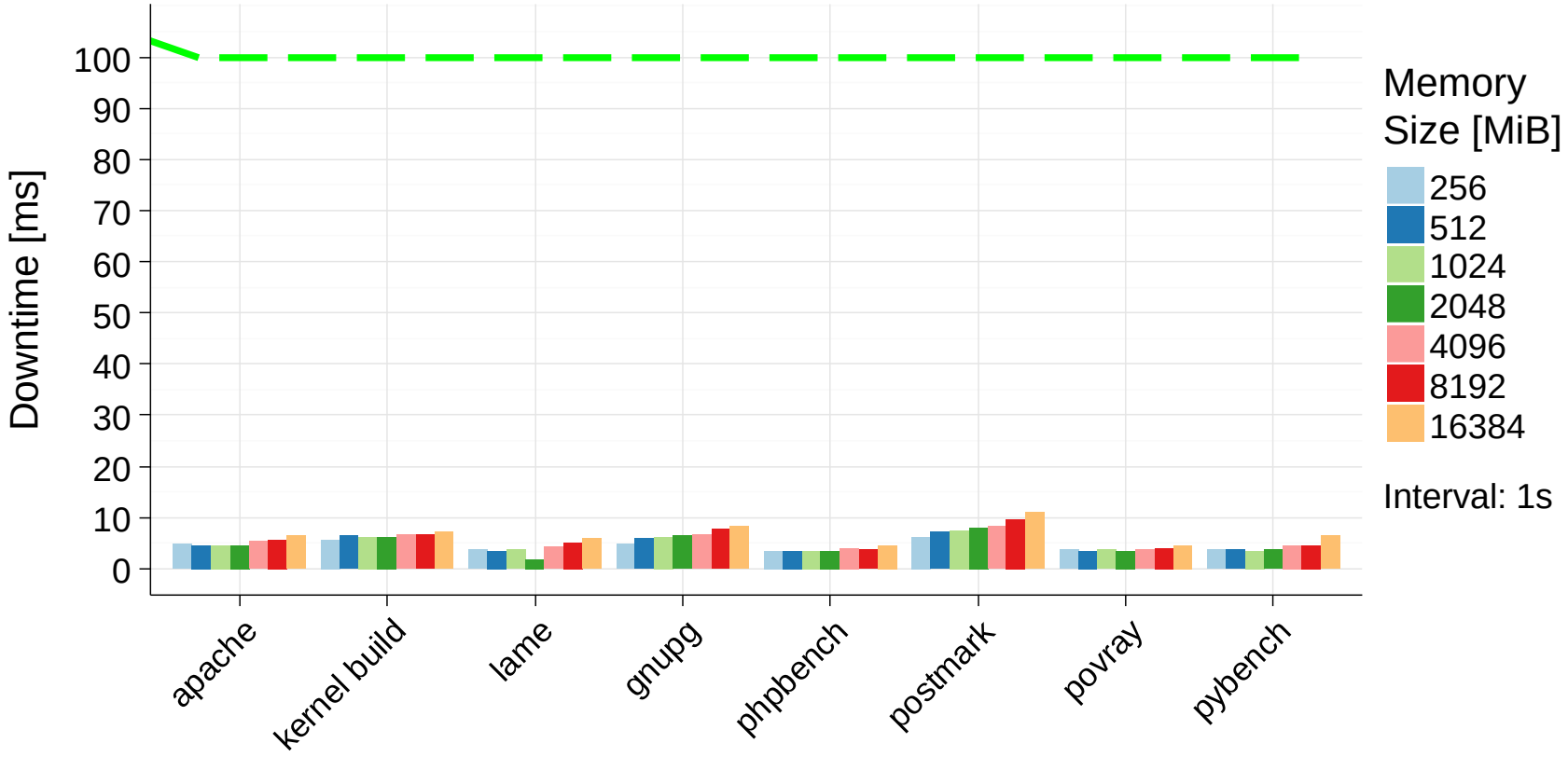
Linux Kernel Build	SPECjbb2005
22000 pages/s (85 MiB/s)	53000 pages/s (200 MiB/s)

- Dirty Page Tracking
  - Standard: Use page protections
  - Better: Scan extended page table (EPT)
    - Less page faults: ½ run time overhead, but 2x downtime
    - Pre-Scan keeps downtime low

- Copy-On-Write (CoW)
  - Protect modified pages (only)
  - Asynchronously copy pages

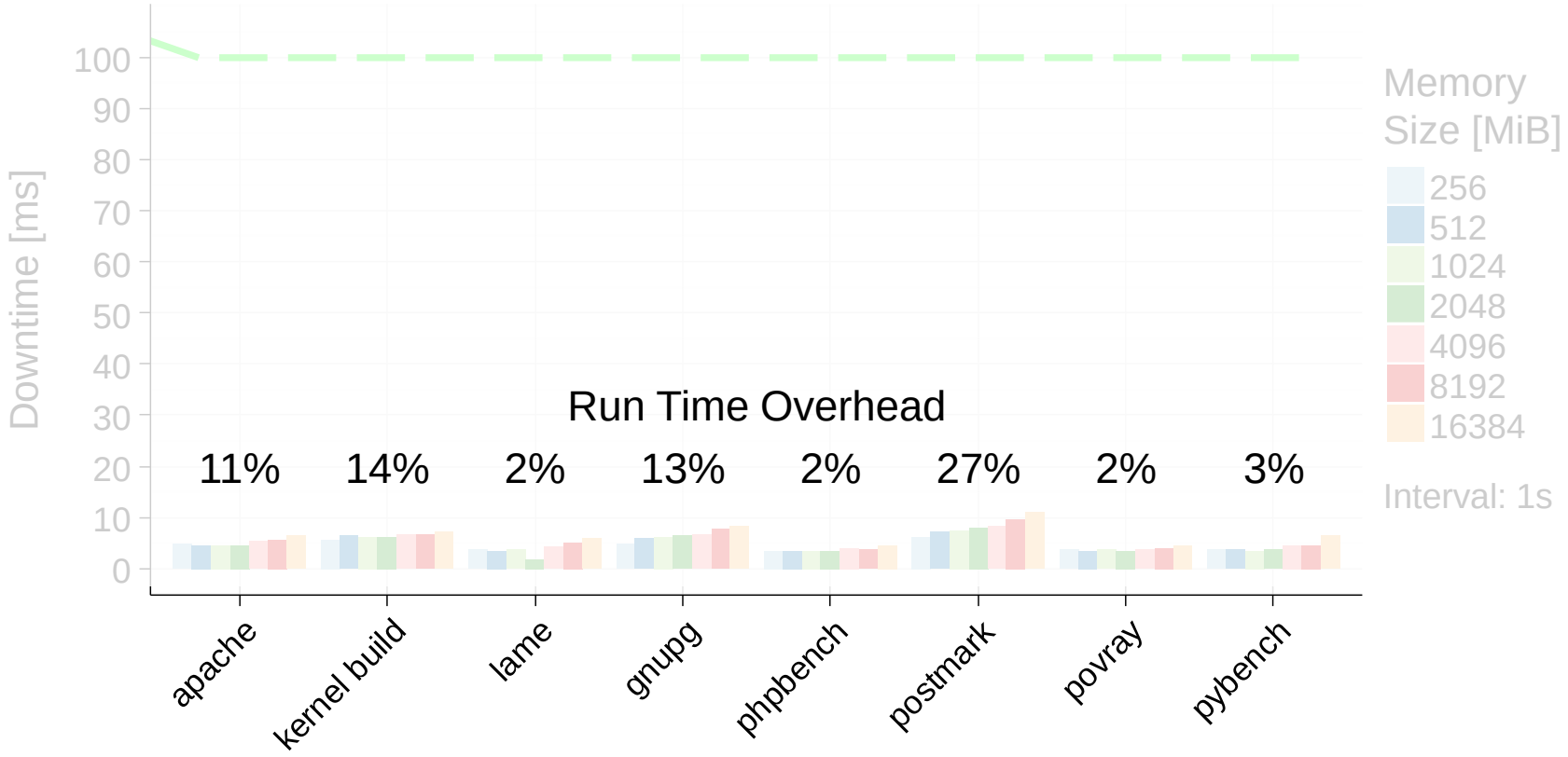


Checkpointing II



- Baseline: Simple Stop-And-Copy (4GiB VM)
  - Downtime: 1.2s
  - Run time overhead: ~3x

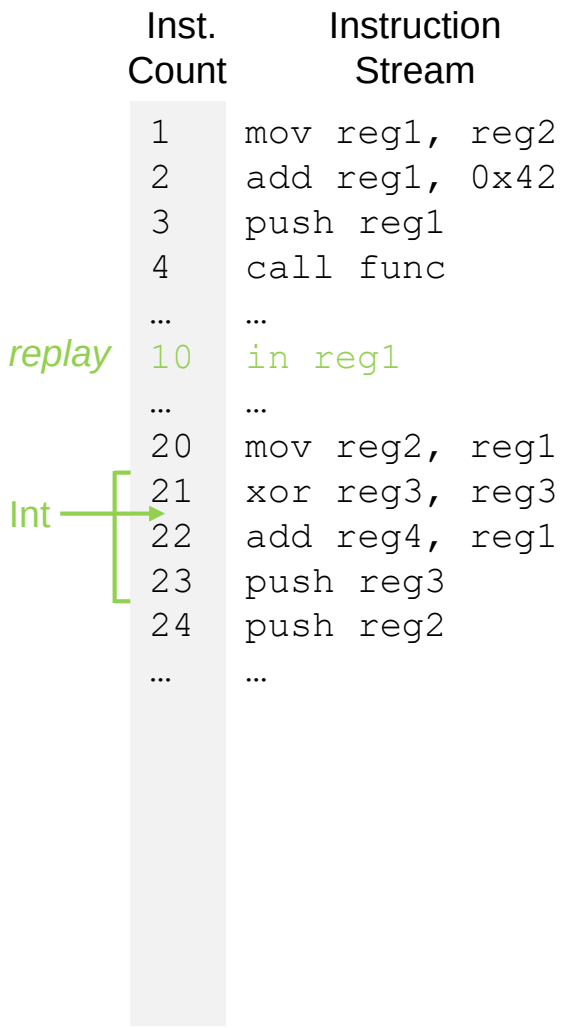
Checkpointing II



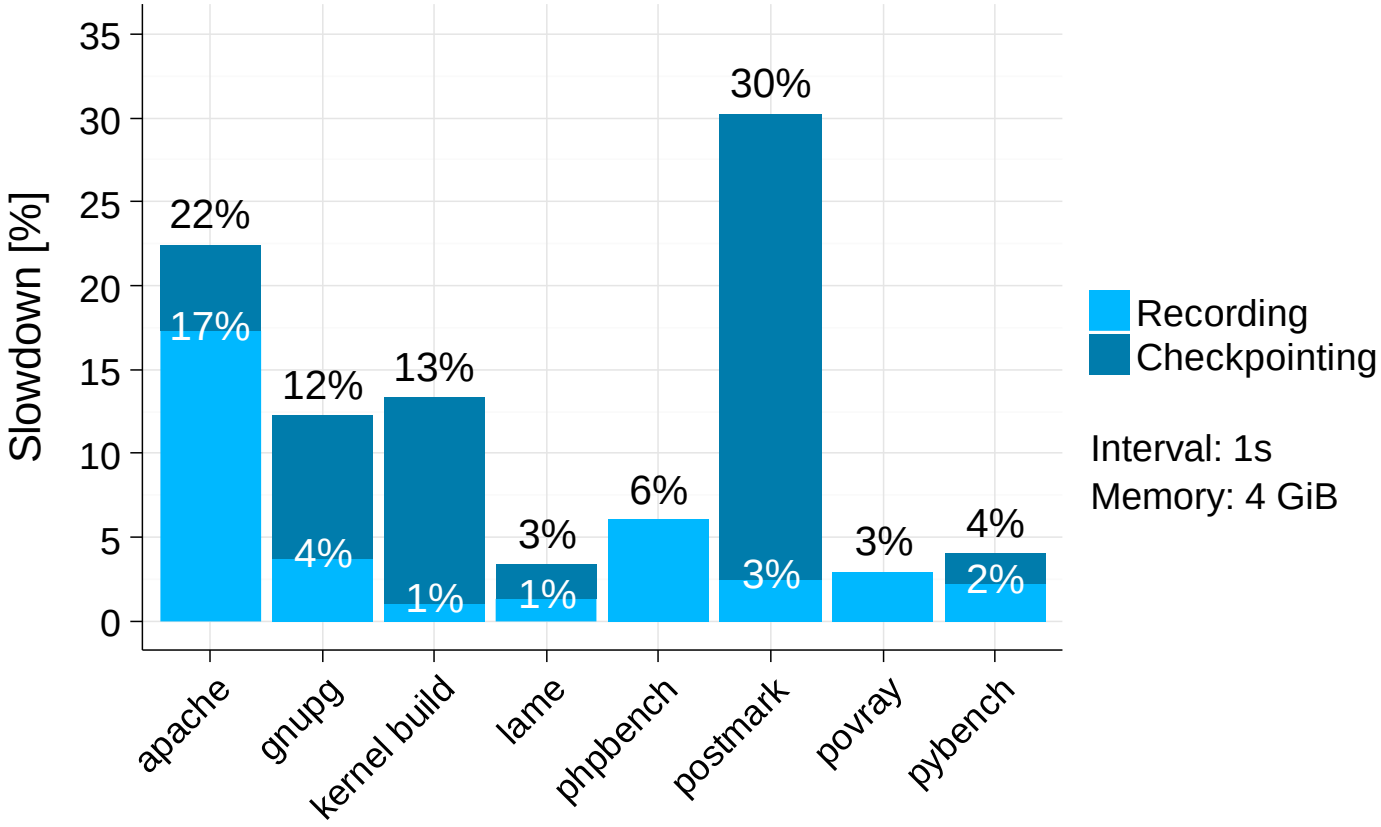
- Baseline: Simple Stop-And-Copy (4GiB VM)
  - Downtime: 1.2s
  - Run time overhead: ~3x

Deterministic Replay

- Synchronous events (`cpuid`, `rdtsc`, port I/O, …)
  - Trap & record `<value>`
  - Replay value in simulation
- Asynchronous events (interrupts, DMA)
  - Trap & record `<landmark, value>`
  - Landmark: Instruction counter + CPU registers
  - Inject event at landmark (e.g., raise interrupt)
- Improve accuracy of simulation
  - Match instruction counting with hardware
  - Implement “undefined” status bits
  - ...

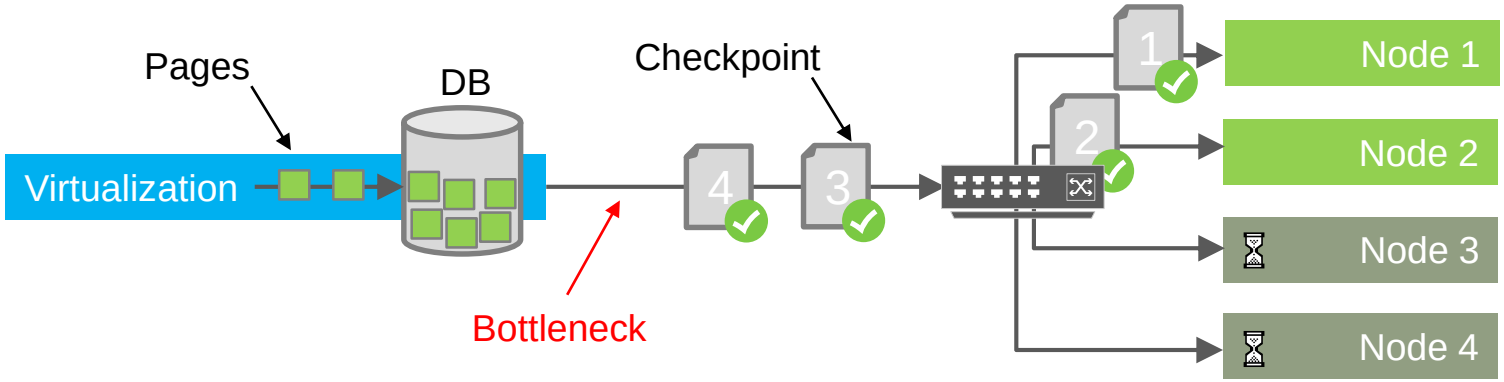


Run Time Overhead



Naive Simulation Startup

1) Nodes request checkpoints from central server



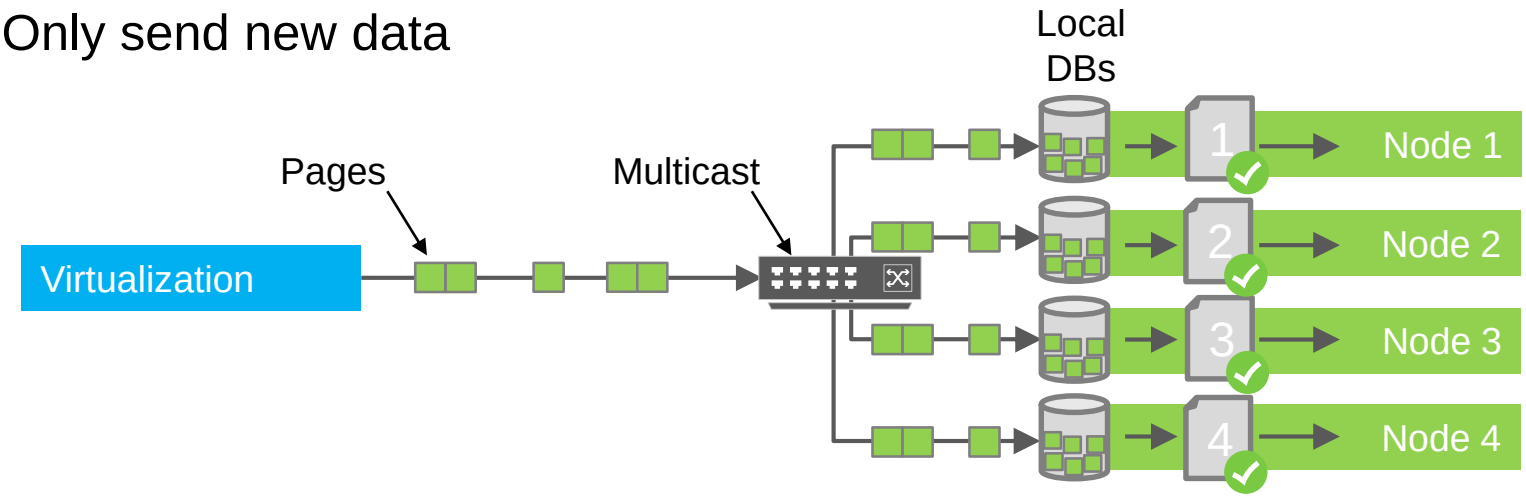
2) Load entire checkpoint into memory

3) Start simulation of interval

- But: Central server becomes bottleneck

Simulation Startup

- Only send new data



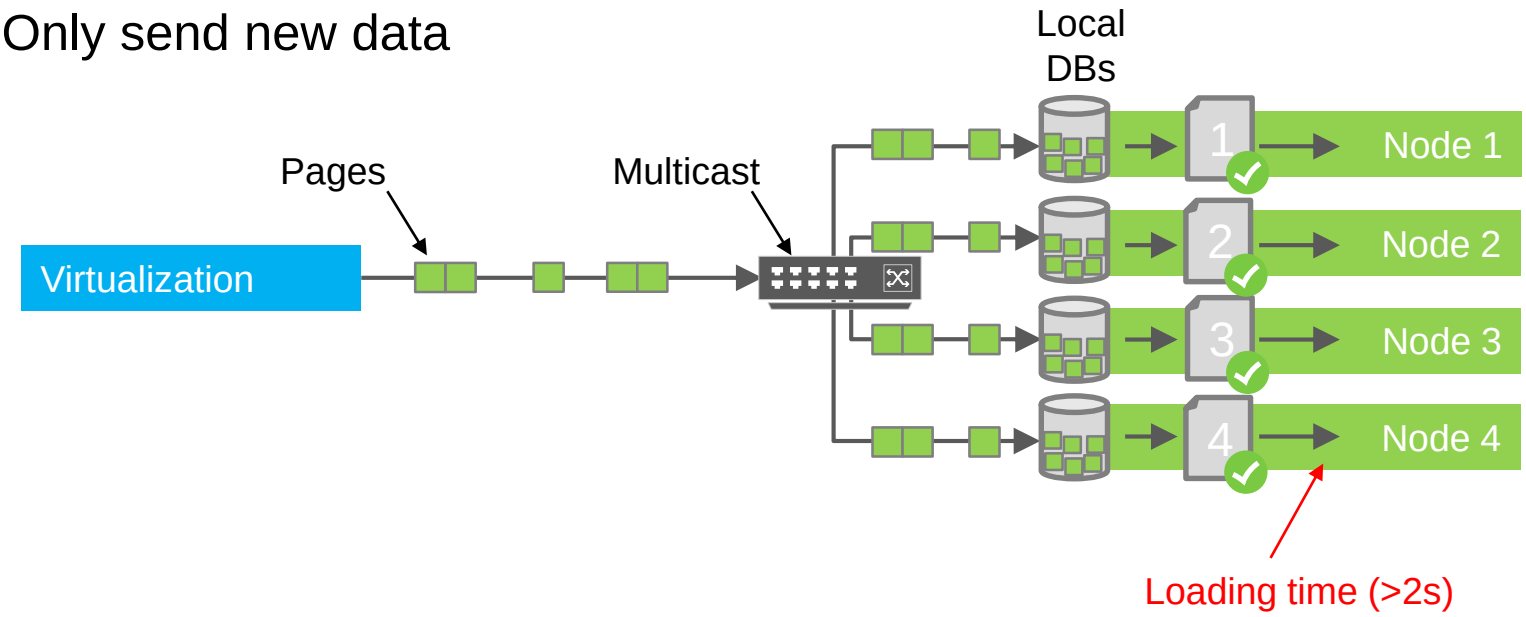
- Deduplicate and compress data

Linux Kernel Build	SPECjbb2005
22000 pages/s (85 MiB/s)	53000 pages/s (200 MiB/s)
5000 pages/s (20 MiB/s)	16000 pages/s (65 MiB/s)

Gigabit Ethernet

Simulation Startup

- Only send new data



- Only load pages that will be accessed in interval

Load time: 2s ↘ 200ms

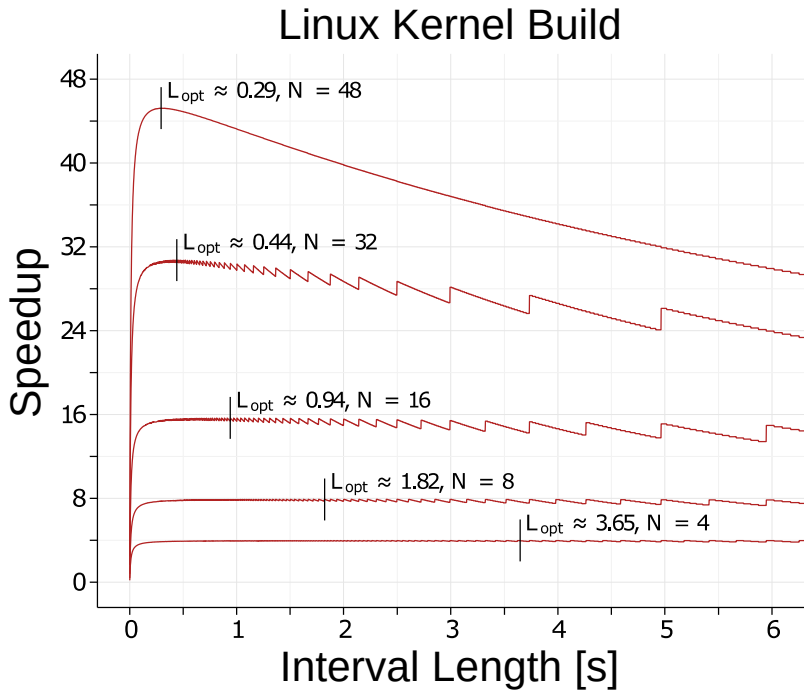
Memory consumption: 4GiB ↘ <500MiB

⇩

Increase simulation density

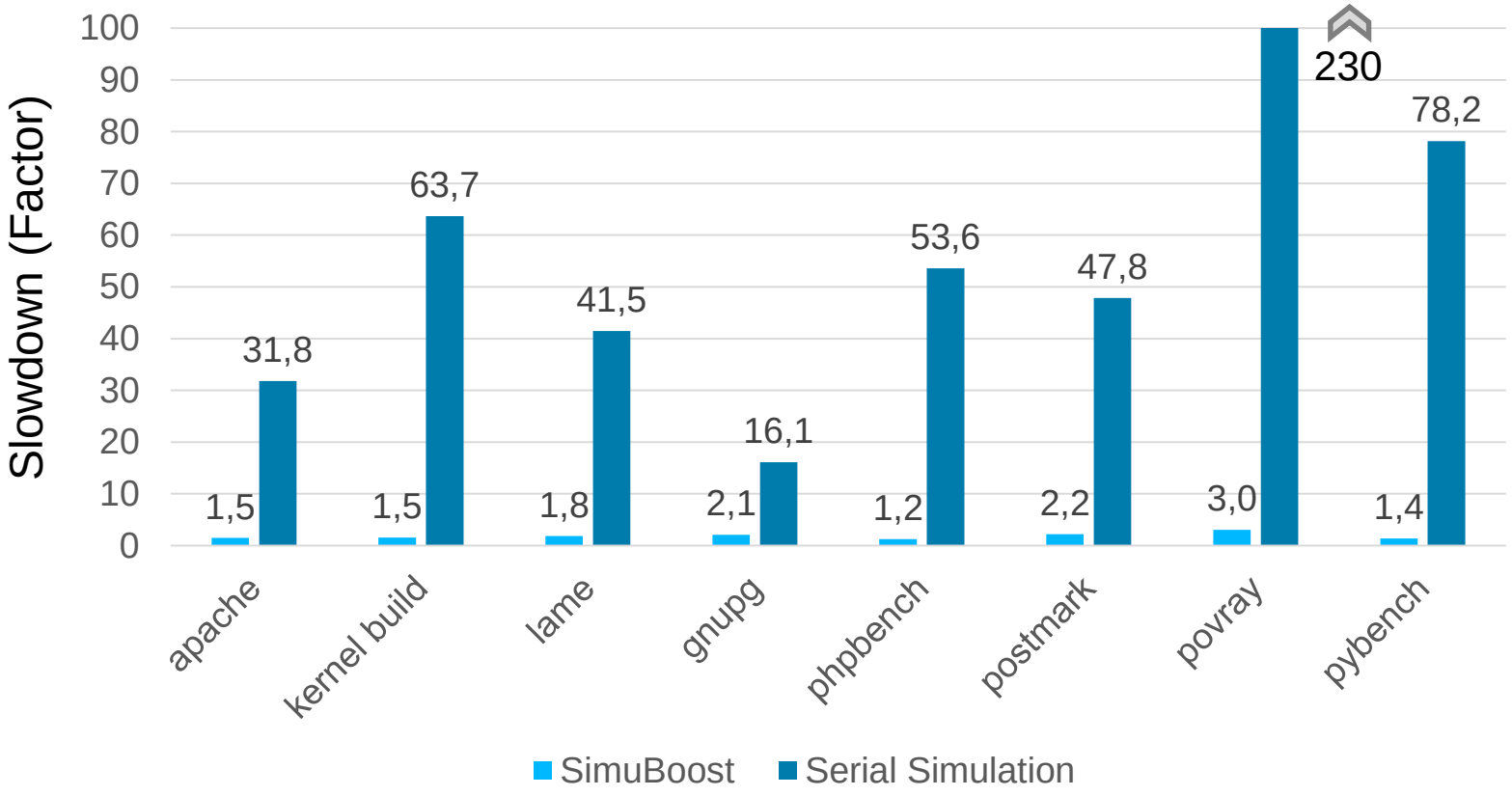
Performance Model

- Want: Optimal interval length
- Input
  - Workload run time without SimuBoost
  - Virtualization overhead (slowdown, downtime)
  - Simulation overhead (slowdown incl. analysis, startup time)
- Output
  - Parallel simulation time
  - Speedup
- Differentiation
  - ➢ Optimal interval length



Evaluation

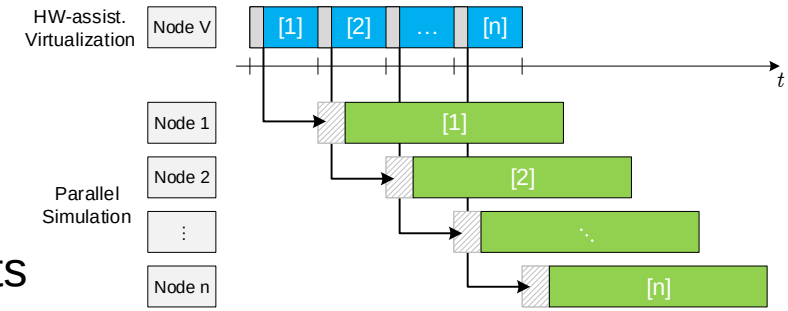
- Baseline: Hardware-assisted virtualization without SimuBoost



Conclusion

- Slowdown of functional full system simulation: >100x

- SimuBoost: Accelerate simulation
  - Run workload with fast virtualization
  - Take checkpoints in regular intervals
  - Start parallel simulations on checkpoints



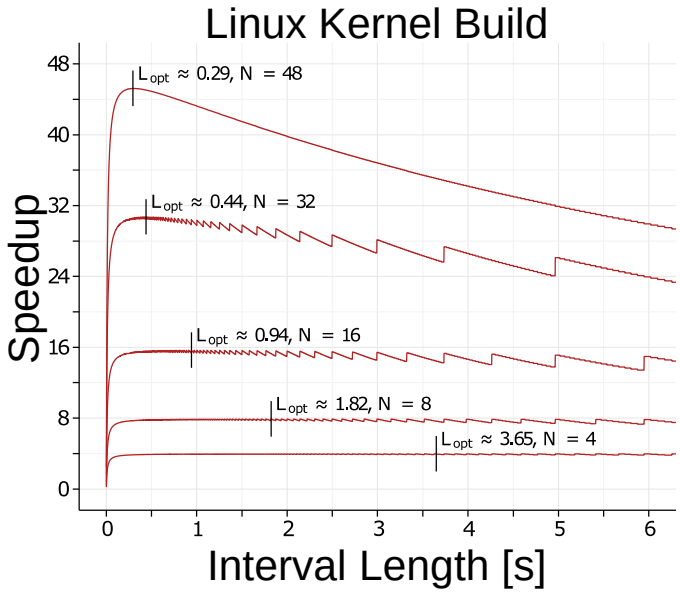
- Contribution
  - Drastically reduces slowdown (e.g., 230x → 3x)
  - Enables interactivity (users and network)
  - Moderate probe effect
    - Run time overhead on average 40%

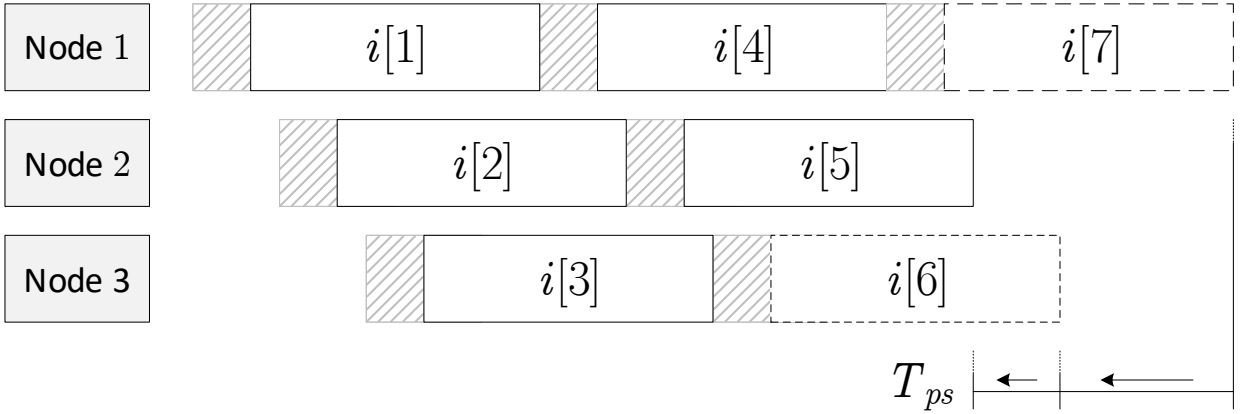
SimuBoost: Functional full system simulation made practical

Evaluation Raw Data

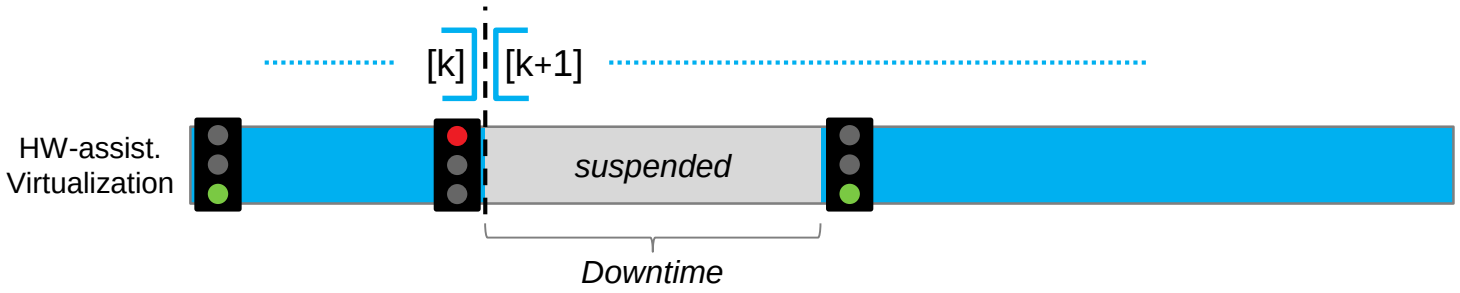
	apache	kernel build	lame	gnupg	phpbench	postmark	povray	pybench
HW Time	166,1	439	37,5	21,66	271	38,7	611	33,78
HW SimuBoost	225	554	66	27	306	82	669	43
Overhead	1,35	1,26	1,76	1,25	1,13	2,12	1,09	1,27
Parallel Time	247	665	68	45	337	86	1857	47
Serial Time	5280	27957	1556	349	14528	1851	141202	2640
SimuBoost	1,5	1,5	1,8	2,1	1,2	2,2	3,0	1,4
Serial Simulation	31,8	63,7	41,5	16,1	53,6	47,8	231,1	78,2
Speedup	21,4	42,0	22,9	7,8	43,1	21,5	76,0	56,2
Nodes	28	64	42	16	53	40	88	78
Interval Length [ms]	200	230	65	100	145	100	120	45

Source of Sawtooth



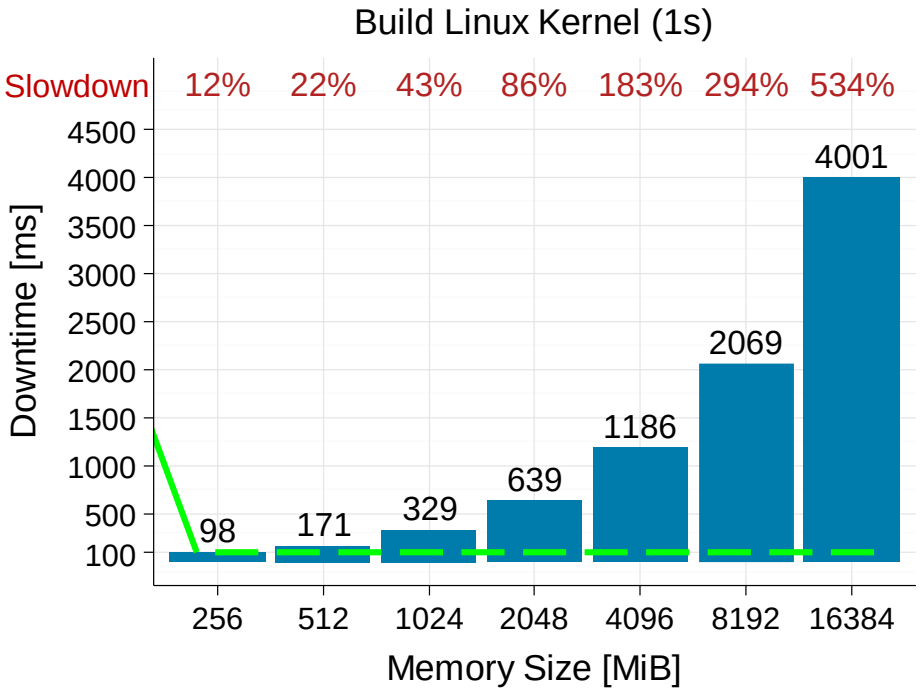


Stop-And-Copy Checkpointing



- Device states: 1 – 3 ms
- Guest physical memory
  - Dominates downtime
  - Downtime depends on VM size

- Not suited for interactive use
- Impairs parallelization



Selected Previous Research

- Workload Reduction
  - MinneSPEC [KleinOsowski02]
- Simulate samples and extrapolate
  - Truncated Execution
  - SimPoints [Sherwood02]
  - SMARTS [Wunderlich03]
- Improve simulation engine
  - Optimize engine: below 5x speedup mark
  - Parallelize simulation of vCPUs [Ding11]
- Divide simulation time
  - For microarchitectural simulations: DiST [Girbal03]
  - SuperPin

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