Fine-Grained Dynamic Instrumentation of Commodity Operating System Kernels

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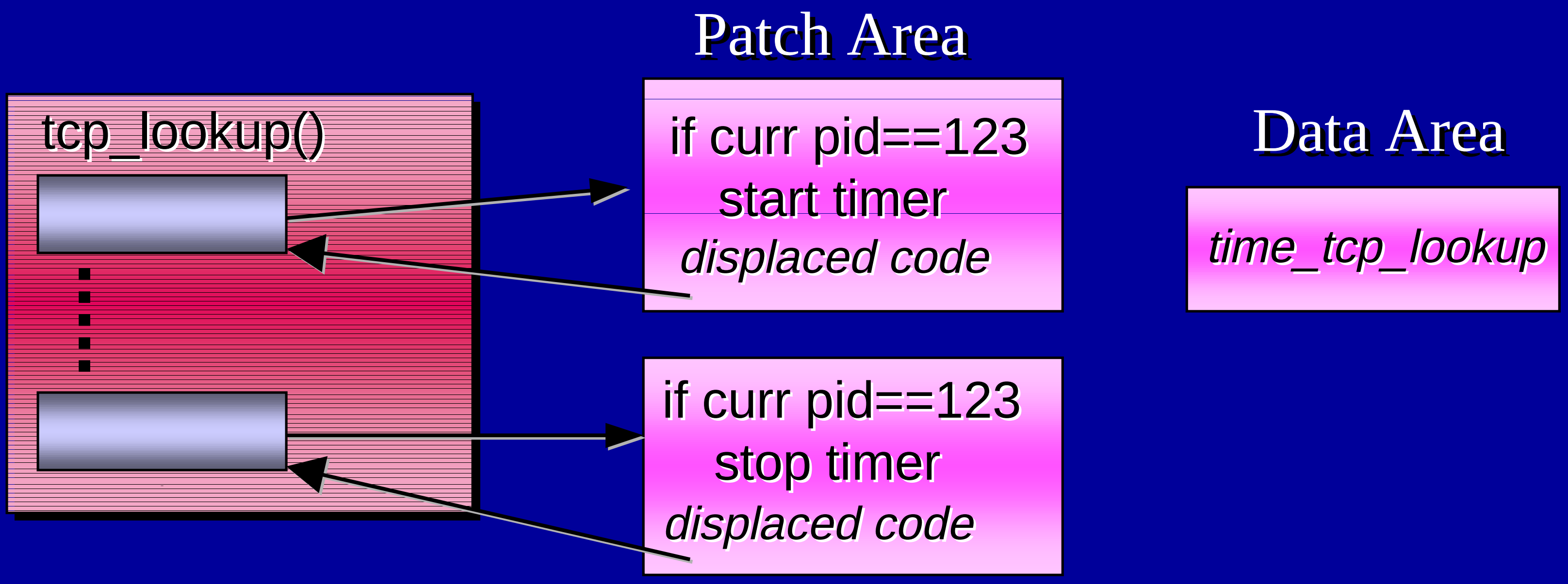
The Vision

- A unified infrastructure for dynamic OS's
- Fine-grained runtime code instrumentation for:
  – Performance measurement
  – Tracing
  – Testing (e.g., code coverage)
  – Debugging: conditional breaks, access checks
  – Optimizations: specialization, code reorganization
  – Extensibility

Motivation: Measurement

- Measurement primitives
  - Counts, elapsed cycles, cache miss cycles (on-chip counters)
    - Instrument kernel to self-measure as it runs
- Predicates
  - Specific code path; when a process is running, etc.
- Many interesting routines in the kernel:
  - Scheduling: preempt, disp, swtch
  - VM management: hat_chgprot, hat_swapin
  - Network: tcp_lookup, tcp_wput, ip_csum_hdr, hmeintr

Time Spent Demuxing TCP Packets

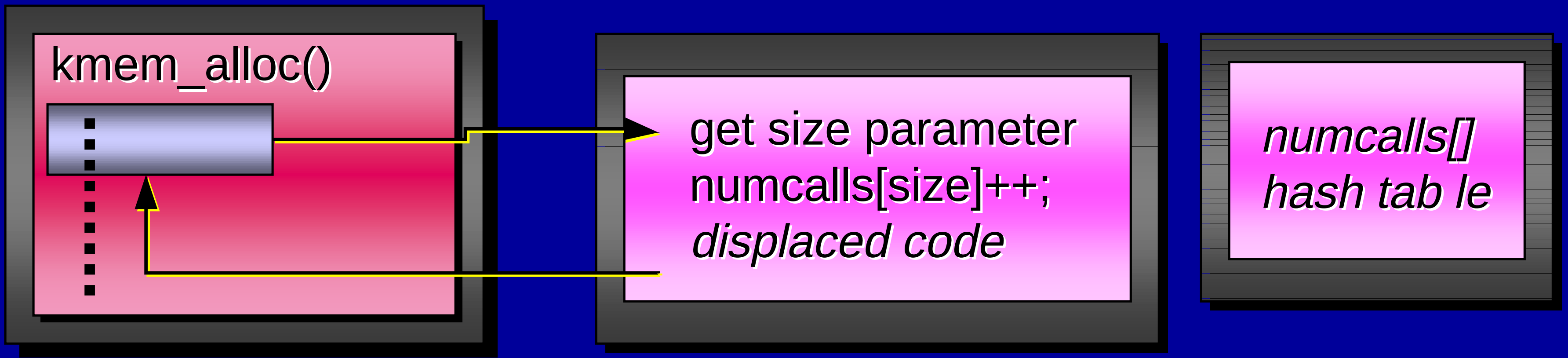


Motivation: Optimization

- Performance measurement shows slow code? Pick from a cookbook of on-line optimizations
  - Specialization
    - Instrument function to find common params
    - Generate specialized function
    - Install (old version jumps to new if condition met)
    - Can predicate specialization (e.g. a specific process)
  - Reorganize code to improve i-cache
    - Instrument function to measure icache miss cycles
    - Then instrument to find cold basic blocks
    - Generate “outlined” function & install

Motivation: Specialization

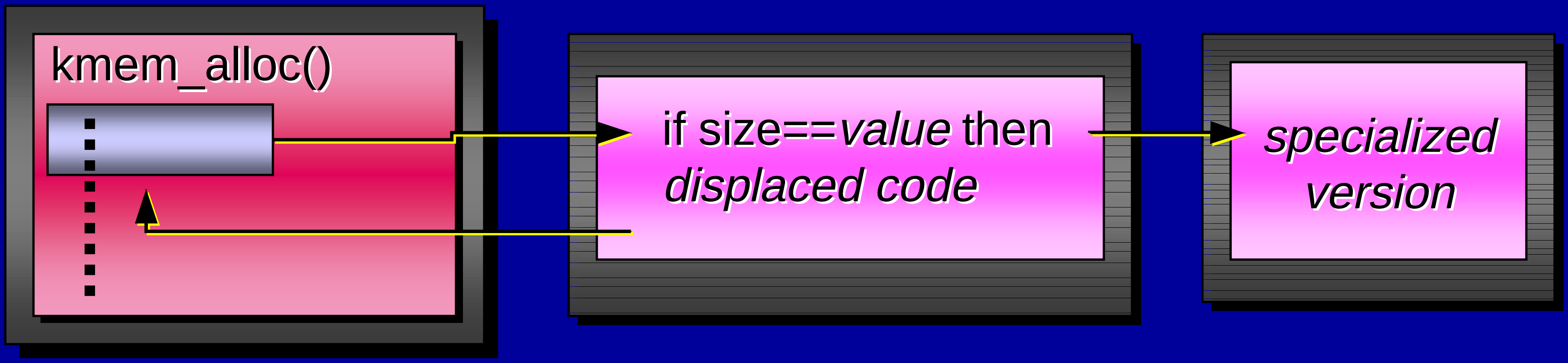
- Profile:



- Decision: examine hash table
- Generate specialized version:
  - – choose fixed value & run constant propagation
  - – expect unconditional branches & dead code

Motivation: Specialization

- Splice in the specialized version:



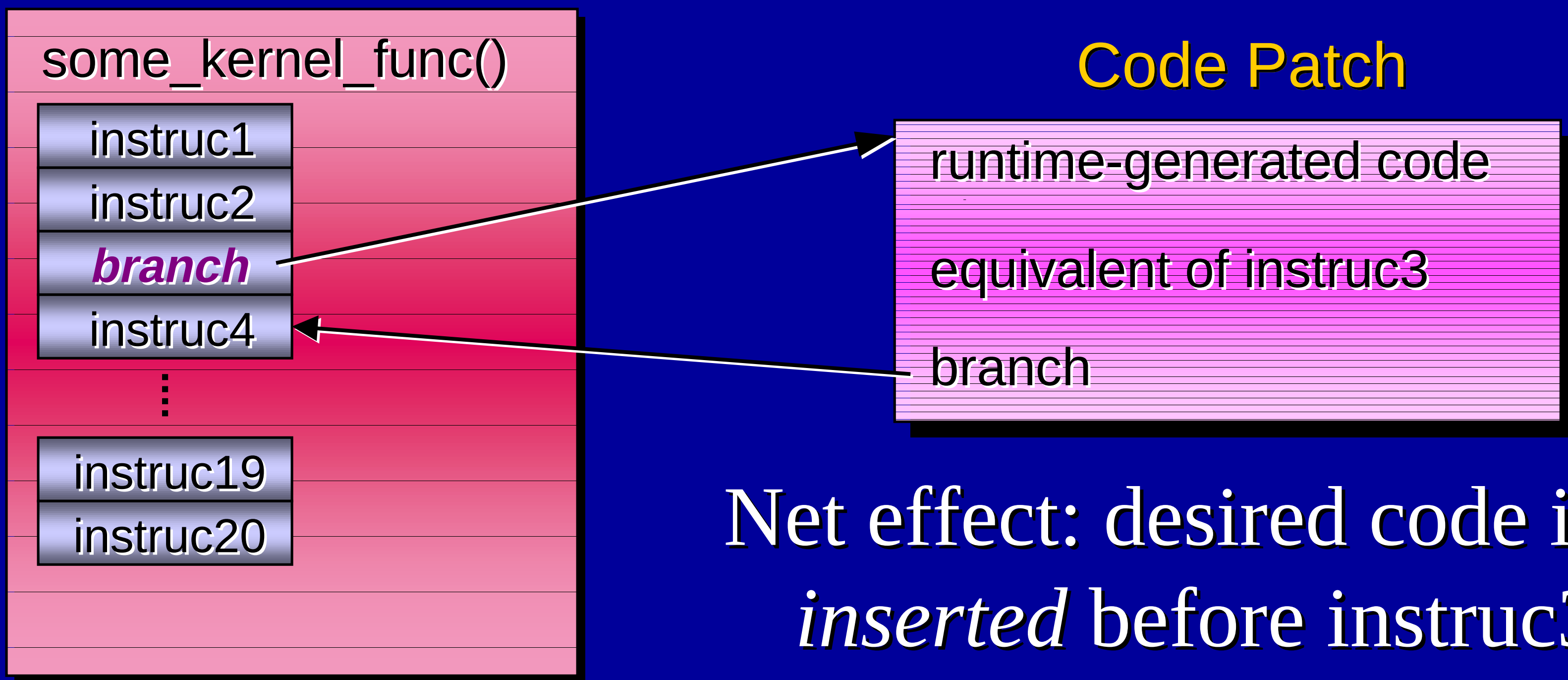
- Patch calls to kmem_alloc
  - Detect constant values for size, where possible
  - If specialized version appropriate, patch call
    - No overhead in this case

Technology to Make it Happen

KernInst: fine-grained dynamic kernel instrumentation

- Inserts runtime-generated code into kernel
- Dynamic: everything at runtime
  - no recompile, reboot, or even pause
- Fine-grained: insert at instruction granularity
- Runs on unmodified commodity kernel
  - Solaris on UltraSparc

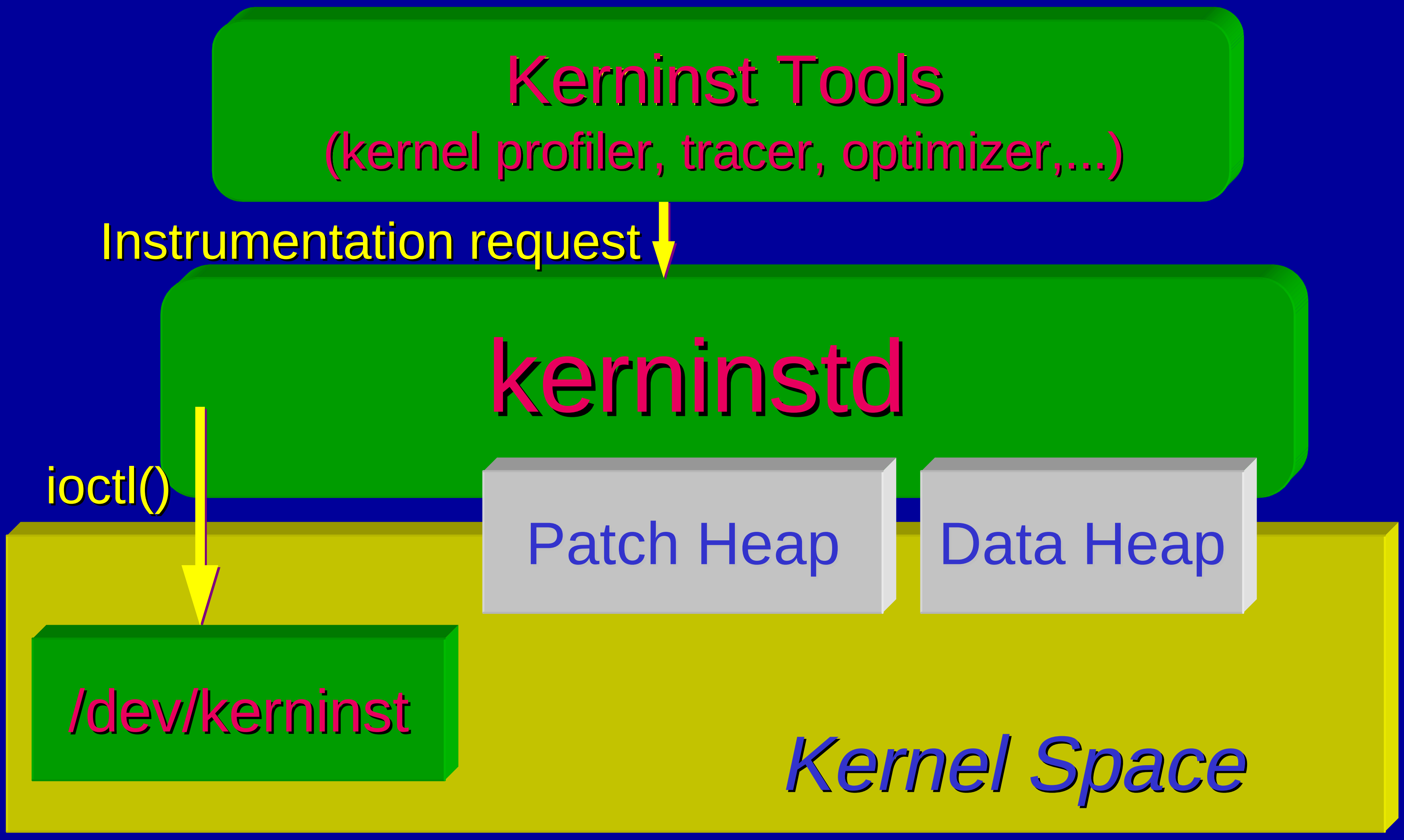
Dynamic Instrumentation



Net effect: desired code is *inserted* before instruc3

- Insert any code, almost anywhere (fine-grained), entirely at runtime (dynamic)

Our System: *KernInst*



How KernInst Works

kerninstd startup:

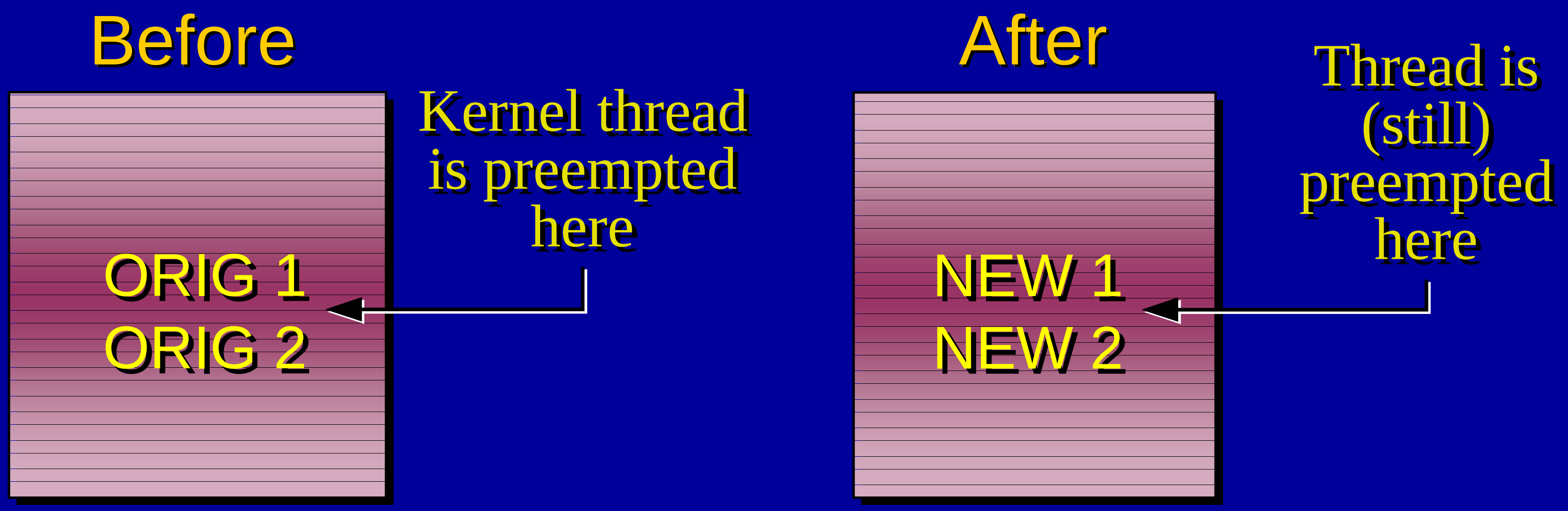
- Installs the KernInst driver, /dev/kerninst
- Allocates patch and data heaps, and reads kernel symbol table (with assistance from /dev/kerninst)
- Parses kernel code into CFG
  - Finds all kernel code, organized as basic blocks
- Finds unused registers
  - Inserted code will use these registers (avoid spills)
  - From an interprocedural data-flow analysis on the CFG
- Fast: 15 seconds

How KernInst Works (2)

- To splice in instrumentation code, kerninstd:
  - Allocates code patch
  - Fills code patch with instrumentation code, overwritten instruction, and a jump back
  - Overwrites instruction at instrumentation point with a branch to the code patch
- Writing to kernel memory
  - /dev/kmem works for *most* of the kernel
  - Have /dev/kerninst map into D-TLB for nucleus

Code Splicing Hazard

Jumping to the patch using two instructions:

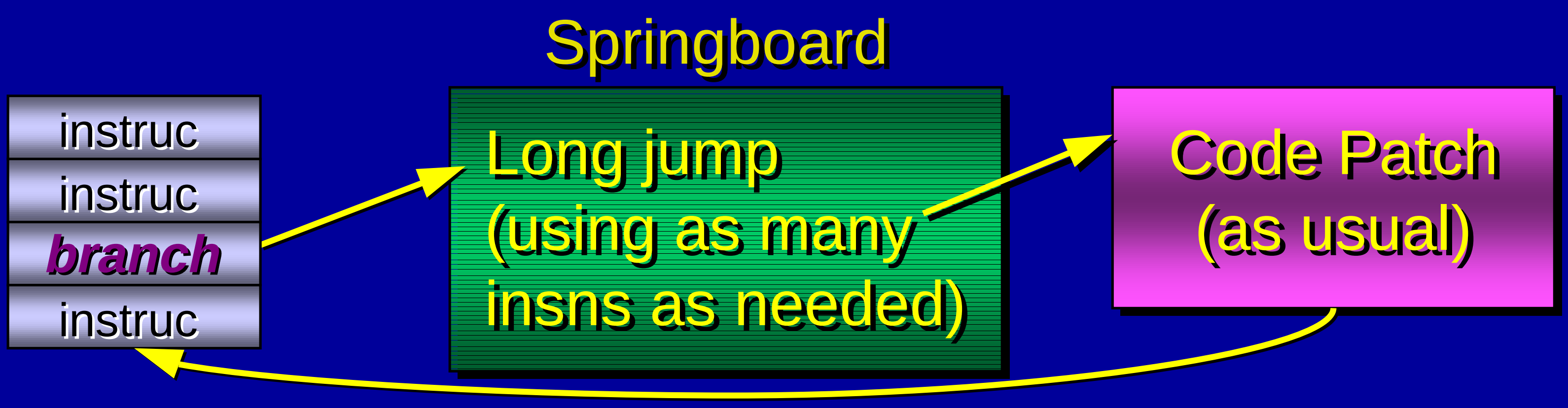


Execution sequence: (ORIG1, NEW2) ⟶ *crash!*

- Cannot pause kernel to check for hazard
- Splicing must replace *only one* instruction!

Code Splicing: Reach Problem

- Tough to reach patch with just 1 instruction!
  - Usually too far from the instrumentation point.
  - SPARC branch instruction has only +/- 8MB displacement (ba,a)
- General solution: *springboards*



Springboard Heap

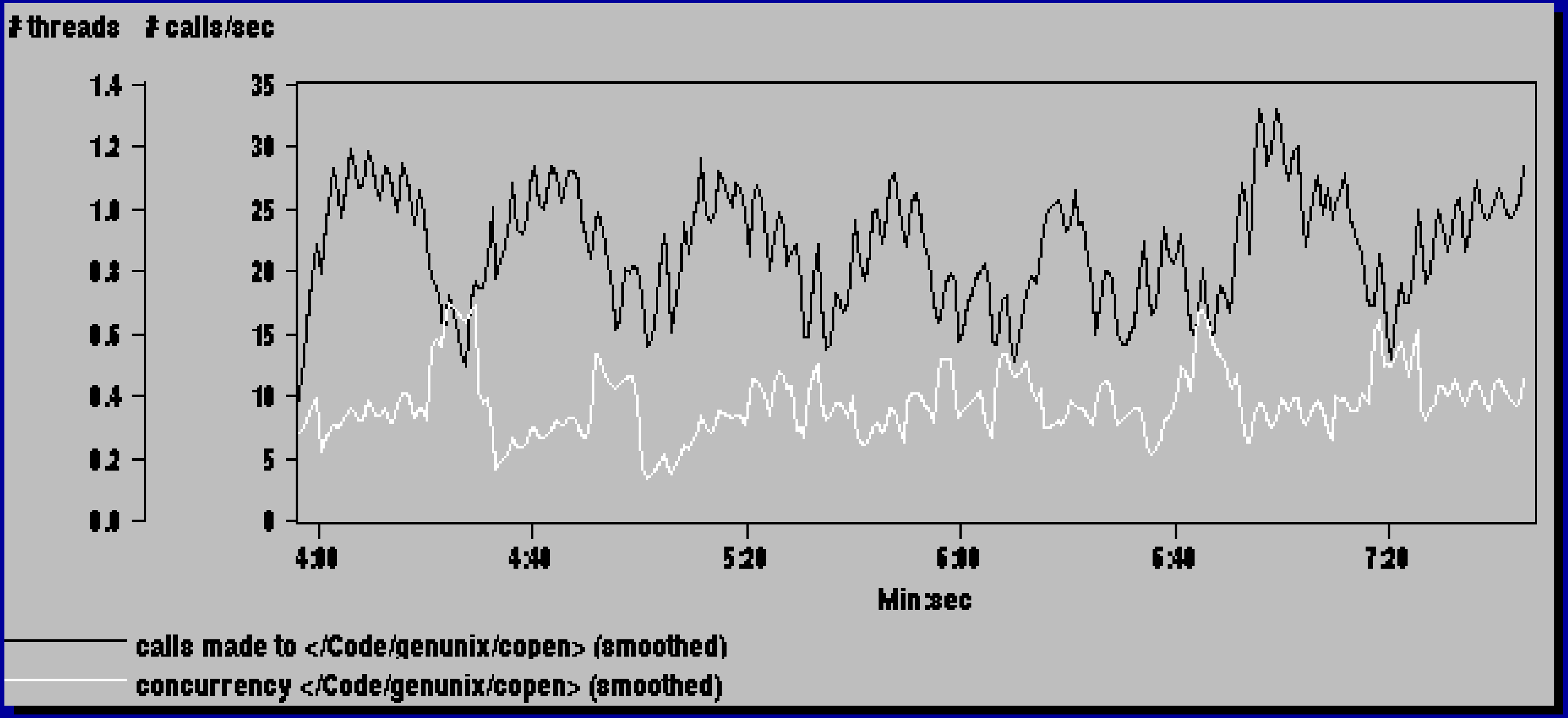
- Chunks of scratch space throughout kernel
  - So every instruction is close to a springboard
  - Overwrite module initialization and termination routines
    - Ideal: located throughout the kernel
    - _init and _fini on SVR4
    - Turn off module unloading so they're not called
  - Also overwrite boot time routines
    - _start and main

Web Proxy Server Measurement

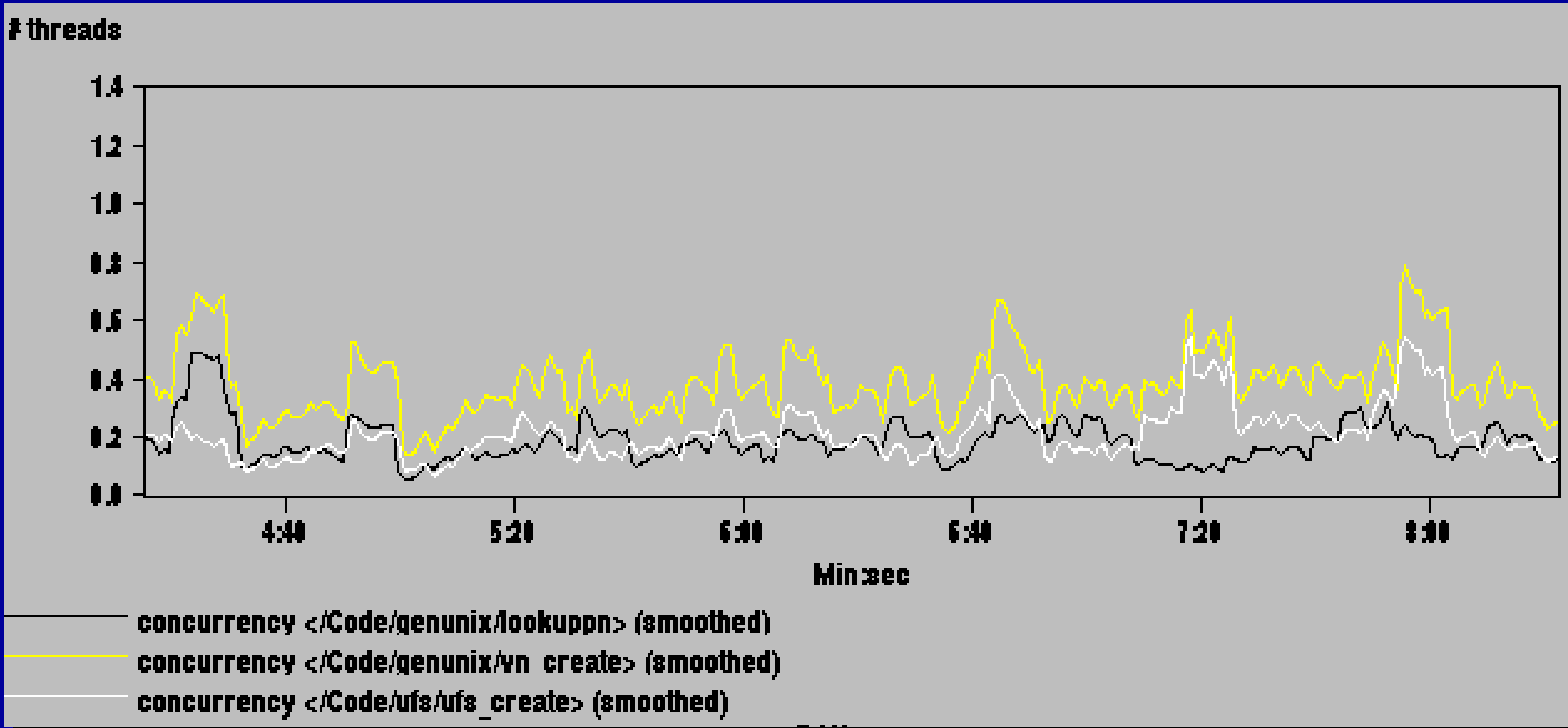
- Simple kernel measurement tool
  - Number of calls made to a kernel function
  - Number of kernel threads executing within a kernel function (“concurrency”)
- Squid v1.1.22 http proxy server
  - Caches HTTP objects in memory and on disk
  - We used KernInst to understand the cause of two Squid disk I/O bottlenecks.

Web Proxy Server Measurement

- Profile of the kernel open() routine



- Called 20-25 times/sec; taking 40% of time!



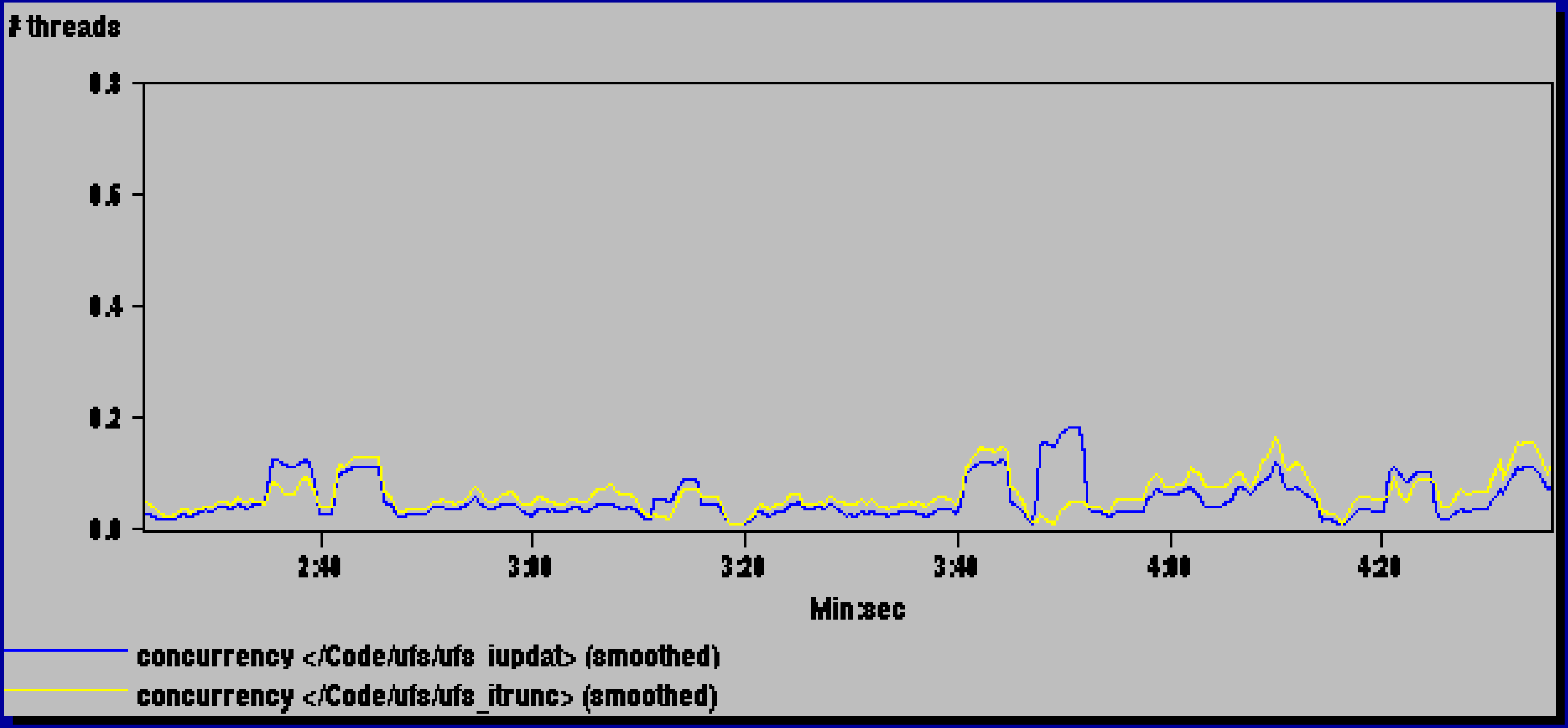
- open() calling vn_create; has 2 sub-bottlenecks:
  - – lookuppn (a.k.a. namei): path name translation (20%)
  - – ufs_create: file create on local disk (20%)

File Creation Bottleneck

- How Squid manages its on-disk cache:
  - 1 file per cached HTTP object
  - A fixed-size hierarchy of cache files
  - Stale cache files overwritten
- lookuppn bottleneck
  - Too many files overwhelms DNLC
- File creation bottleneck
  - When overwriting a stale cache file: truncates first
  - UFS semantics: meta-data changed synchronously

File Creation Optimization

- Overwrite cache file; truncate only if needed



- What took 20% now takes 6%

What's Up Next

- Improved measurements
  - New metrics: mutex waiting time, branch mispredict stall time, icache stall time
  - Measure individual basic blocks
  - Measure for specific processes
    - Instrument the kernel's context switch handler
- Automated runtime optimizations
  - Specialization, outlining

What's Up Next

- Safety and security (Zhichen Xu)
  - Now: must be root
  - Future (Zhichen Xu): allow untrusted instrumentation code
- x86/Solaris port (Vic Zandy)
  - As before, overwrite just 1 instruction
    - The catch: tough given variable-length instructions
    - Prefer a 5 byte jump instruction. Use when overwriting an instruction *at least* that long.
    - For overwriting smaller instructions: INT 3

Conclusion

- Fine-grained dynamic kernel instrumentation is feasible on an *unmodified* commodity OS
- *A single infrastructure* for
  - – Profiling, debugging, code coverage
  - – Optimizations
  - – Extensibility
- The foundation for an evolving OS
  - Measures and constantly adapts itself to runtime usage patterns
- For papers: visit Paradyn web page

The Big Picture