The Enhancement of Kernel Probing
- Kprobes Jump Optimization

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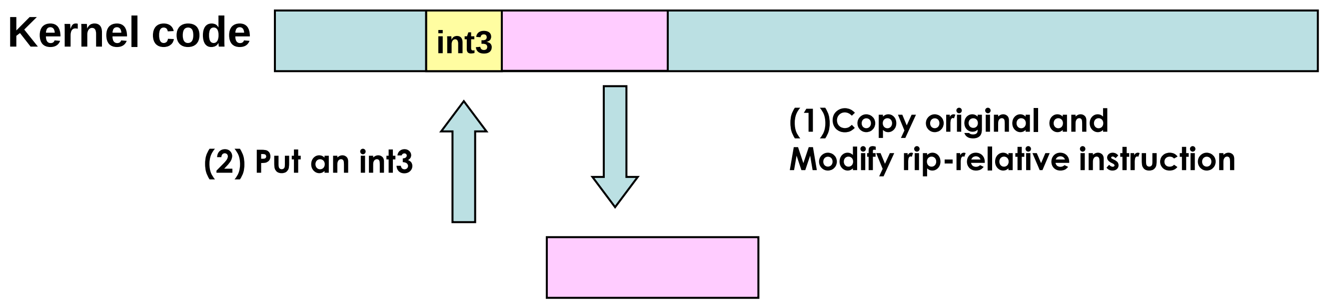
Agenda

- Kprobes – Why it is useful
- Kprobes – How it works
- Performance Enhancing Ideas
  - Booster
  - Jump Optimization
- Technical Issues
  - Interrupts
  - Instruction Boundary
    - X86 Instruction Decoder
  - Jumps
  - Cross Code Modifying
- Implementation
  - Transparency of API/ABI
  - Greedy Optimization
  - Reserve Text
- Results
  - Kprobes
  - Kretprobes
  - Results on KVM
- Conclusion

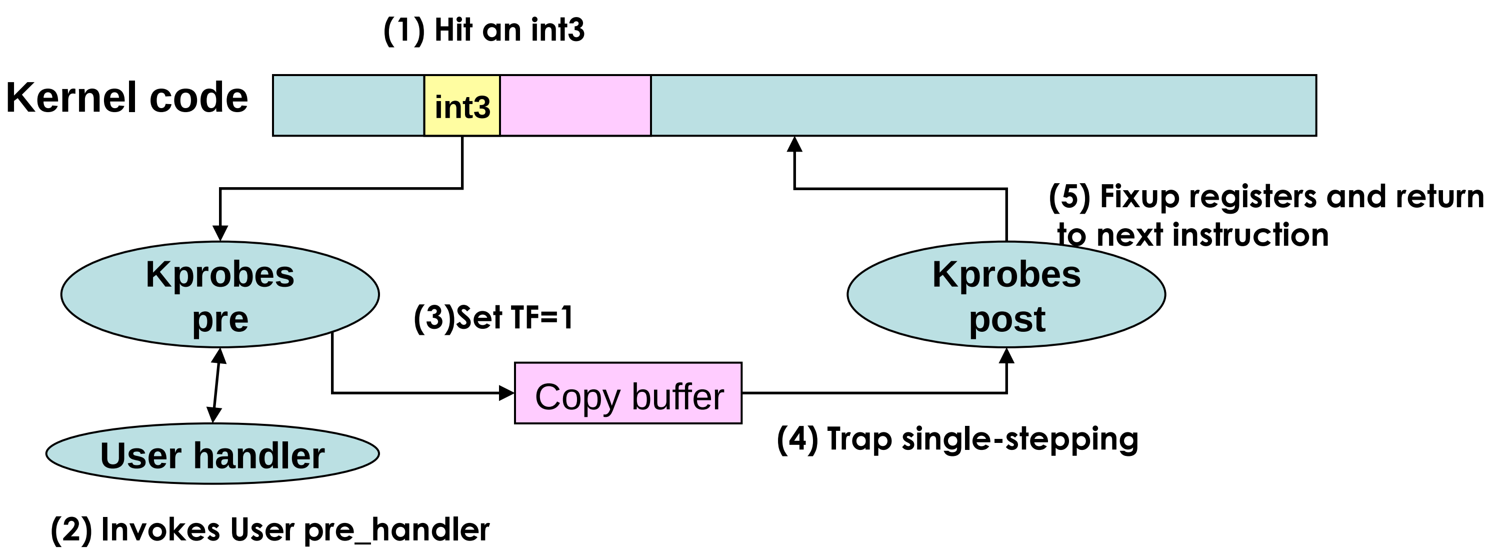
- Kprobes is a dynamic software breakpoint function in the kernel
  - This allows you to add breakpoints inside kernel
    - User can check the kernel internal state almost anywhere
    - This allows user to tweak kernel internal state too (e.g. fault injection, and dynamic patching)
  - Dynamically add and remove the breakpoints.
  - Manage the breakpoint handlers
    - Handling breakpoint exception and call handlers
    - Aggregate probes on the same address
    - Disable probes when a target module is gone
    - Etc.

- Kprobes uses a breakpoint and a single-step

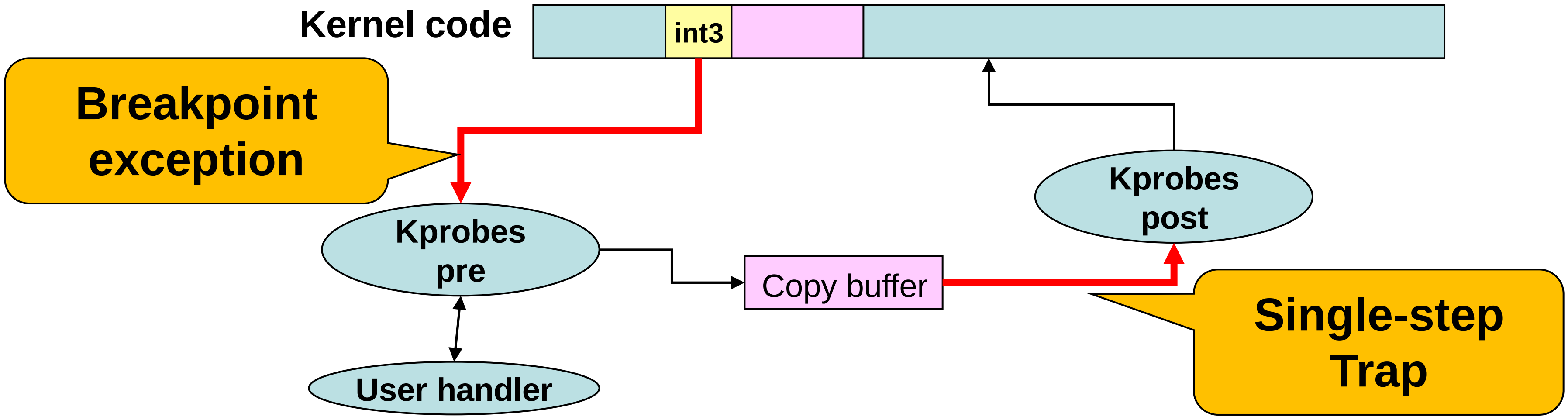
Preparing



Running

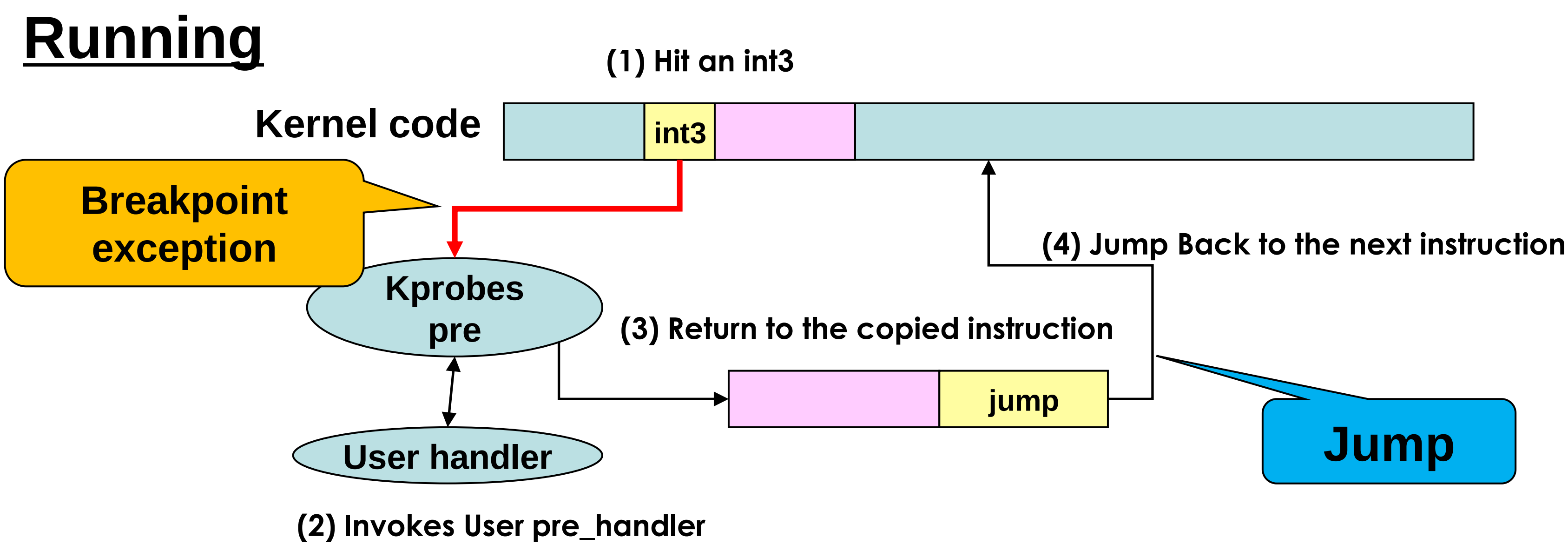


- Kprobes uses 2 exceptions
  - Software Breakpoint exception
  - Single-step trap

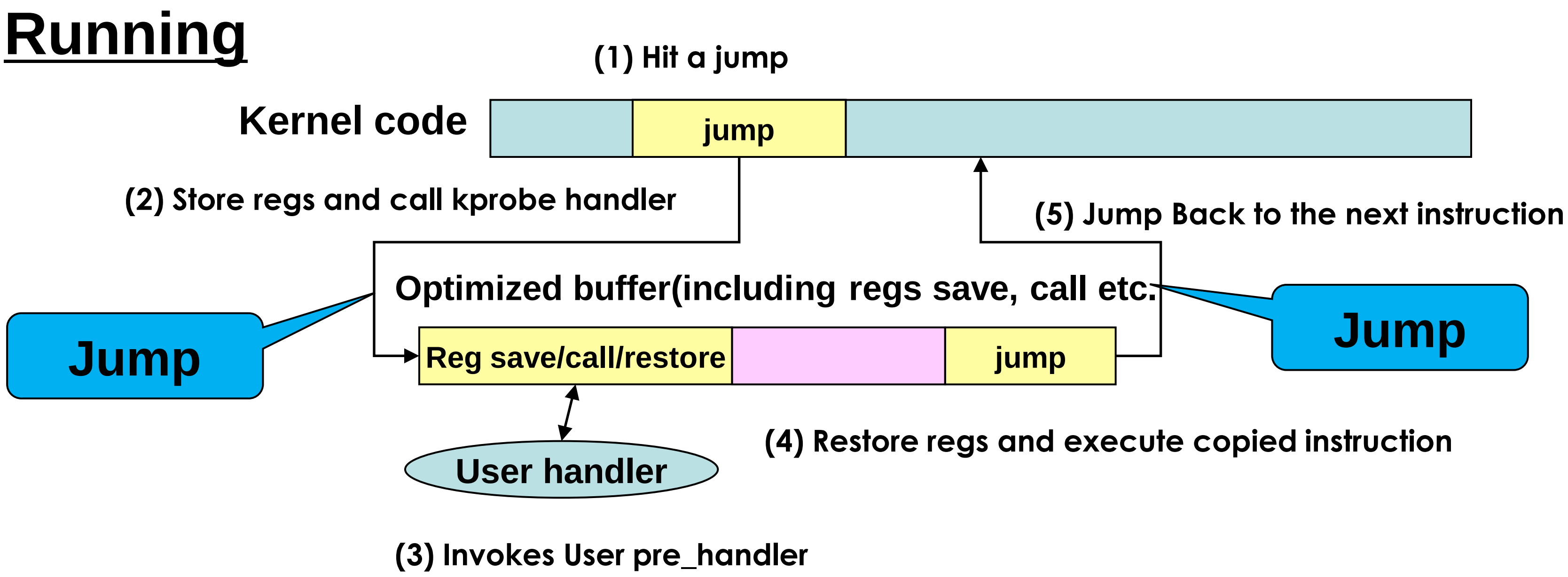


Normal kprobe consumes >1500 cycles/probe

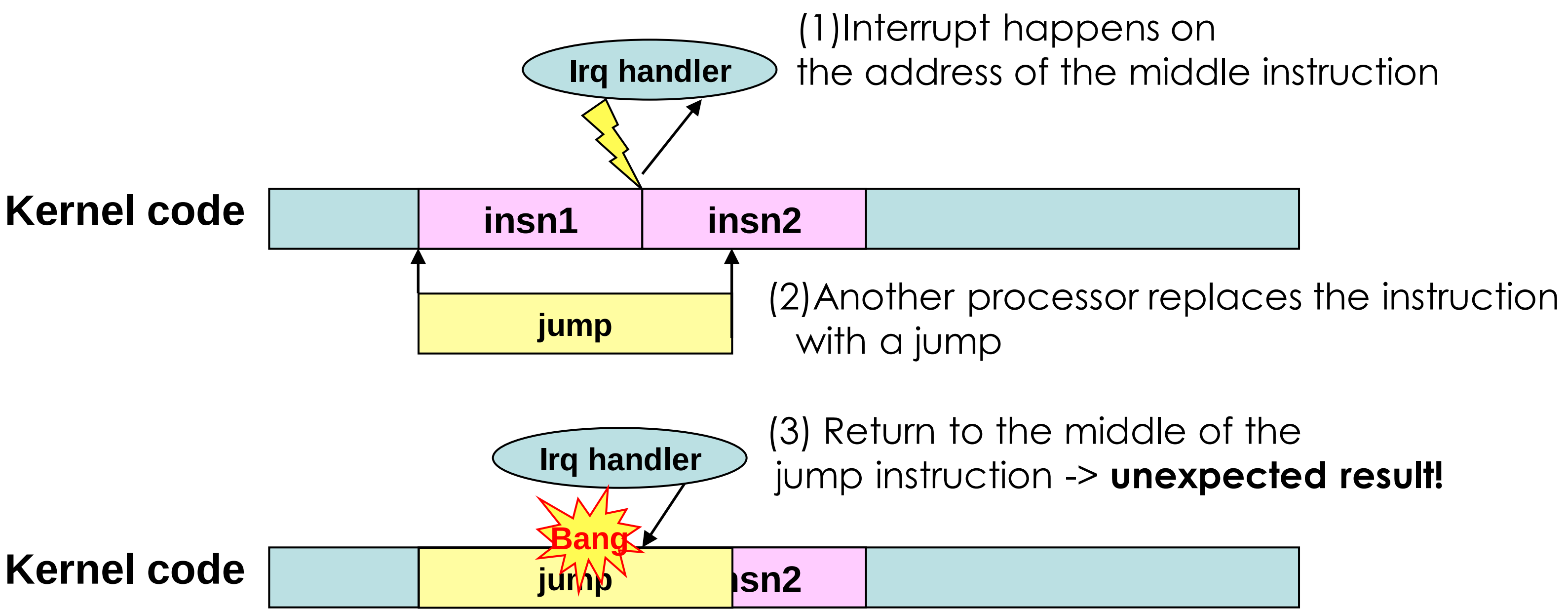
- Kprobes Booster skips Trap exception
  - Add a jump which jumps back to next instruction
  - Execute copied instruction and the jump
  - Some instructions can't be boosted
    - Call, near jump, etc



- Kprobes Jump Optimization
  - Skips software breakpoint too
    - No exception: Reduce the overhead drastically
  - It's not easy – of course.
    - This will replace **several instructions** with one jump
      - Kprobes just replace one instruction.

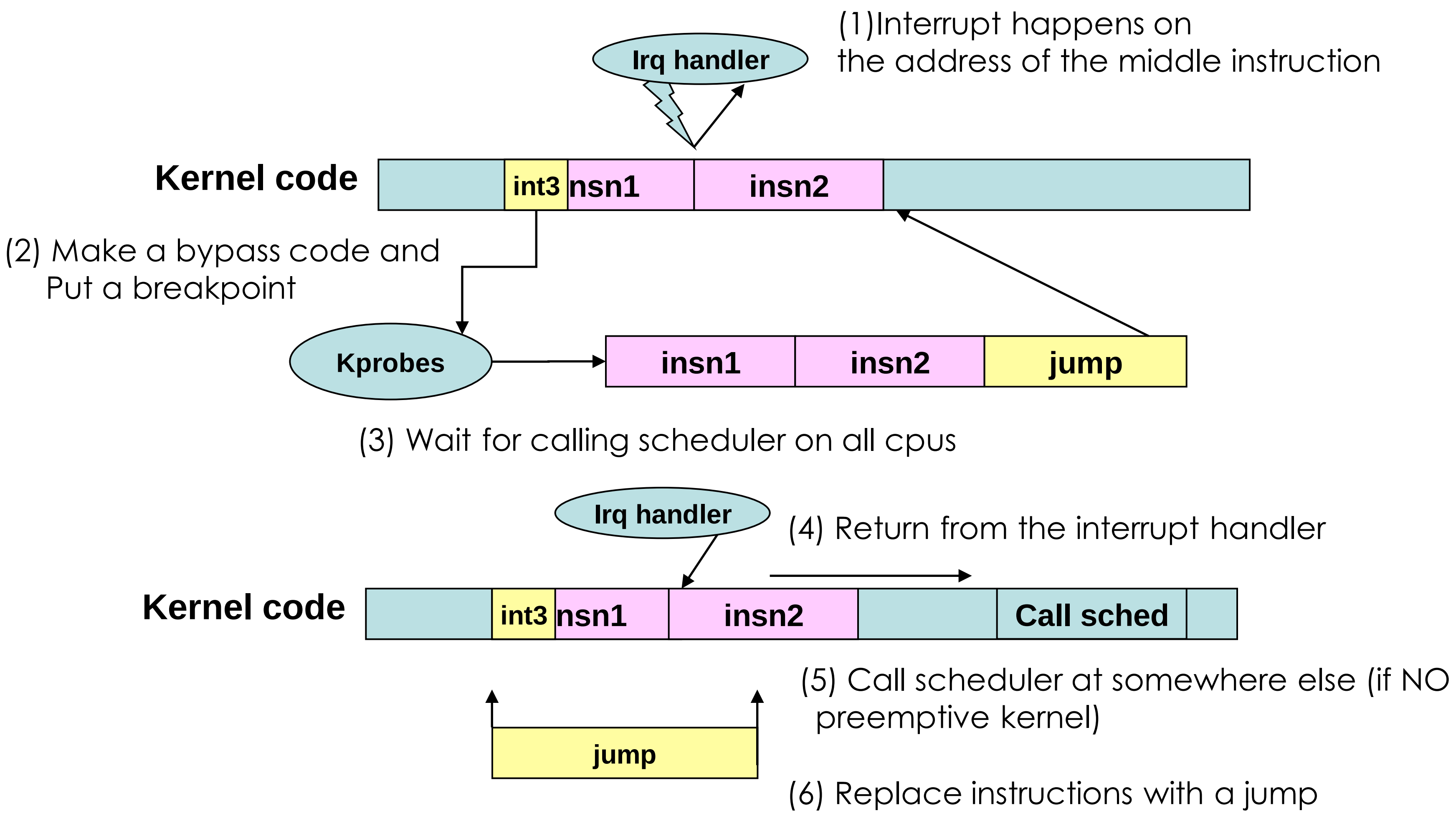


- Interrupts can happen on other processors

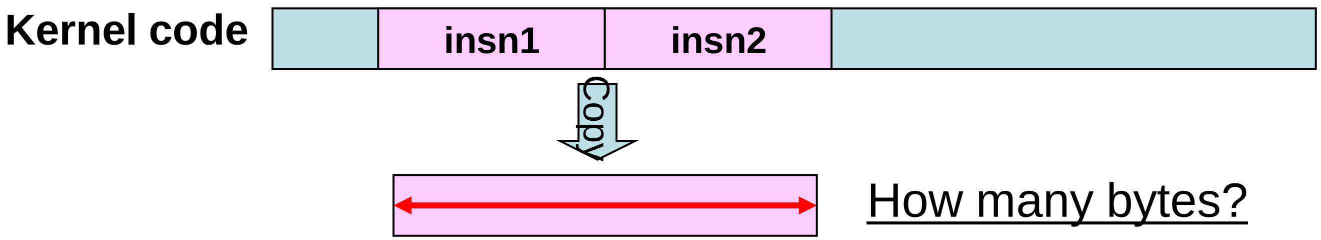


Make sure no process is interrupted on the address where will be replaced by the jump

- Make a bypass and wait for scheduler



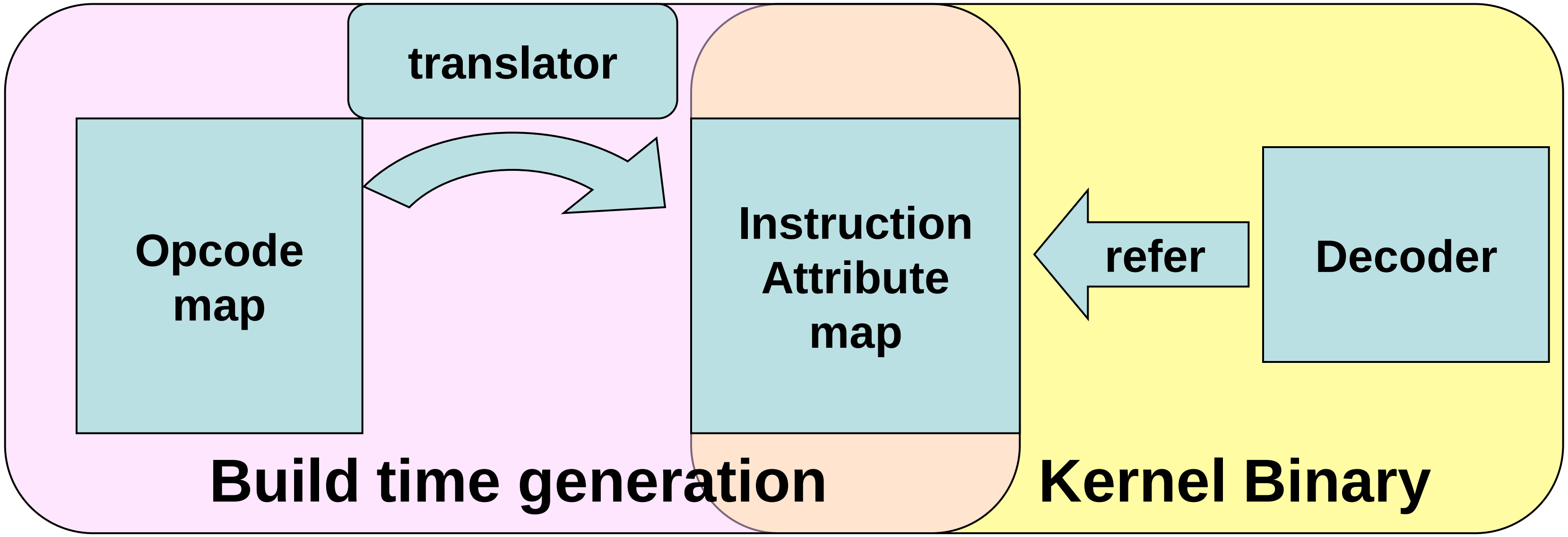
- x86 is a CISC processor
  - Instructions vary in length
  - How many bytes do we need to copy?



- Check non-relocatable instructions
  - Some IP-related instructions can’t execute directly on copy buffer (Call, relative-jump, etc)
  - How can we find those instructions if it is in the middle?

We need something to decode instructions!

- Introduce in-kernel x86 instruction decoder
  - Simple instruction decoder
    - Just ~350 logical lines including AVX(Intel® Advanced Vector Extensions) decoding support
  - Generic & easy maintain
    - Based on x86 opcode map (in Intel's software developers manual)
    - Generate instruction attribute map from the opcode map when compiling kernel

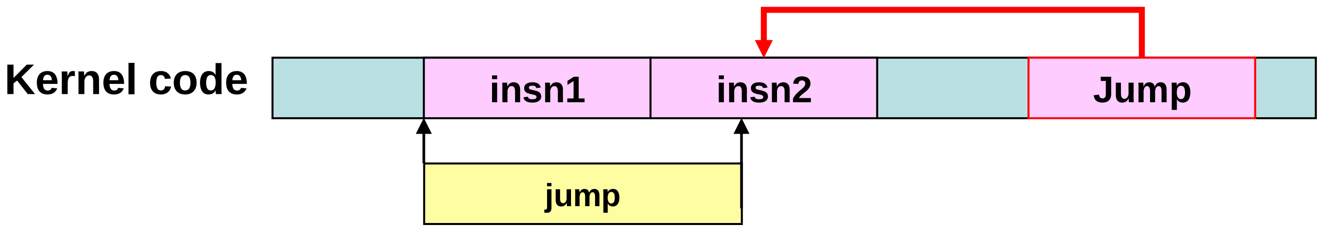


- x86 instruction decoder has two parts
  - insn
    - Data structure represents an instruction
    - insn_init() and insn_get_XXX()
    - users usually use this part
  - inat
    - Instruction attribute maps for decoding
      - Each opcode has attributes

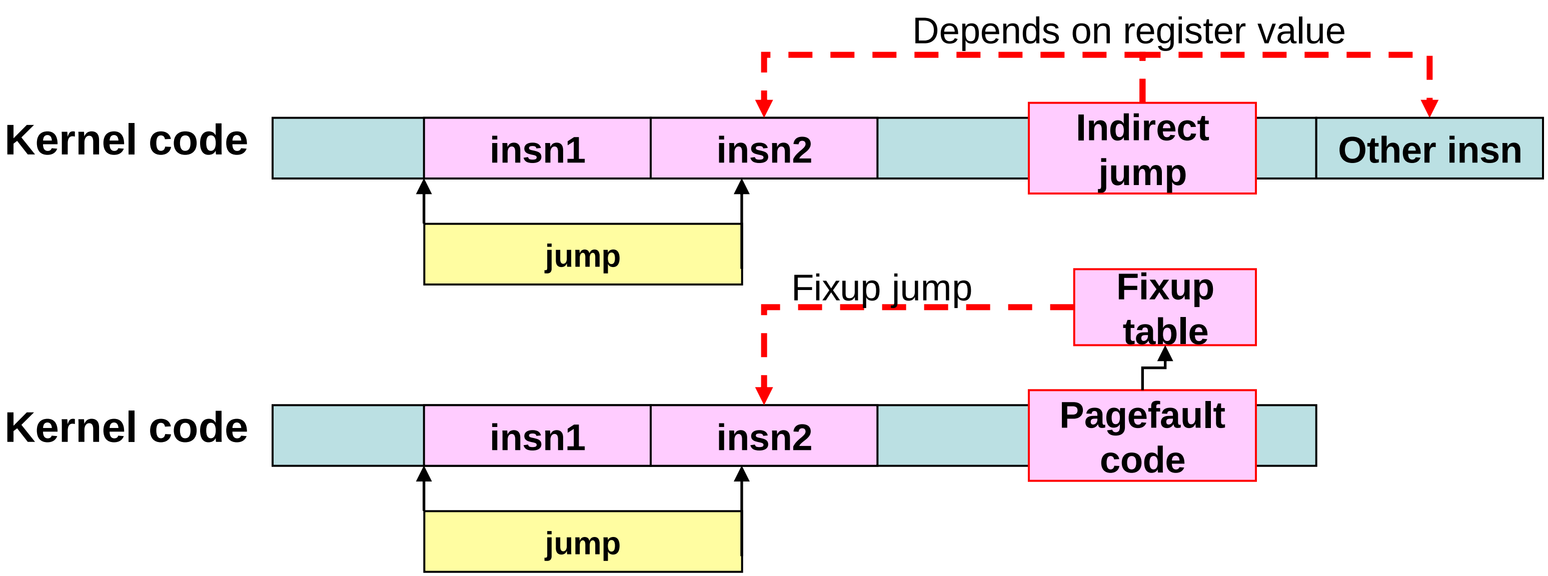
```
struct insn;
int x86_64 = 0; /* depends on the arch */
insn_init(&insn, target_address, x86_64);
insn_get_length(&insn); /* insn_get_length() decodes the entire instruction */
printk("opcode size:%d, instruction length:%d¥n", insn.opcode.size ,insn.length);
```

Jump-in Issues

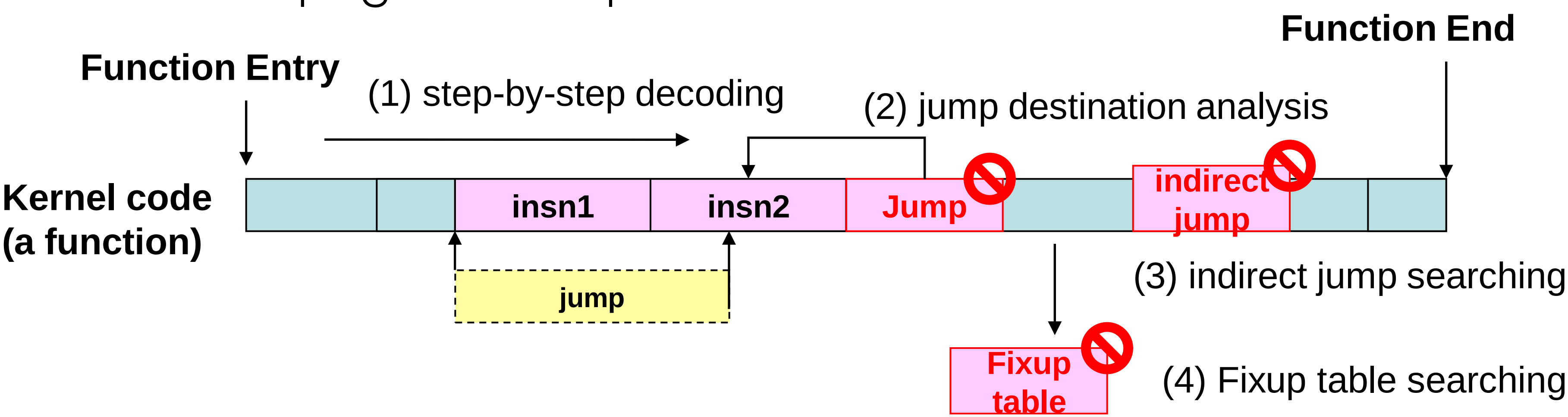
- There are some jump-in issues
  - Kernel jumps into the middle of target instructions



  - Kernel MAY jump into the middle of target instructions



- Check a target function to find those jumps
  - Decode an **entire function**
  - Check pagefault fixup table

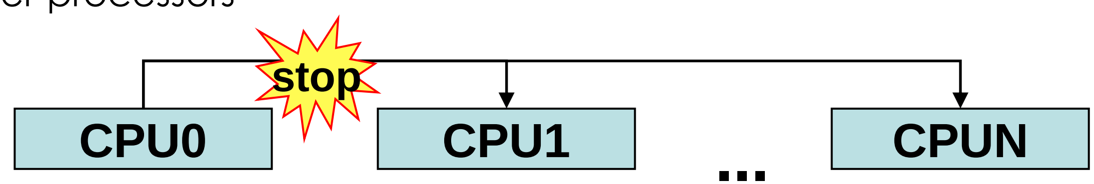


- Reject optimization and just use normal kprobe
  - If a jump destination is the middle of target
  - If the function including indirect jump
  - If the function including an address in fixup-table

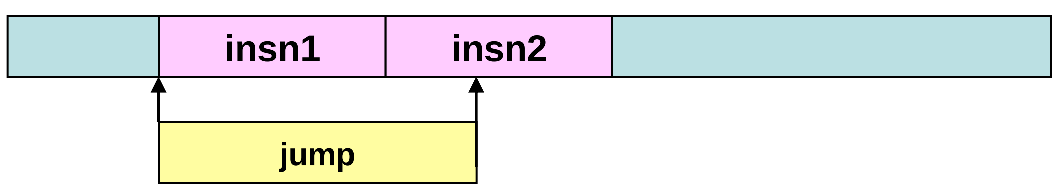
Cross Modifying Code (Self Modifying on MP)

- Cross modifying code needs a special operation
  - Documented method
    - Intel® 64 and IA-32 Architectures Software Developer's Manual Vol. 3 8.1.3
  - Stop-machine and modify code
    - This can't use in NMI handler, but kprobes itself doesn't allow to probe NMI handler too.
  - Stop-machine is slow, so modifying should be batched.

(1) Stop other processors



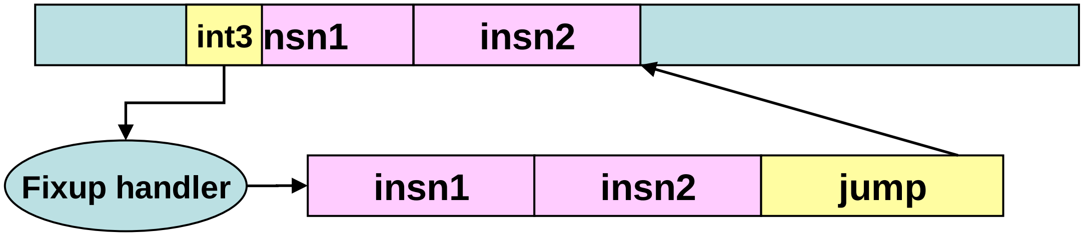
(2) Write a jump



(3) Serializing and continue to run on other processors

- Int3 bypass method
  - Make a bypass by using int3 while XMC
  - No stop machine required
  - Still be under discussion

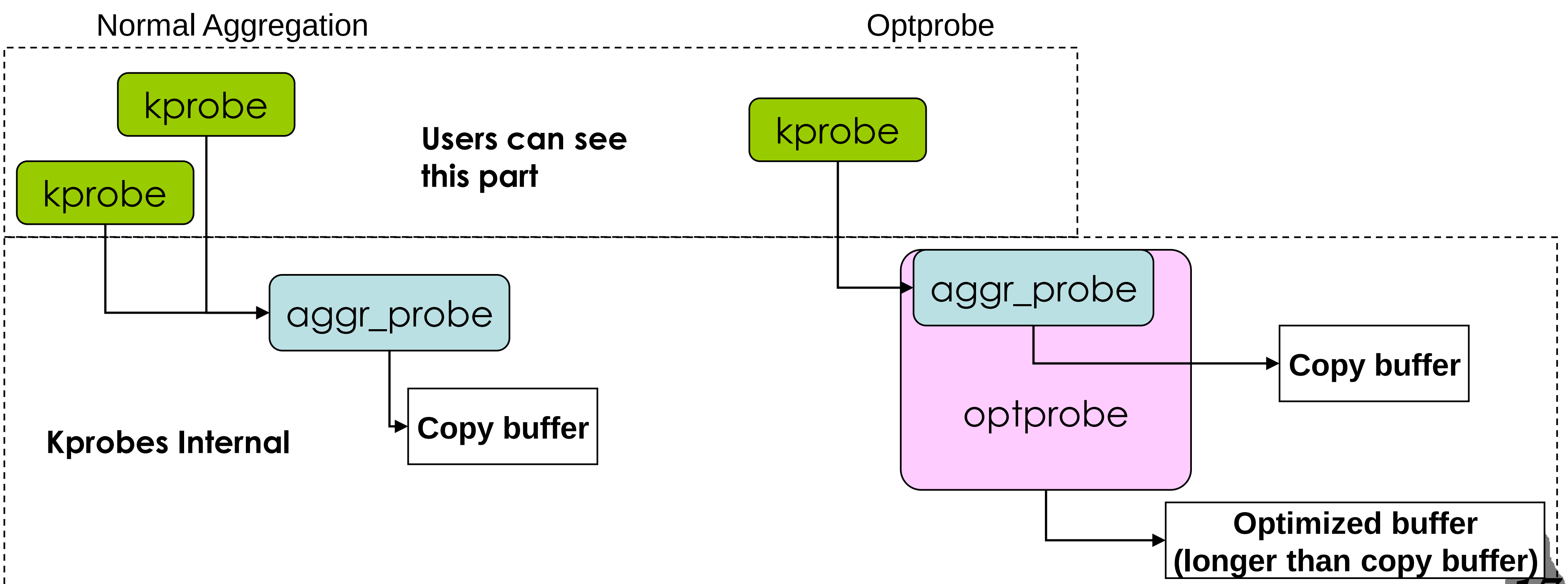
(1) Make a bypass



(2) Write a jump destination
and sync all processors(send IPI)

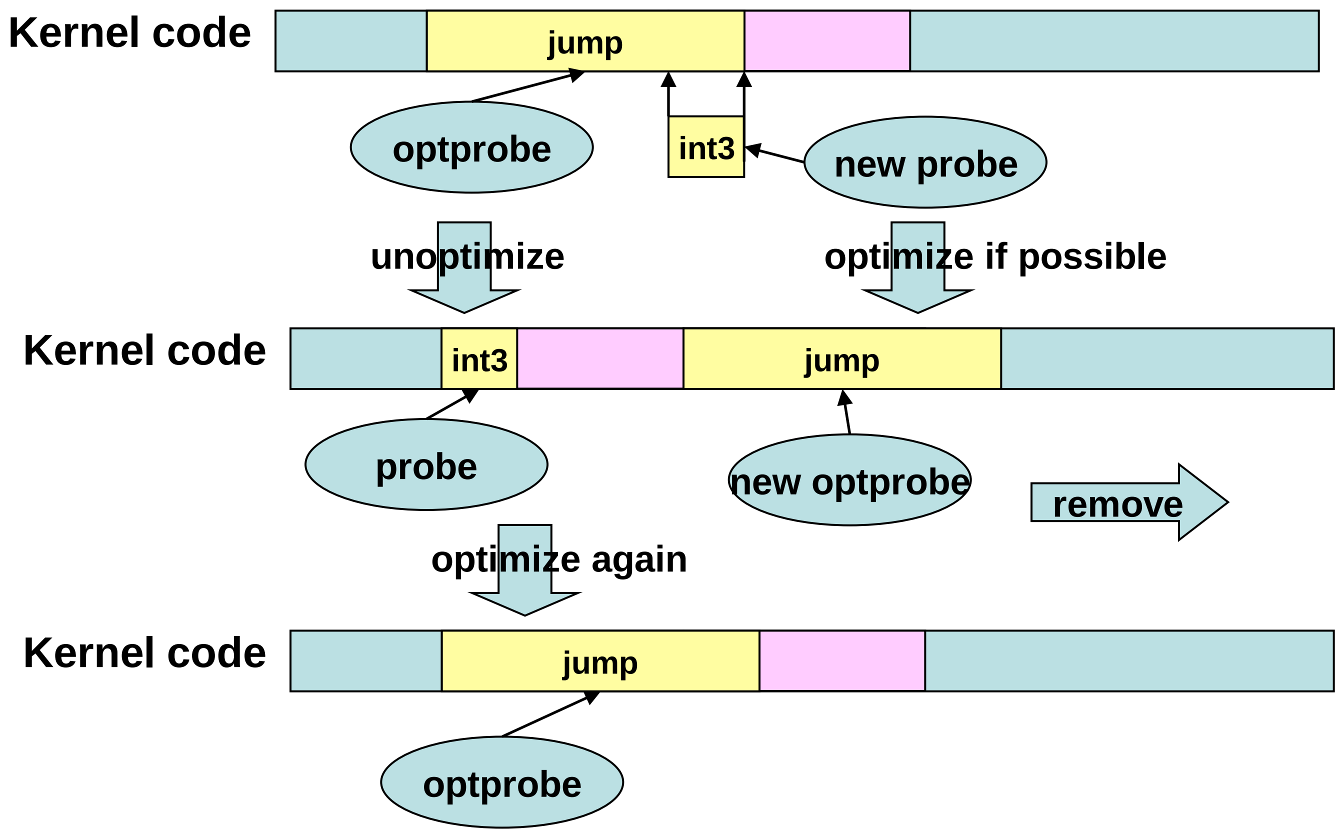
(3) Write a jump opcode
and sync all processors(send IPI)

- Optimization without changing APIs
  - Optimized kprobe is hidden in aggr_probe
    - Aggr_probe is usually used for aggregating multiple probes on the same address
  - User don't know their probe is optimized or not.



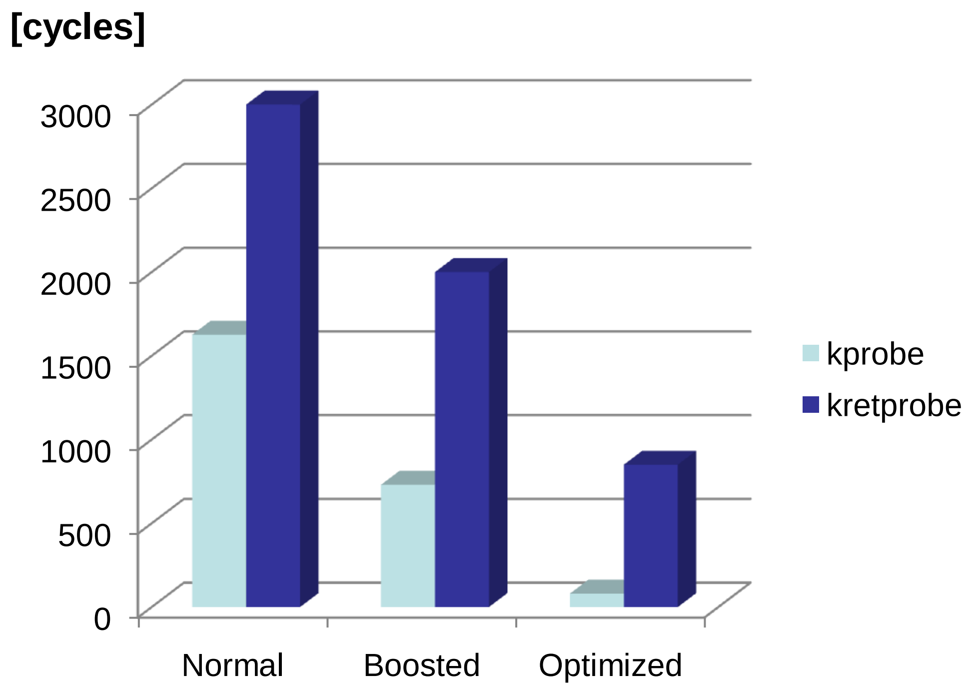
- Optimization is transparently done (No explicit APIs)
  - Jump code modifying is done in background
  - Some probe state changes requires unoptimizing
    - Unoptimizing is also done in background
  - Only one knob for debugging
    - /proc/sys/debug/kprobes-optimization

- Optimizing/Unoptimizing probes automatically
  - Kprobes tries to optimize probes every state change if possible
    - A probe removed from the instruction next to another probe
    - An aggregated probe which has a post_handler is removed



- Some other functions can modify text too
  - Ftrace, alternatives, jump labels
  - Only kprobes is modifying code anywhere
  - Introduce text_reserve interface
    - Checking specified area can be modified by other functions
    - If so, kprobes gives up putting a probe on it.

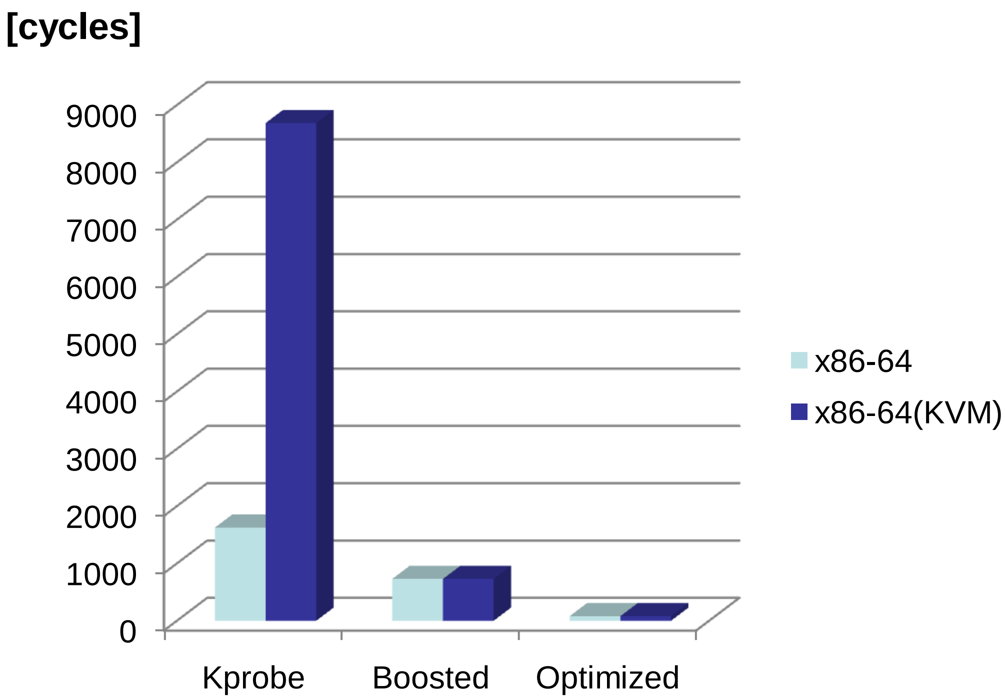
- Performance results (unit is cycles)



Intel® Core™ i7 920 (2.67Ghz)

•Optimization can reduce the overhead to ~100cycles
•Kretprobe is also optimized

- Performance results on KVM
  - On KVM, kprobes is much heavier, because trap is emulated

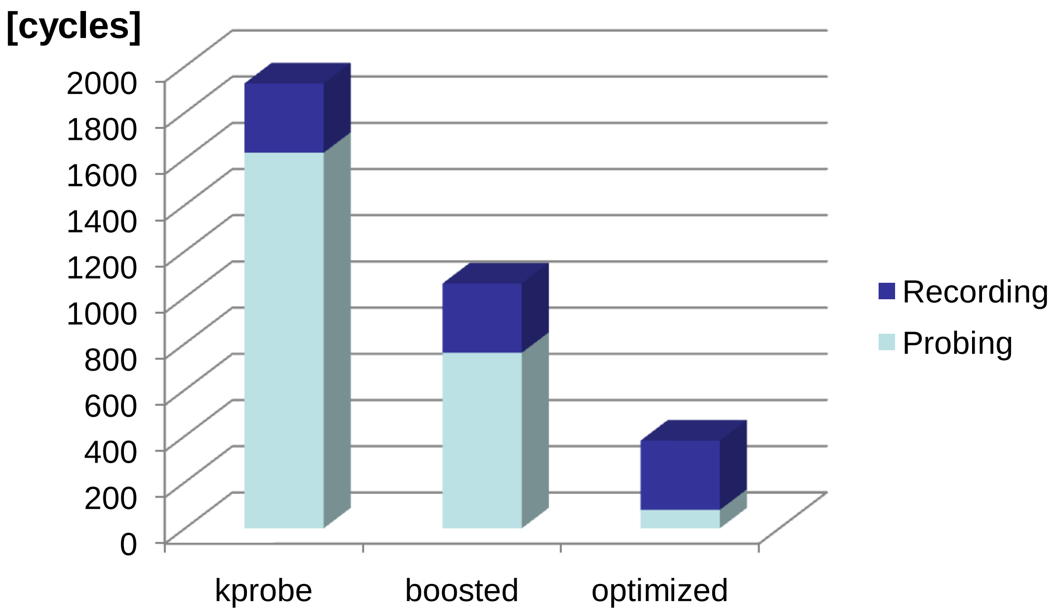


Intel® Core™ i7 920 (2.67Ghz)

Optimized and boosted probes can run inside guest.

What is the benefit of less overhead?

- Lower overhead allows us to trace more events
  - Tracing overhead breakdown
    - Probing overhead (depends on optimization)
    - Recording overhead (~300 cycles)



  - Total ~400cycles overhead/event allows us to trace **100K** events/sec with just **1~2%** overhead on 3GHz CPU

- Kprobes
  - Dynamic/Flexible in-kernel probing function
  - But heavy, especially with Virtualization
- Kprobe jump optimization
  - Drastically reduce overhead of kprobes
  - Some limitations
  - Transparent optimization
    - User need nothing to change
  - Good performance with Virtualization

- Long history of kprobes jump optimization

- 2005 May: Got an idea for jump optimization
- 2005 Jul: First Prototype Release
- 2005 Aug: 1st Upstream Try
- 2006 Oct: 2nd Upstream Try
- 2007 Jul: 1st Presentation of “djprobe” in OLS
- 2008 – silent but things going forward…
- 2009 Jun: x86 instruction decoder Release
- 2009 Jun: Revised “Optprobe” Release
- 2010 Feb: Optprobe is merged!

- Minimizing instrumentation impacts (kprobes jump optimization)
  - http://lwn.net/Articles/365833/
- Kernel documents
  - Documents/kprobes.txt

Thank you!

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