More on Multi-threading

- ➔ 5 steps of `thread_create`
- More on these 5 steps
- 4 steps of `thread_yield`
- Semaphores for testing
- Inter-process communication (IPC)

One possible output

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

void test_code(void *arg) {
    for (int i = 0; i < 3; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
    thread_exit();
}
```

```
thread1 here: 0
thread2 here: 0
thread1 here: 1
main thread here: 0
thread2 here: 1
thread1 here: 2
main thread here: 1
thread2 here: 2
thread1 done
main thread here: 2
thread2 done
main thread done
```

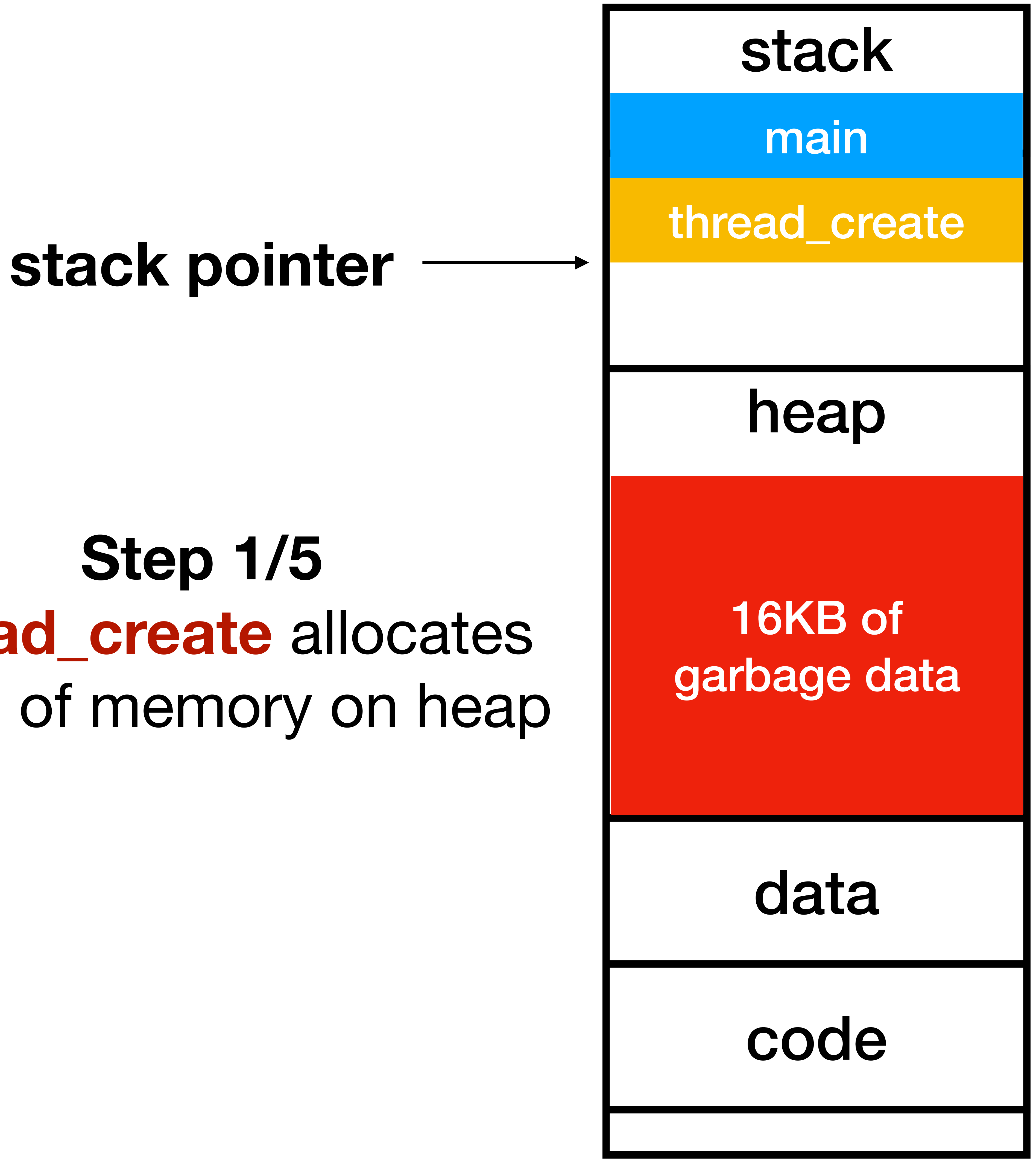
Question: Are other outputs possible?

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

void test_code(void *arg) {
    for (int i = 0; i < 3; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
    thread_exit();
}
```

```
thread1 here: 0
thread2 here: 0
thread1 here: 1
main thread here: 0
thread2 here: 1
thread1 here: 2
main thread here: 1
thread2 here: 2
thread1 done
main thread here: 2
thread2 done
main thread done
```

Create a thread, step 1/5

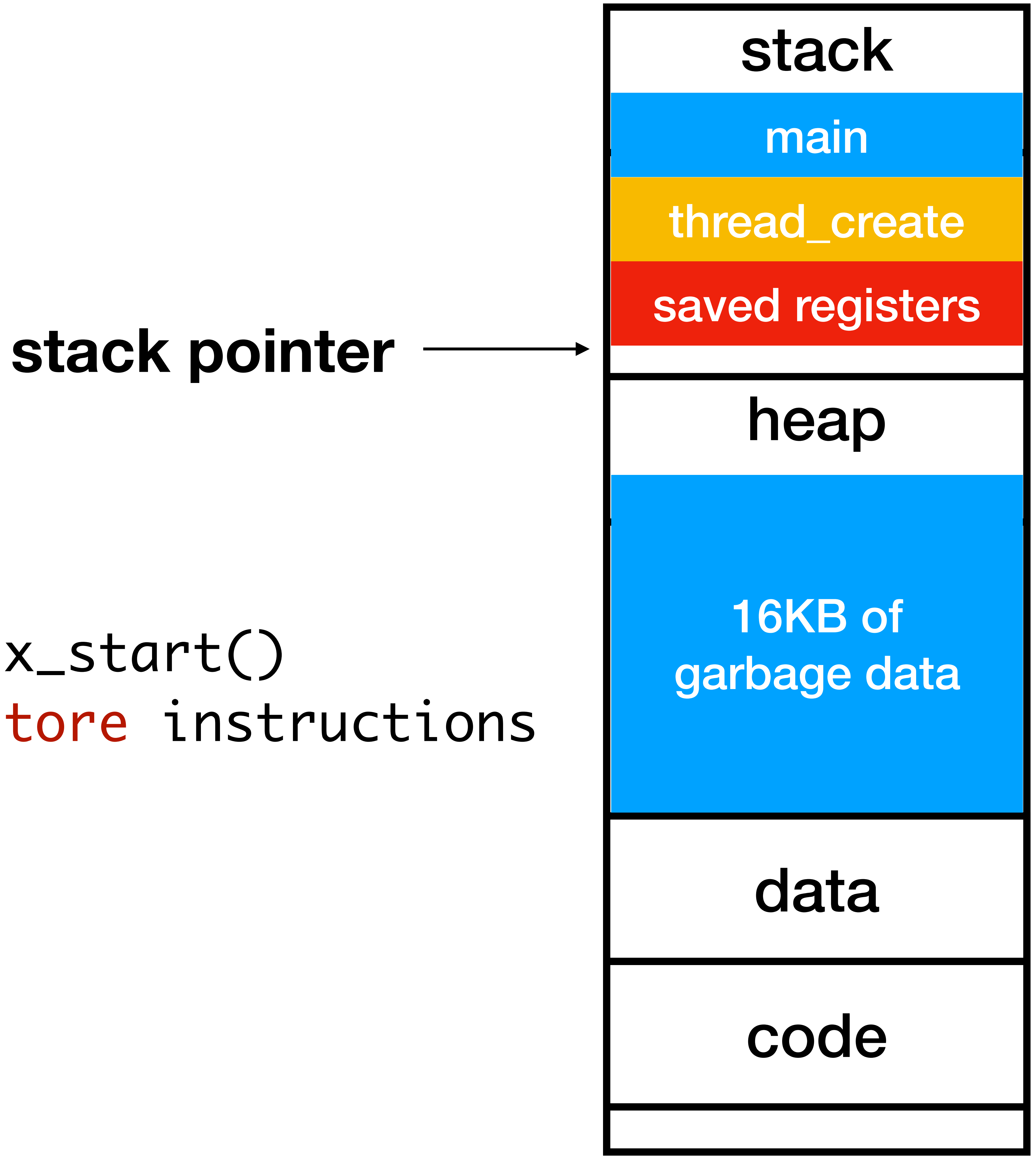
```
int main() {
    thread_init();
  ➡ thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

void test_code(void *arg) {
    for (int i = 0; i < 3; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
    thread_exit();
}
```



Step 1/5
thread_create allocates 16KB of memory on heap

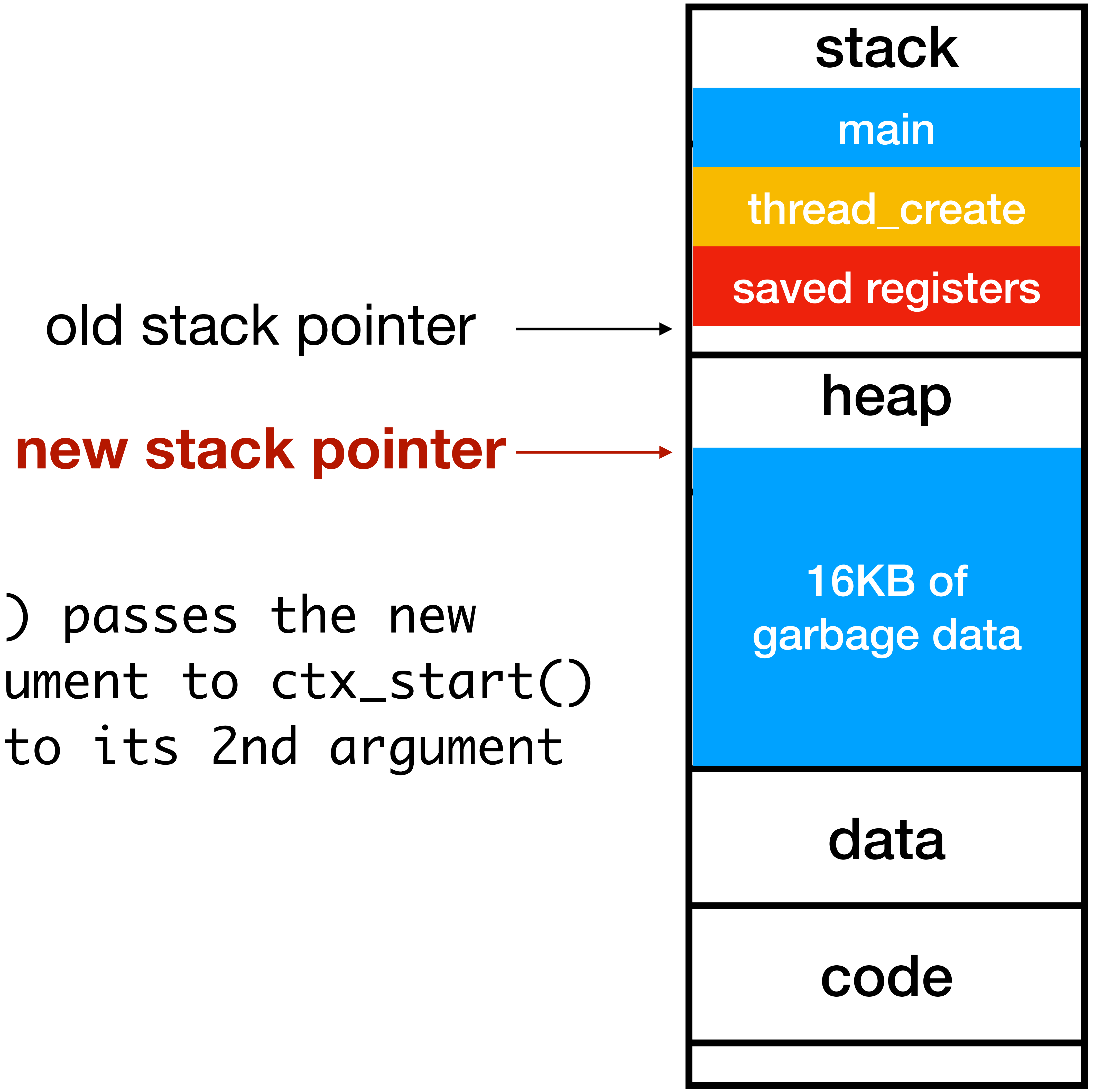
Create a thread, step 2/5

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

ctx_start:  // step 2/5: thread_create() calls ctx_start()
    …       // save registers on the stack with store instructions
    mv sp, a1
    call ctx_entry
```



Create a thread, step 3/5

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

ctx_start:          // step 3/5: thread_create() passes the new
    …               // stack pointer as 2nd argument to ctx_start()
    mv sp, a1       // ctx_start() modifies sp to its 2nd argument
    call ctx_entry
```



old stack pointer

new stack pointer

stack

main

thread_create

saved registers

heap

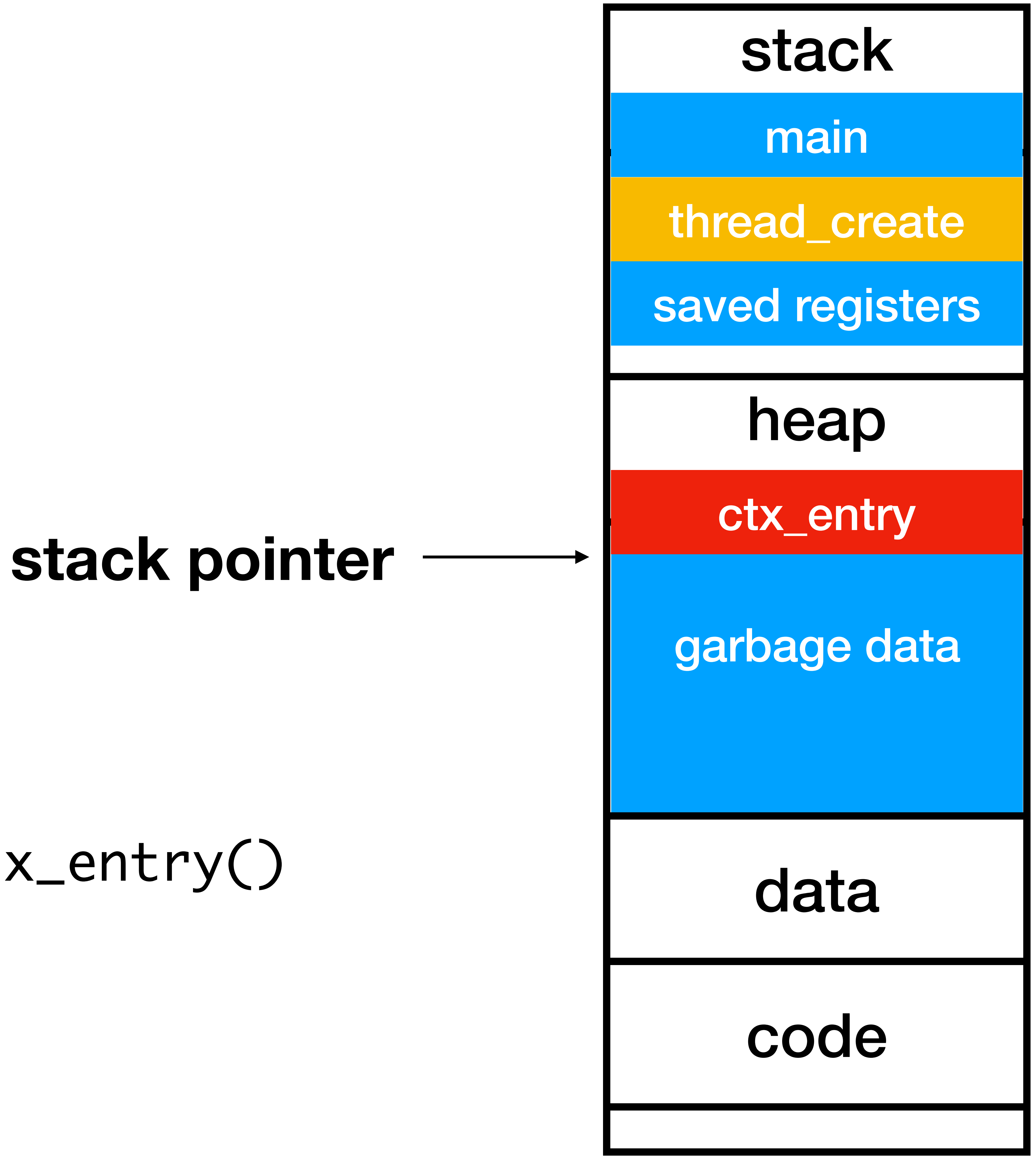
16KB of
garbage data

data

code

Create a thread, step 4/5

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

ctx_start:
    …
    mv sp, a1
    call ctx_entry  // step 4/5: call function ctx_entry()
```



stack

main

thread_create

saved registers

heap

ctx_entry

garbage data

data

code

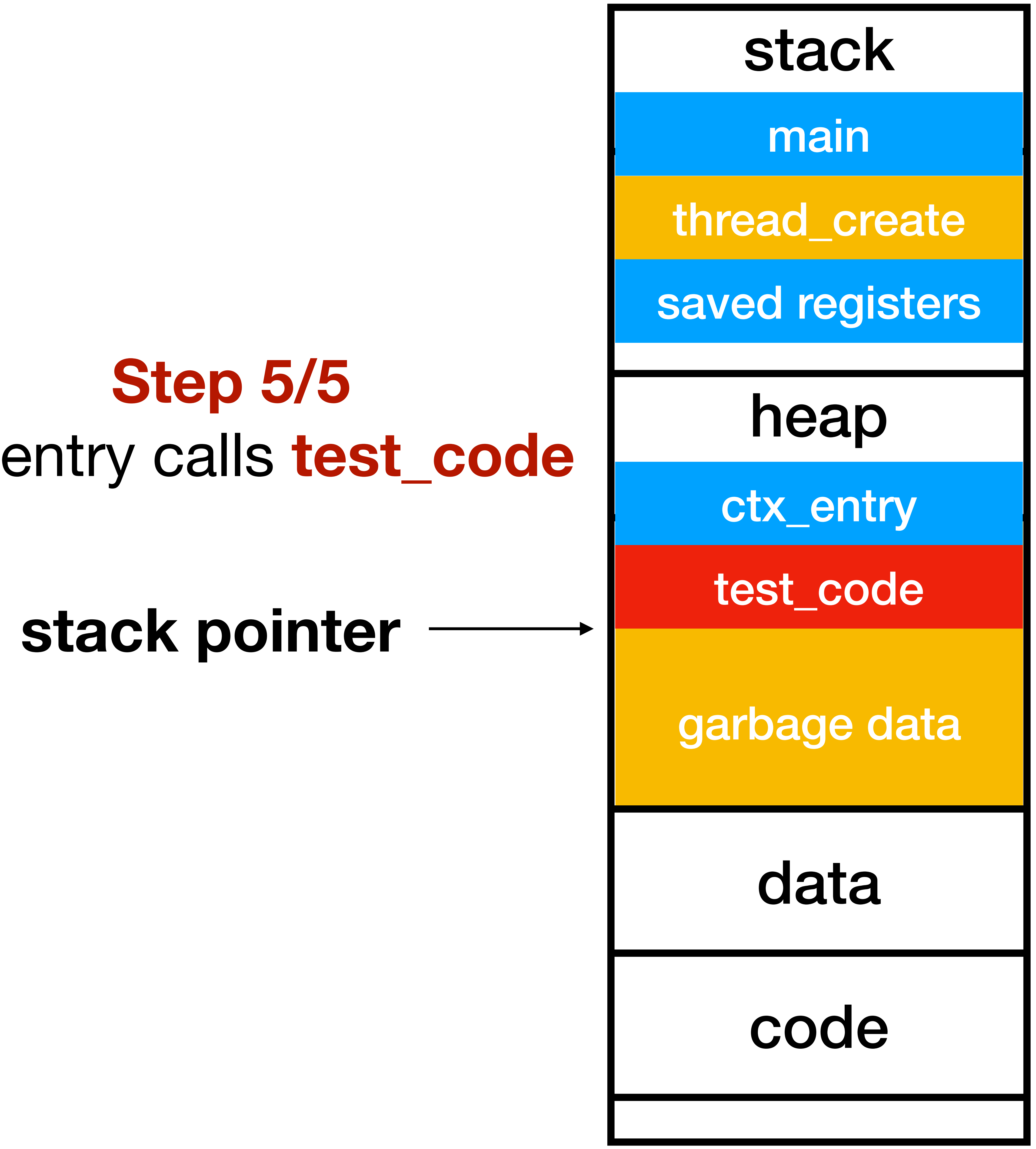
stack pointer

Create a thread, step 5/5

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

void test_code(void *arg) {
    for (int i = 0; i < 3; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
    thread_exit();
}
```

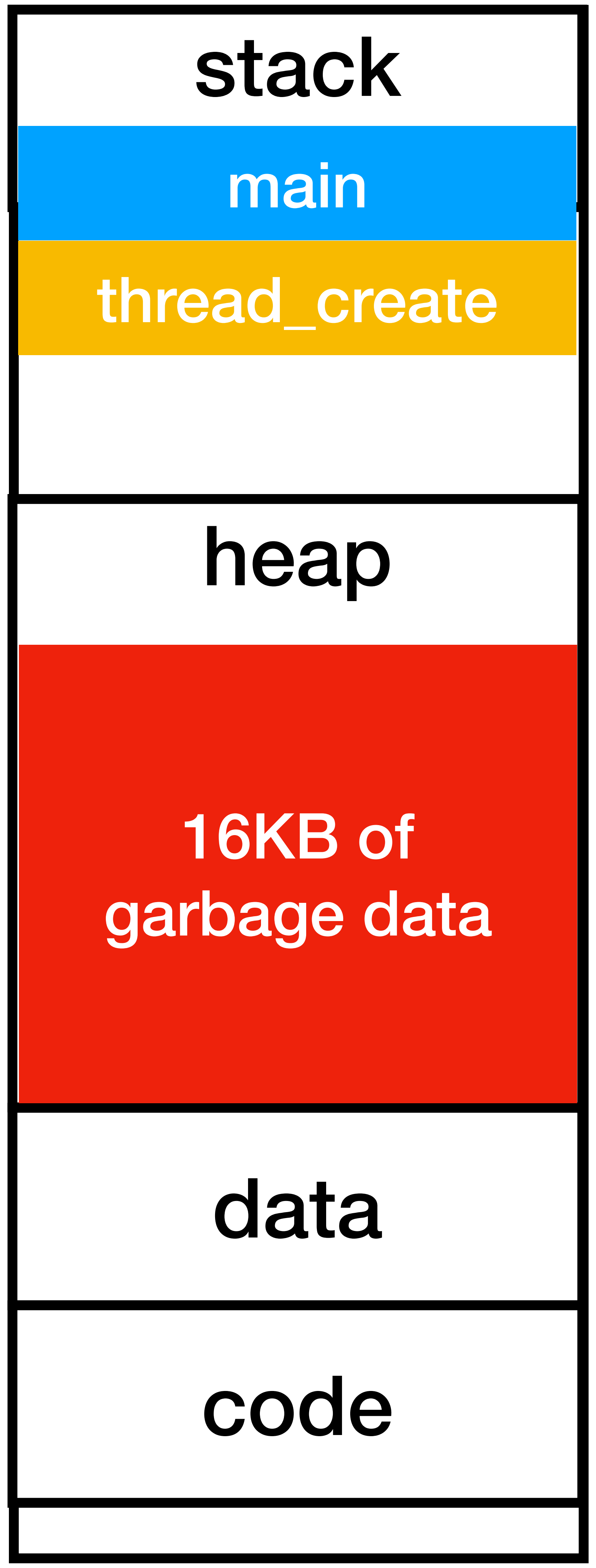
Step 5/5

ctx_entry calls **test_code**



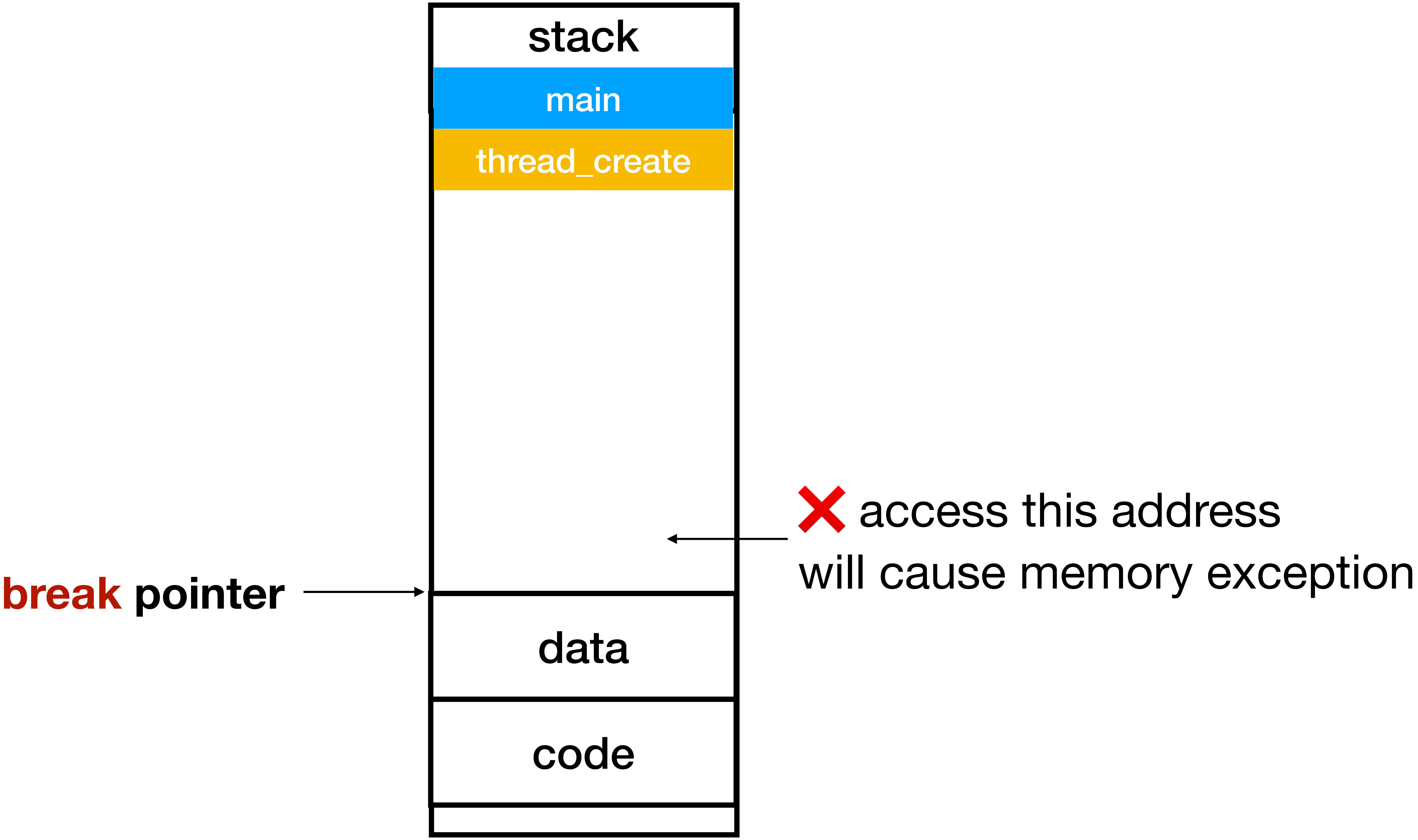
- 5 steps of `thread_create`
- ➡ More on these 5 steps
- 4 steps of `thread_yield`
- Semaphores for testing
- Inter-process communication (IPC)

Question: Is `Malloc` a system call?



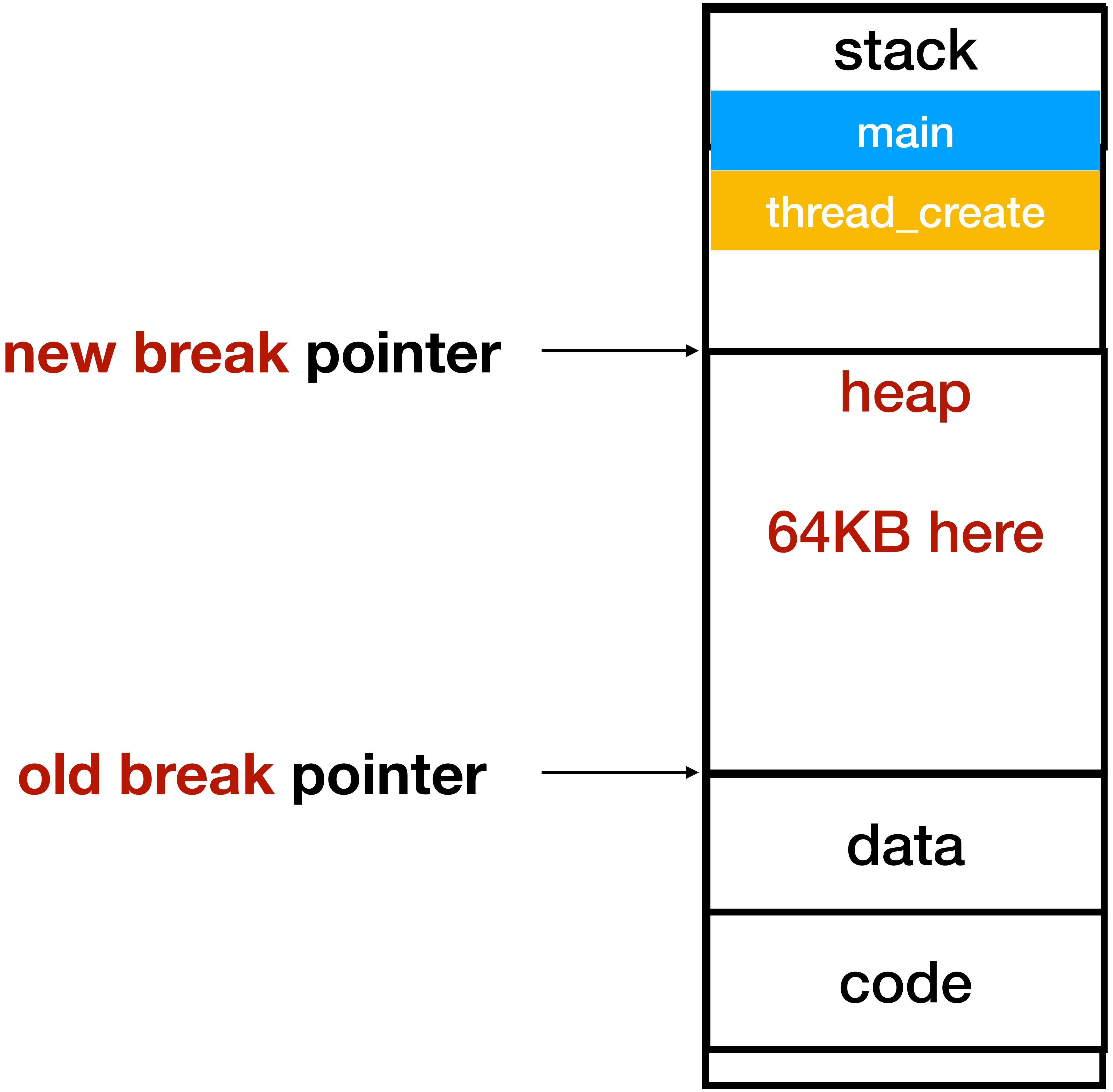
Step 1/5
thread_create allocates
16KB of memory on heap

Before any allocation: Heap is empty



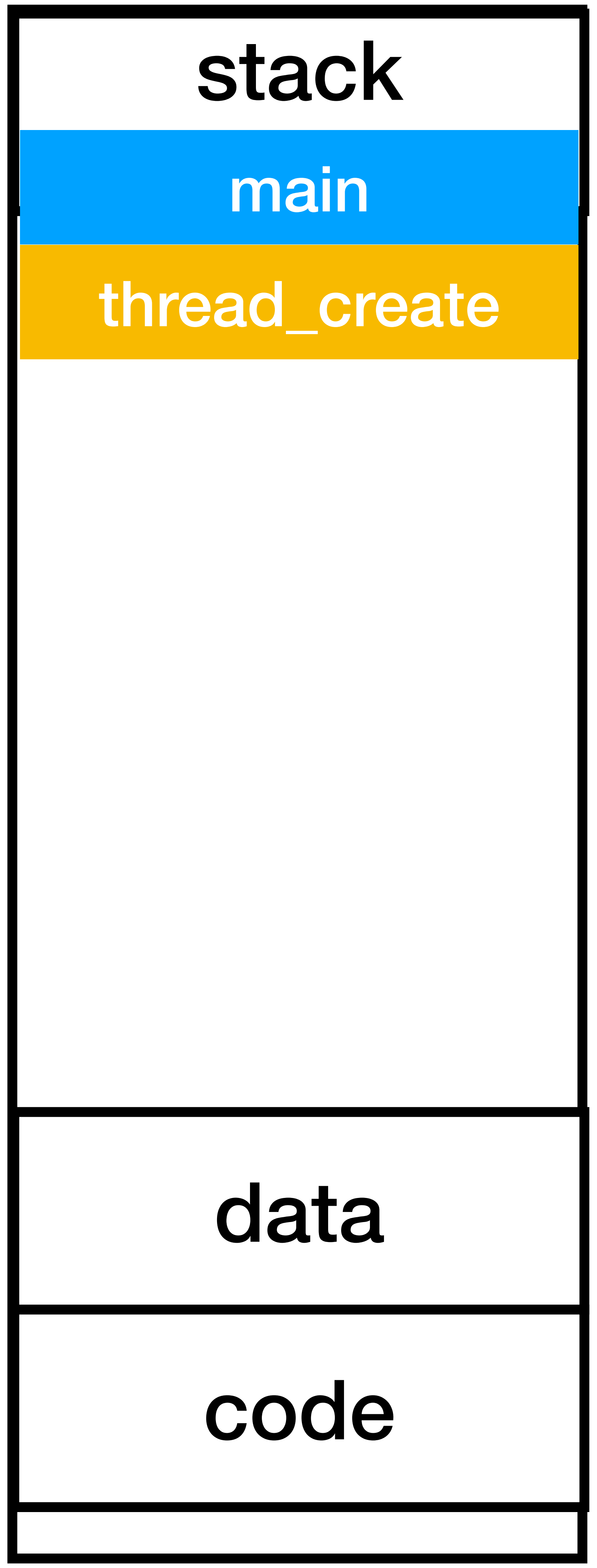
System call sbrk()

```
// by invoking this system call
void* old = sbrk(64 * 1024);
```



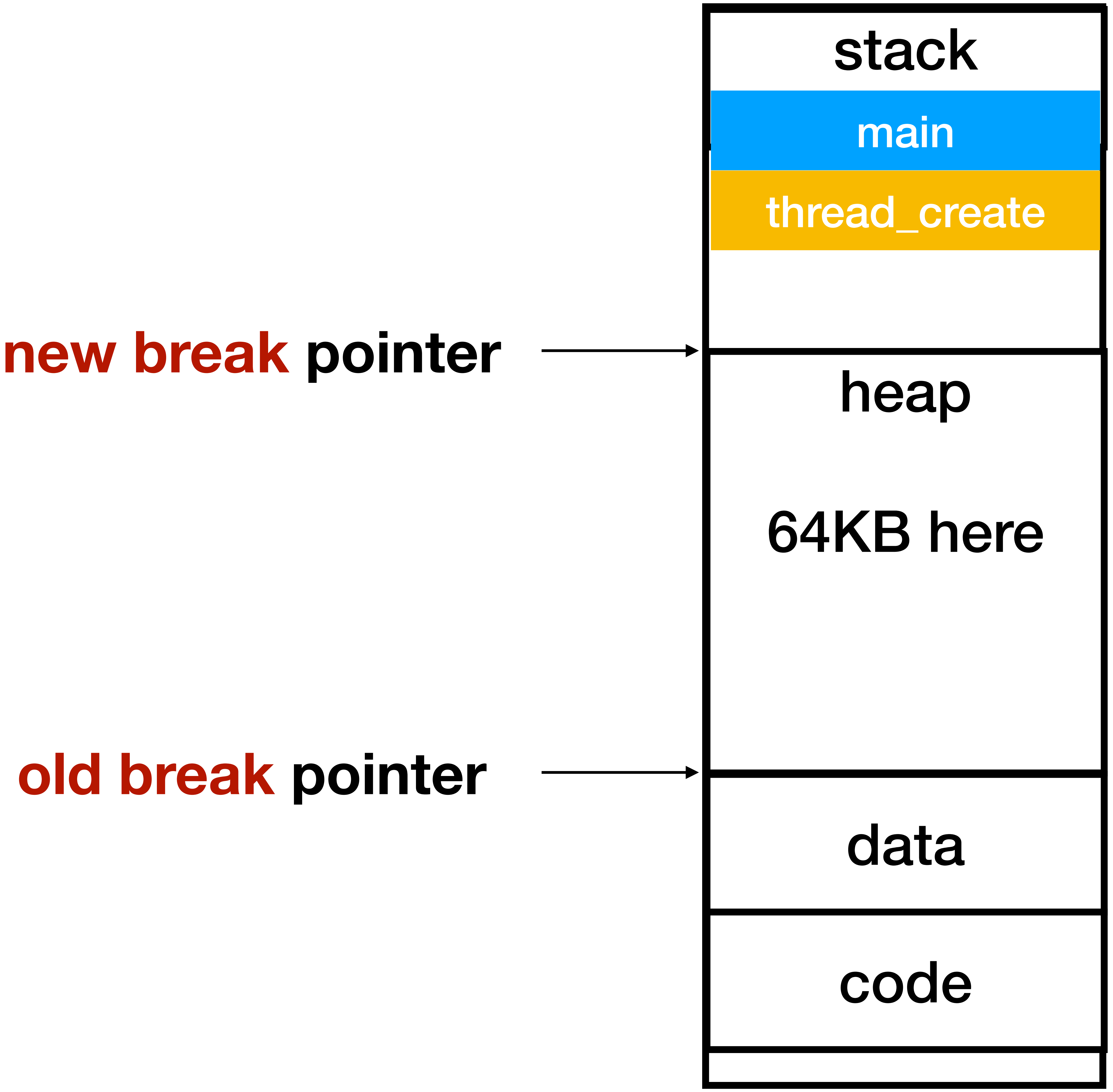
`malloc()` is a C library function

```
// This is compiled with a malloc()
// implementation in the C compiler.
malloc(16 * 1024);
```



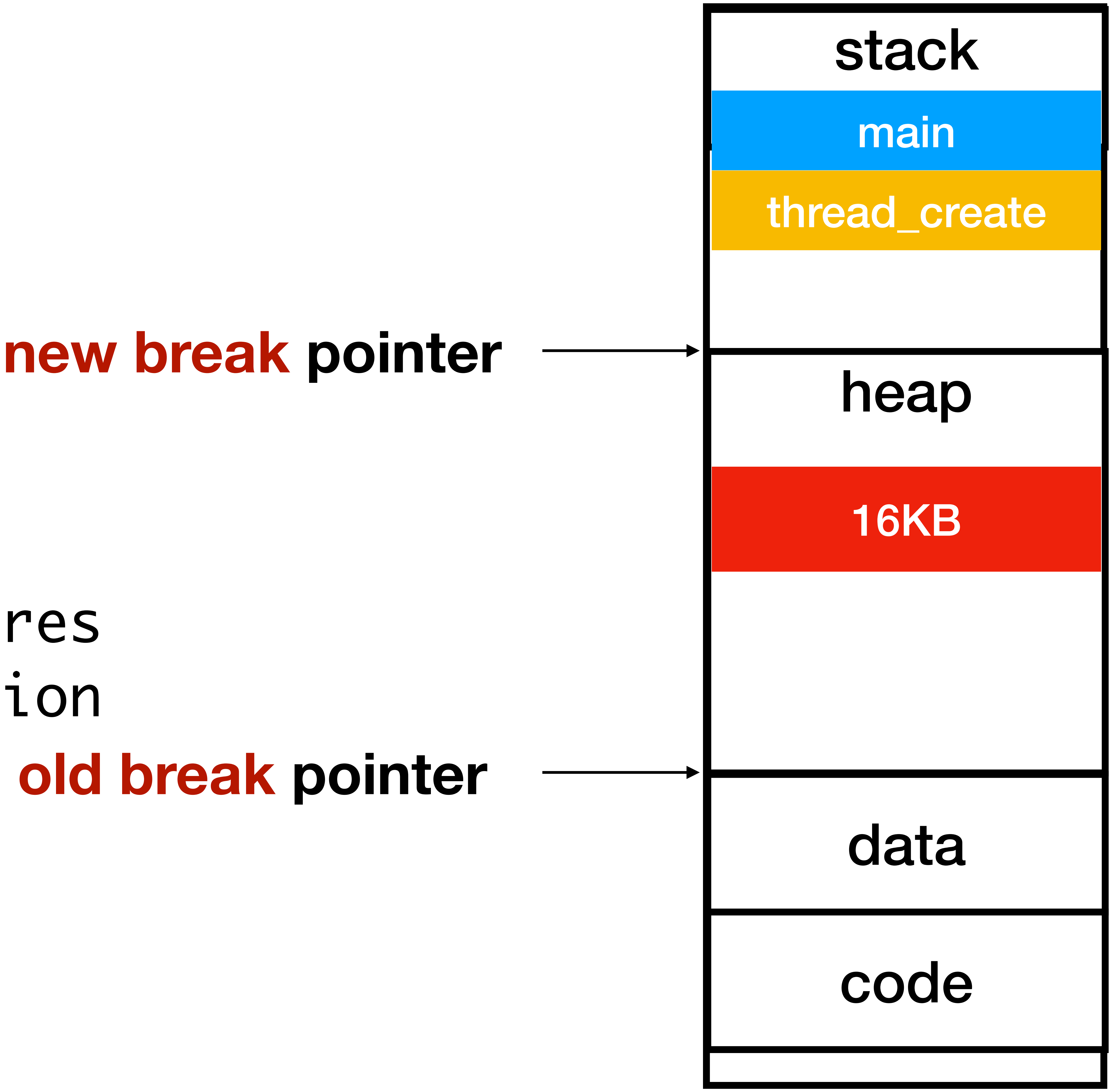
First `malloc()`, step 1/2

```
// when malloc() is first called
malloc(16 * 1024);

// malloc() first gets a larger
// region using sbrk, say 64KB
void* old = sbrk(64 * 1024);
```



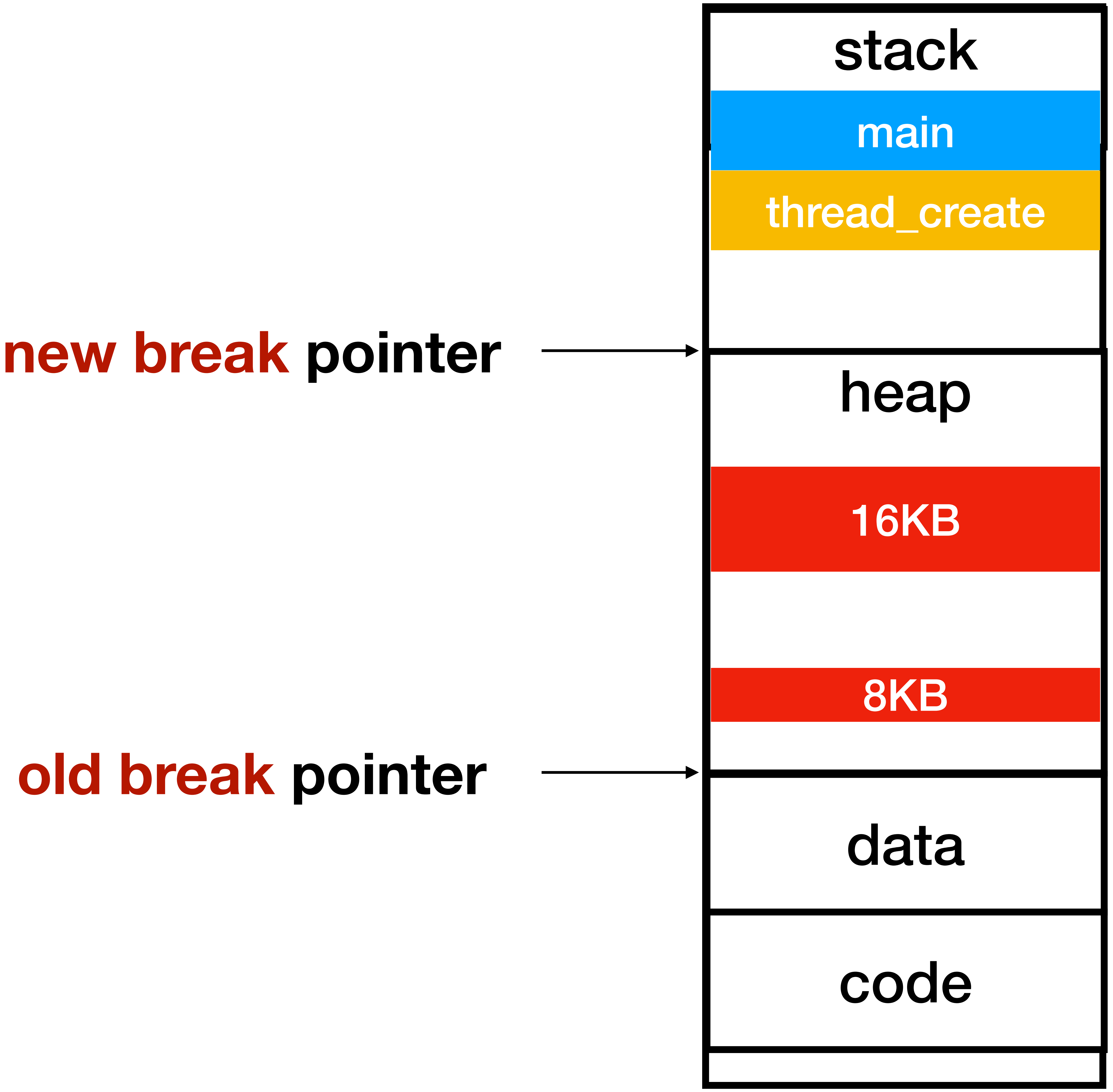
First `malloc()`, step 2/2

```
// when malloc() is first called
malloc(16 * 1024);

// malloc() first gets a larger
// region using sbrk, say 64KB
void* old = sbrk(64 * 1024);

// then malloc creates data structures
// and assigns 16KB to the application
```

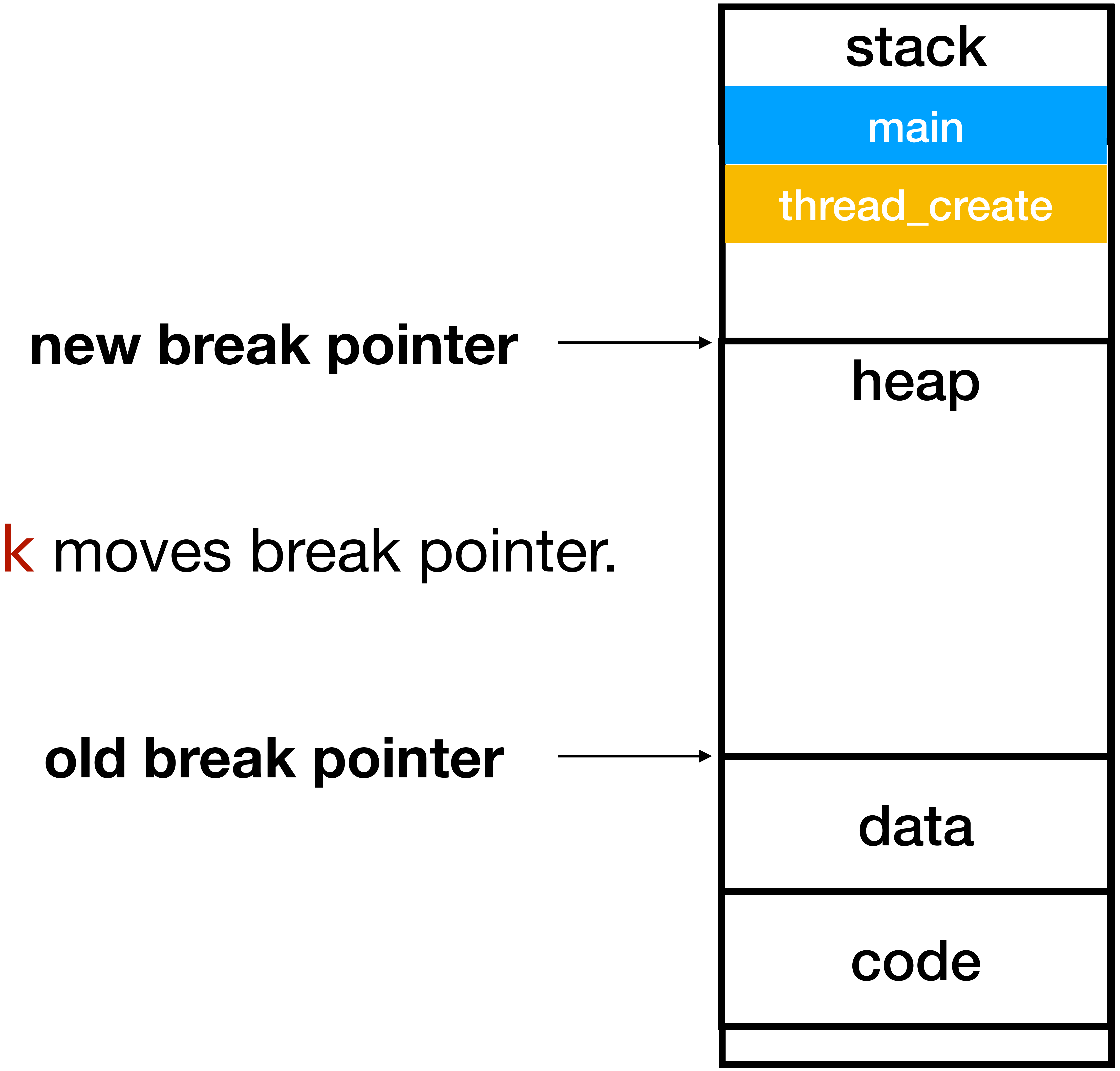


Second `malloc()`, step 1/1

```
// when malloc() is first called
malloc(16 * 1024);

// This time, malloc() may not
// not need to call sbrk again.
malloc(8 * 1024);
```



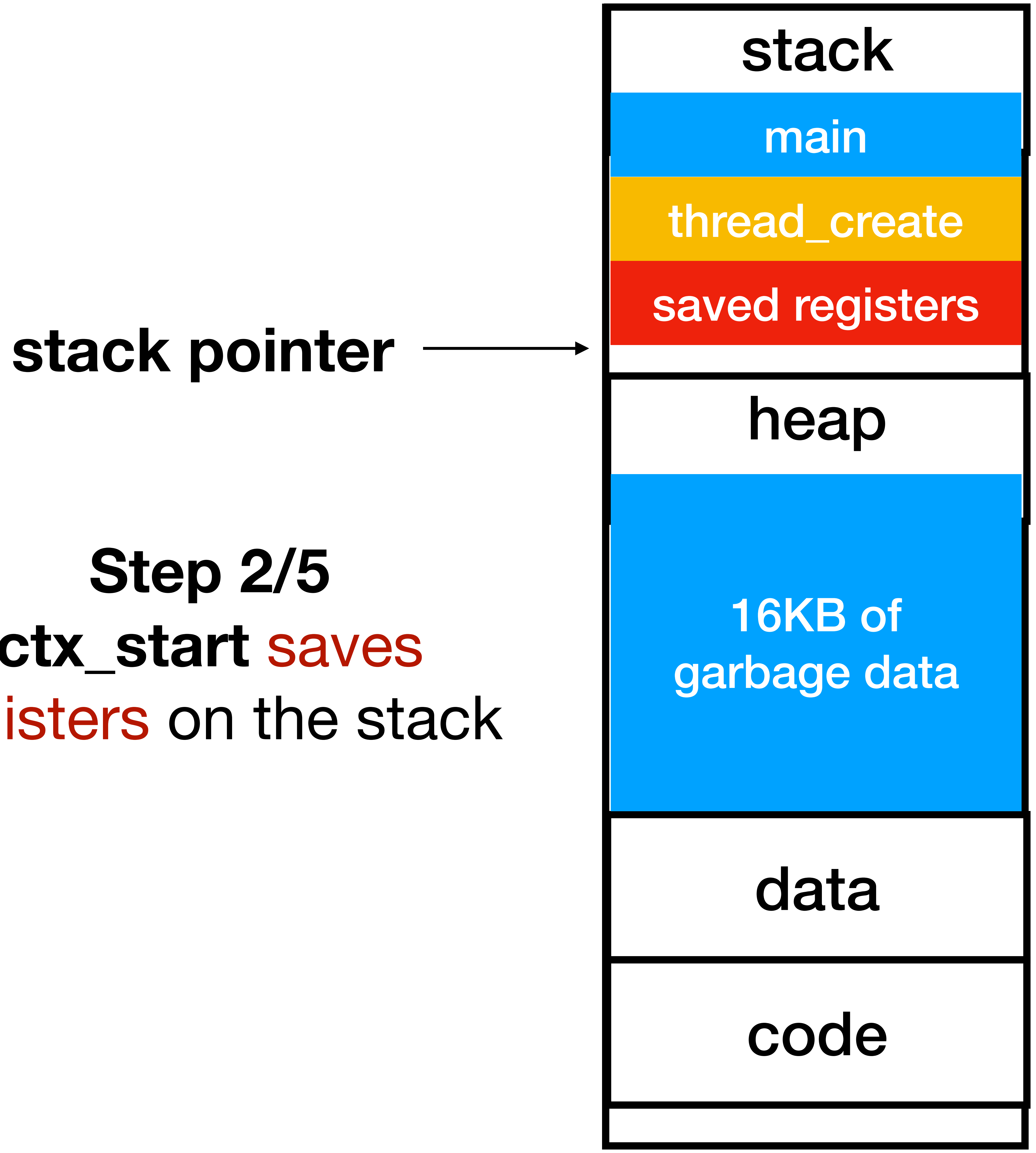
Question: Is `Malloc` a system call?



`sbrk` moves break pointer.

`malloc` maintains the data structures in the heap.

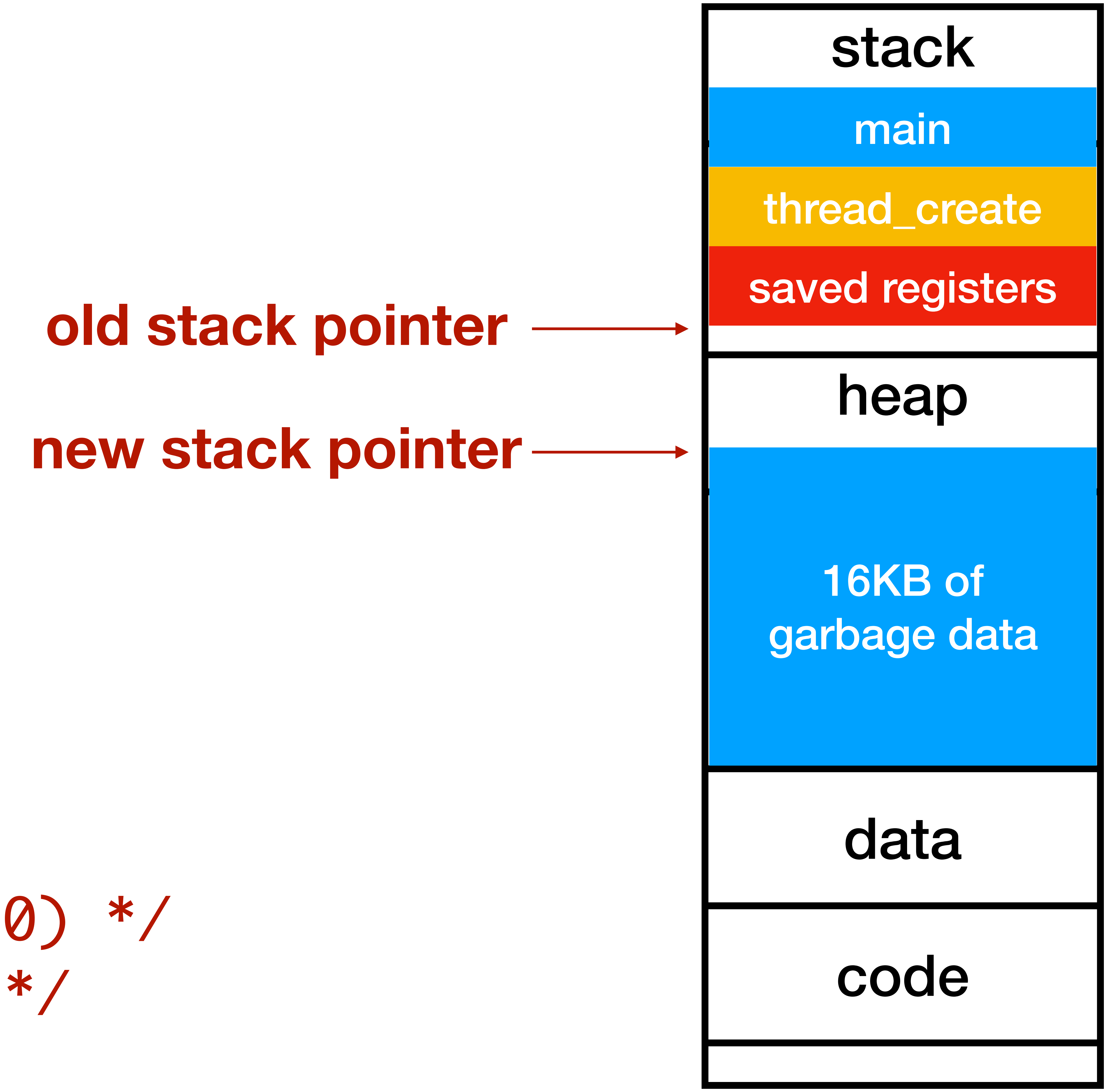
Question: is it necessary to save all registers?



Step 2/5
ctx_start saves registers on the stack

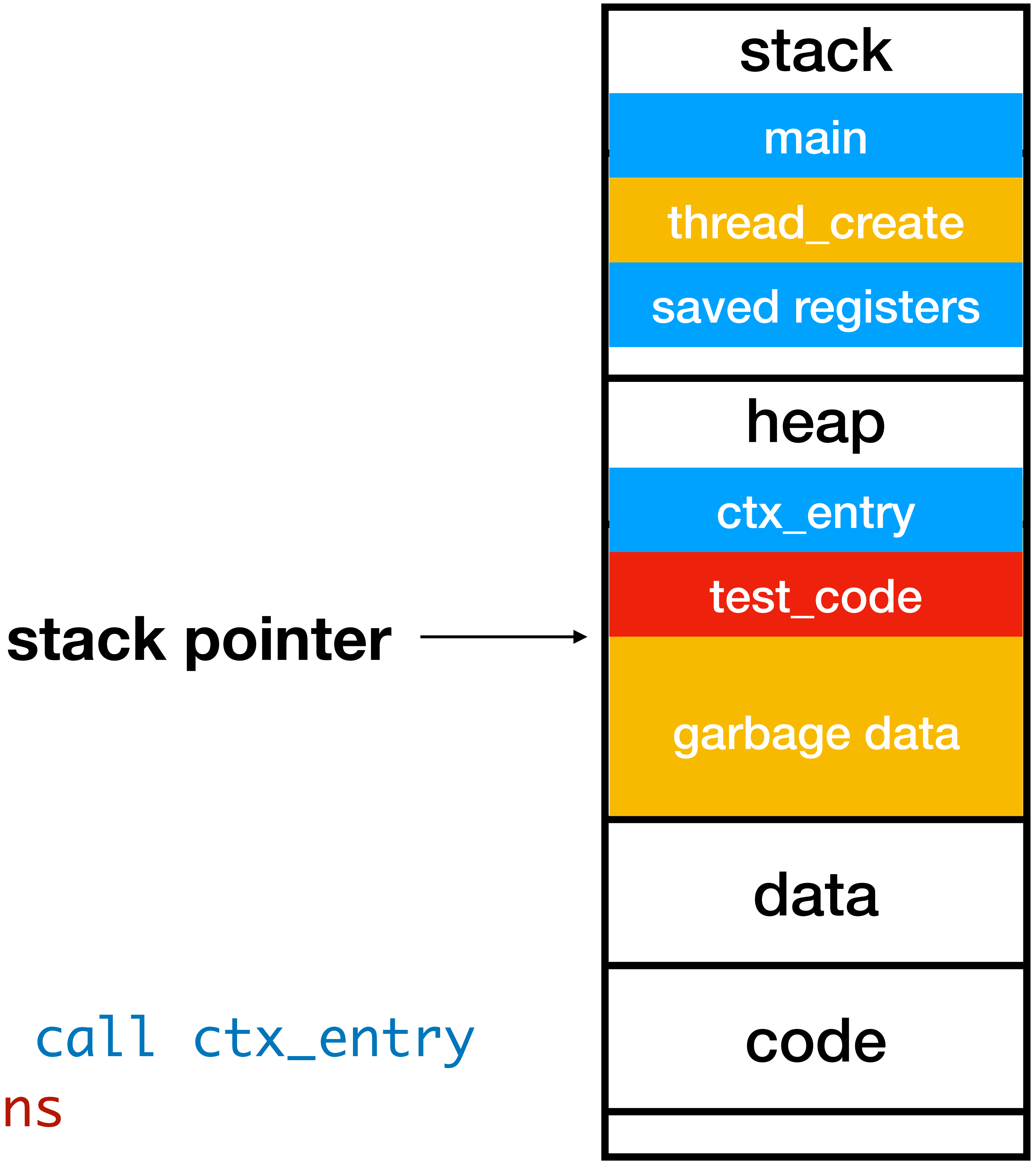
How to save the old stack pointer?

```
struct thread {
      void* sp;
      …
}

// say we have the pointers to
// the current and next threads
struct thread* current, next;

ctx_start(&current->sp, next->sp);
// In ctx_start:
//      sw sp, 0(a0)     /* sp -> 0(a0) */
//      mv sp, a1        /* a1 -> sp */
```



Why not calling `test_code` directly?

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

ctx_start:
    …
    mv sp, a1
    call ctx_entry

    call test_code
    call thread_exit // it is possible to replace call ctx_entry
                     // with these two instructions
```



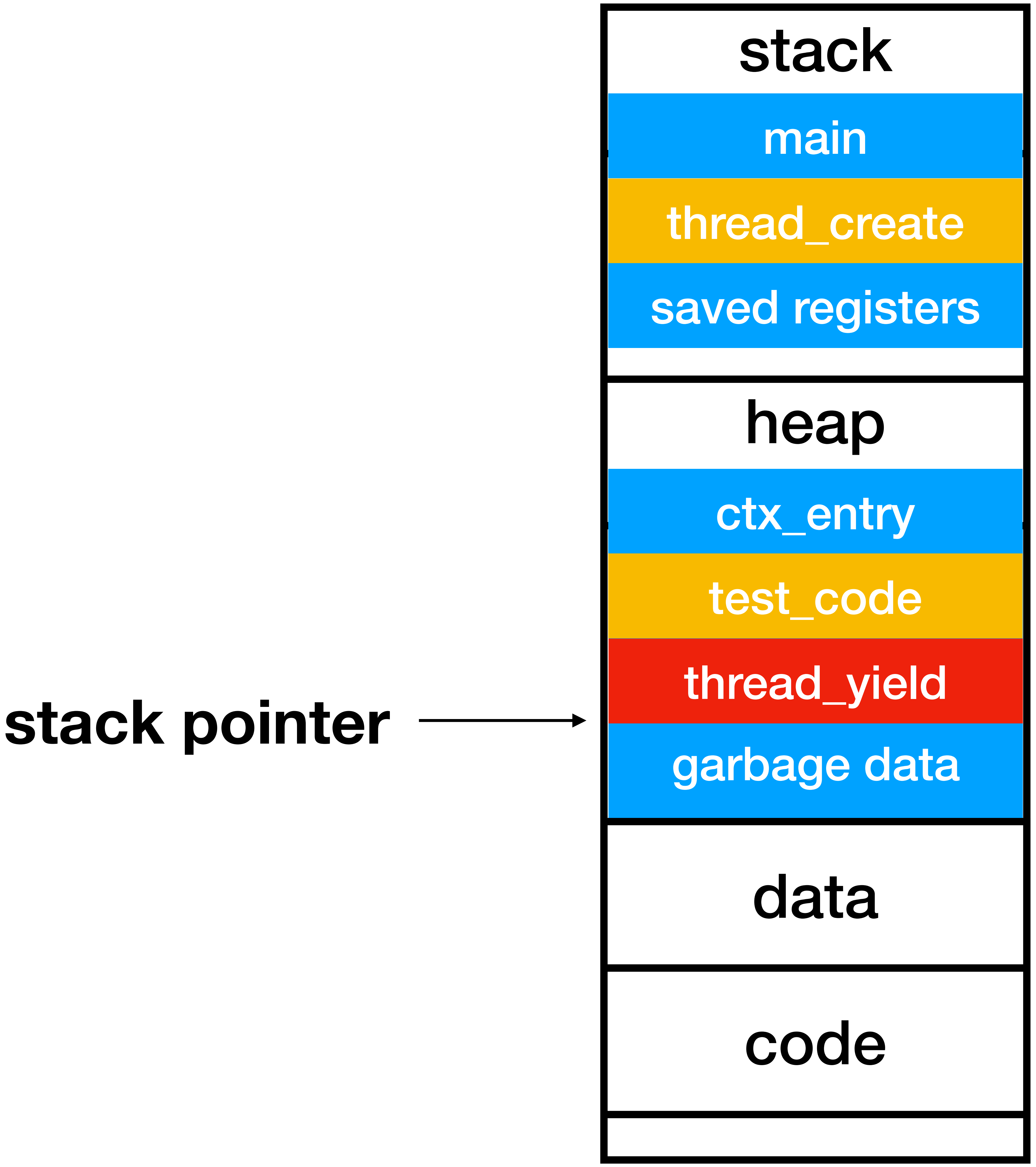
C programs do something similar

```
// Every C program has a main() function.
// The C program is compiled with some assembly by the compiler.

li sp, {some address}  // initialize stack pointer
call main              // return value of main is in register a0
call exit              // a0 is also the first parameter to exit

// exit() is a C library function which invokes a system call
// In RISC-V, system calls are invoked by an ecall instruction
// You will meet the ecall instruction in P3.
```

- 5 steps of `thread_create`
- More on these 5 steps
- ➡ 4 steps of `thread_yield`
- Semaphores for testing
- Inter-process communication (IPC)

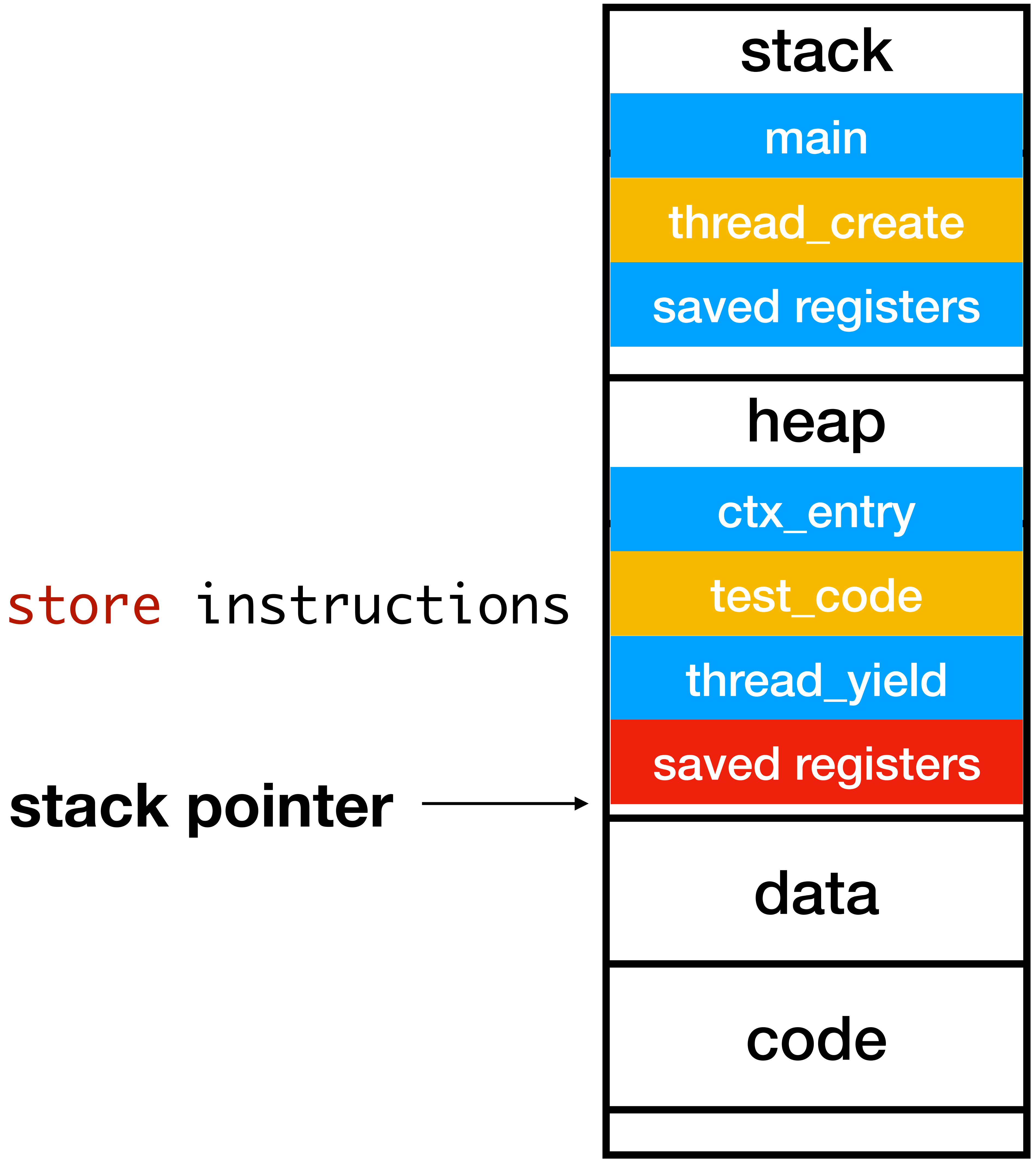
Thread1 yields

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

void test_code(void *arg) {
    for (int i = 0; i < 3; i++) {
        printf("%s here: %d\n", arg, i);
        thread_yield();
    }
    printf("%s done\n", arg);
    thread_exit();
}
```



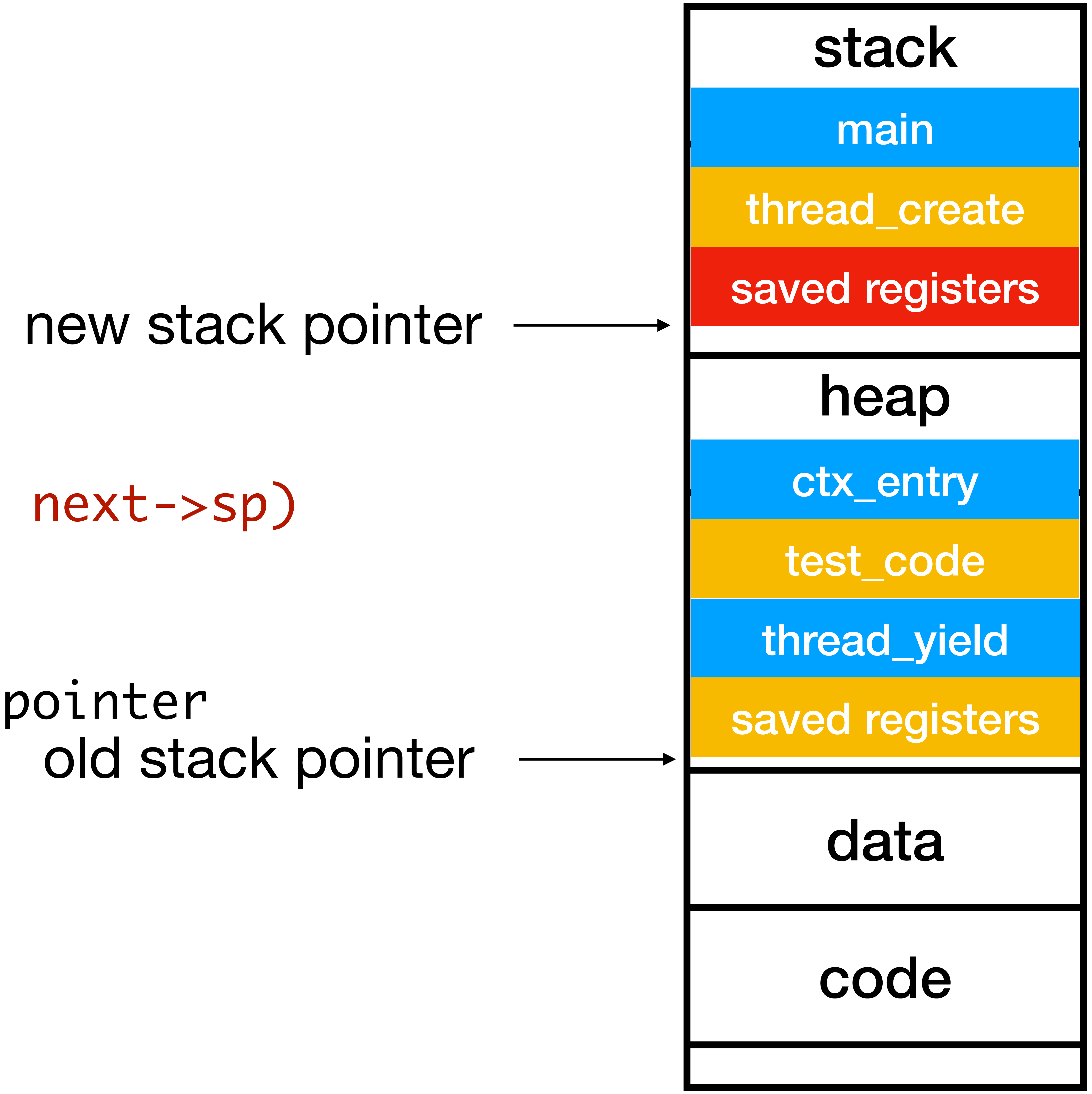
Yield step 1/4

```
void test_code(void *arg) {
      …
      thread_yield();
      …
}

ctx_switch:
    …          // save registers on the stack with store instructions
    sw sp, 0(a0)
    mv sp, a1
    …
    ret
```



Yield step 2/4

```
void test_code(void *arg) {
      …
      thread_yield();
      …
}

ctx_switch:         // ctx_switch(&current->sp, next->sp)
    …
    sw sp, 0(a0)  // save old stack pointer
  ➡mv sp, a1      // switch to the new stack pointer
    …
    ret
```



new stack pointer

old stack pointer

stack

main

thread_create

saved registers

heap

ctx_entry

test_code

thread_yield

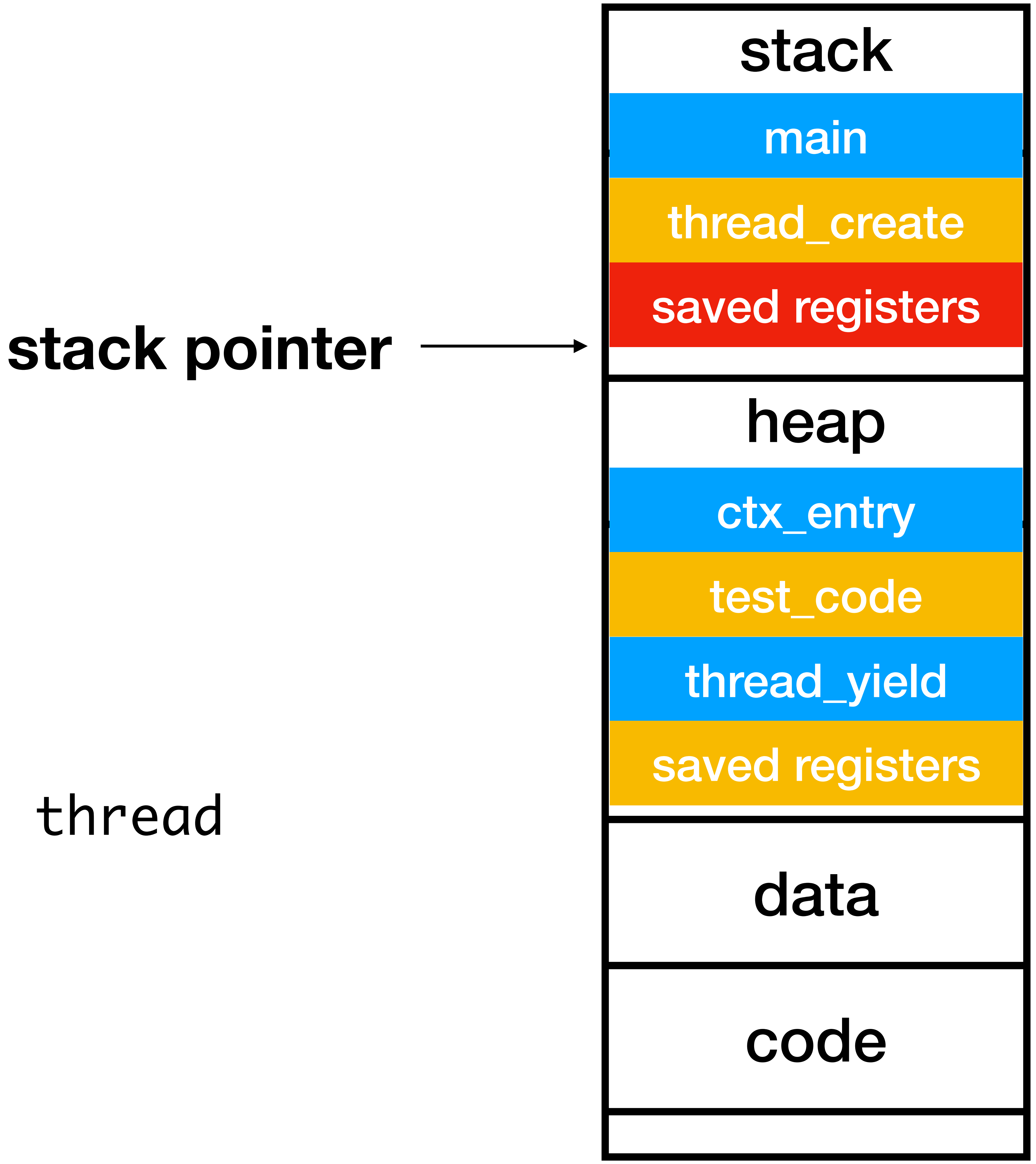
saved registers

data

code

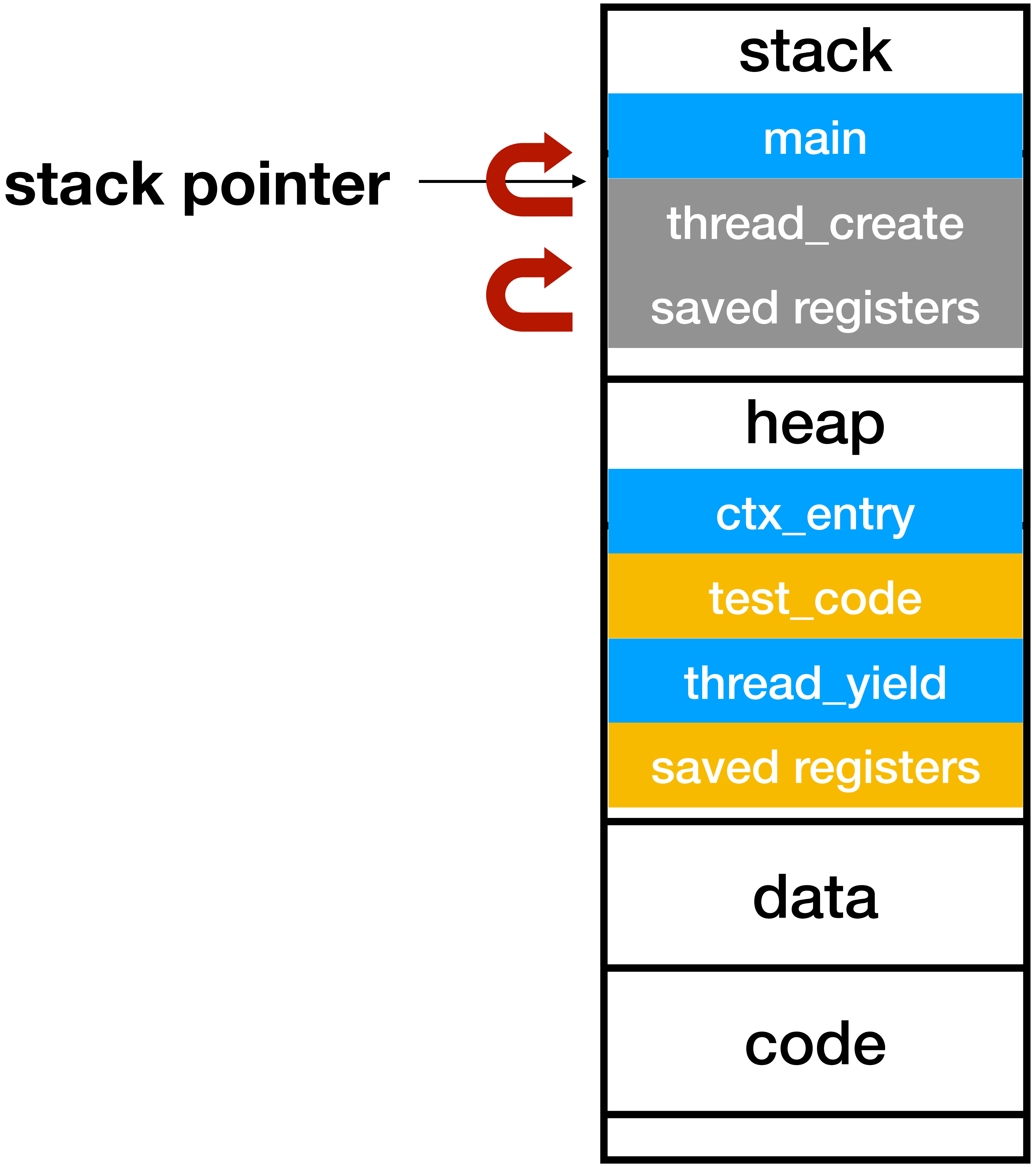
Yield step 3/4

```
void test_code(void *arg) {
      …
      thread_yield();
      …
}

ctx_switch:
    …
    sw sp, 0(a0)
    mv sp, a1
  ➡ …  // restore the registers saved in the main thread
    ret
```



Yield step 4/4

```
int main() {
    thread_init();
    thread_create(test_code, "thread 1",
                  16 * 1024);
    thread_create(test_code, "thread 2",
                  16 * 1024);
    test_code("main thread");
}

ctx_switch:
    …
    ret   // step 4/4: return to thread_create()
thread_create:
    …
    ret   // step 4/4: return to main()
```



- 5 steps of `thread_create`
- More on these 5 steps
- 4 steps of `thread_yield`
- ➡ Semaphores for testing
- Inter-process communication (IPC)

Semaphores as counters

```
// Allocate a counter
void sema_init(struct sema *sema, unsigned int count);

// Increment the counter by 1
void sema_inc(struct sema *sema);

// Wait until counter > 0, then decrement counter by 1
void sema_dec(struct sema *sema);

// Release the counter
bool sema_release(struct sema *sema);
```

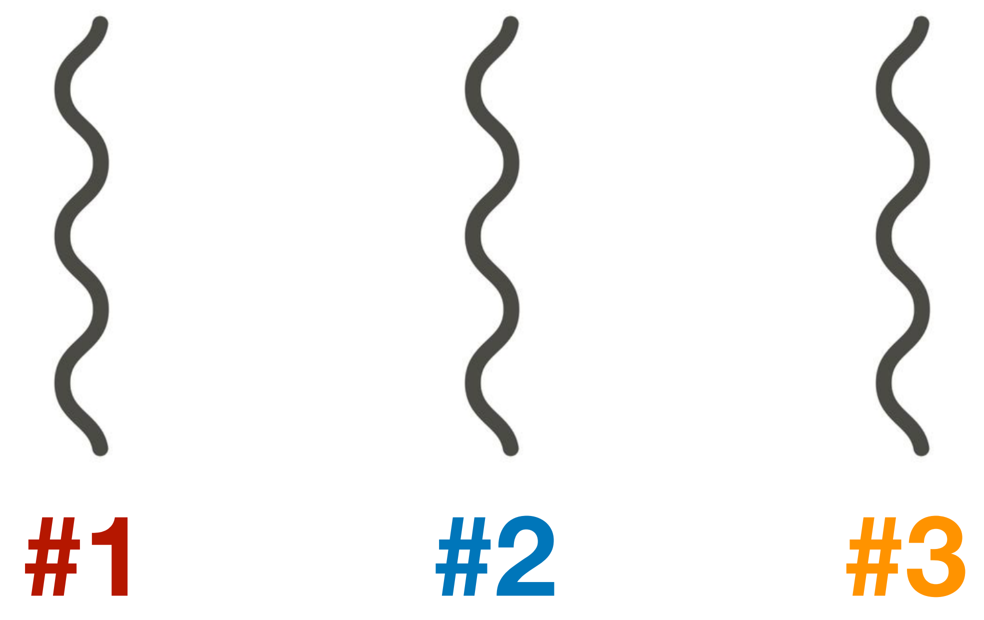
Bounded buffer producer-consumer

A fixed length array as a buffer holding items between producer and consumer threads

Index	#1	#2	#3
Content			

Bounded buffer producer-consumer

producer threads



Index	#1	#2	#3
Content	item from **#1**	item from **#1**	item from **#2**

Now the buffer is full and
all producer threads need to wait.

Bounded buffer producer-consumer

Say **#5** consumes item#1 and #2; **#7** consumes item #3;
Now the buffer is empty and consumer threads need to wait.

Index	#1	#2	#3
Content	item from **#1**	item from **#1**	item from **#2**

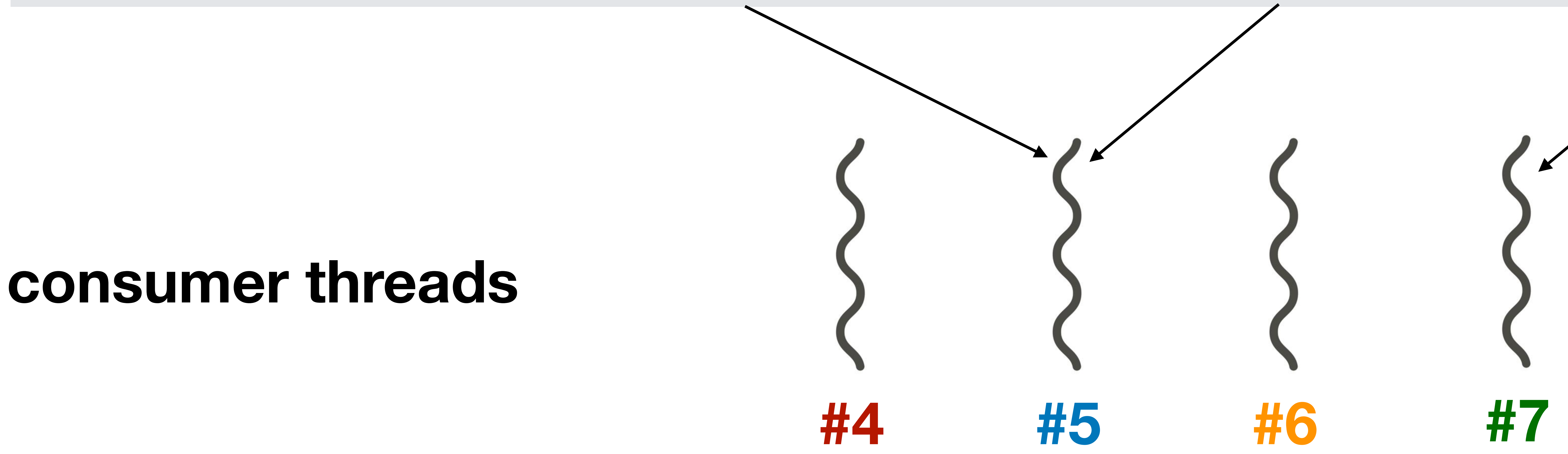
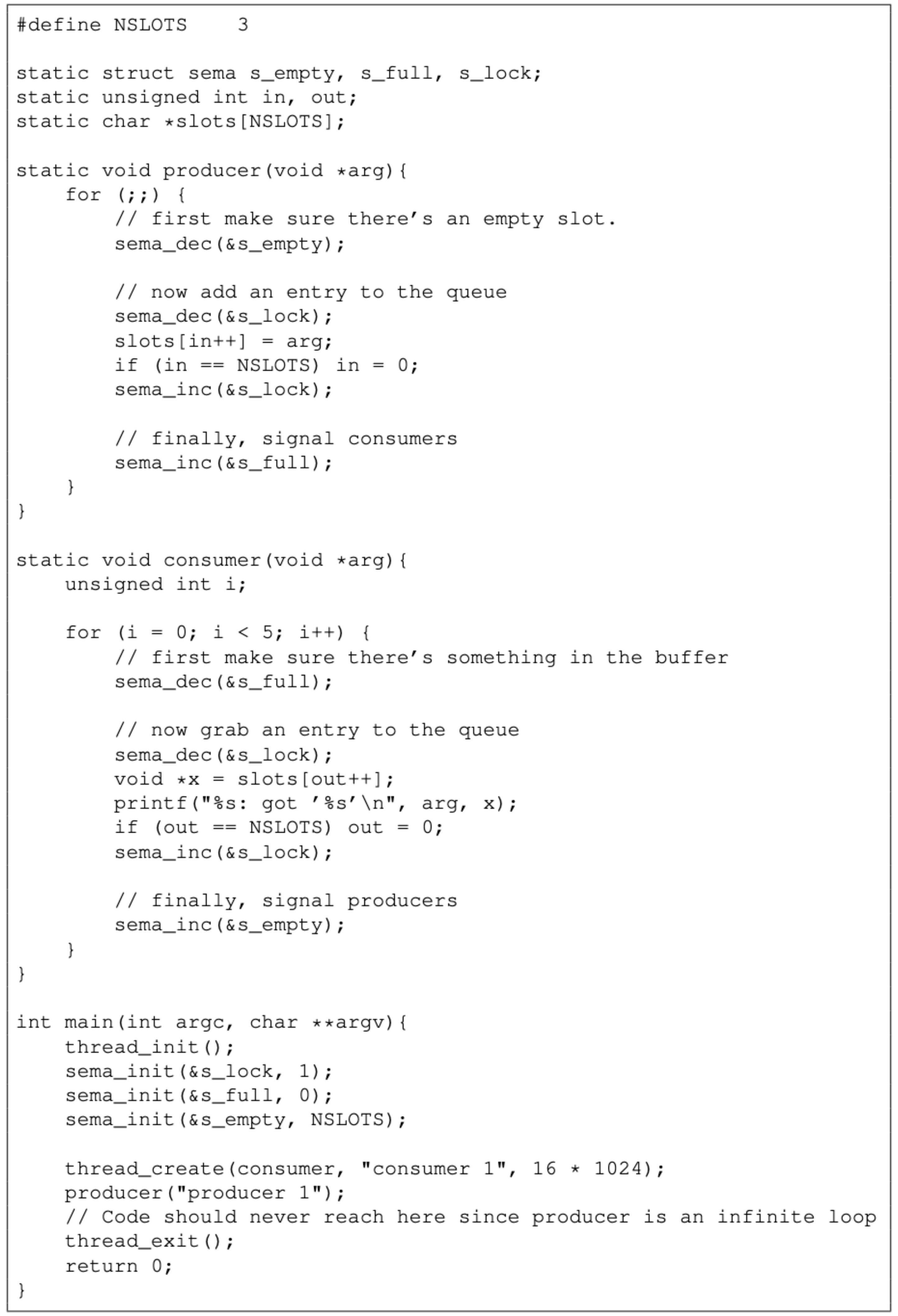


Figure 2 in the handout



```c
#define NSLOTS    3

static struct sema s_empty, s_full, s_lock;
static unsigned int in, out;
static char *slots[NSLOTS];

static void producer(void *arg){
    for (;;) {
        // first make sure there’s an empty slot.
        sema_dec(&s_empty);

        // now add an entry to the queue
        sema_dec(&s_lock);
        slots[in++] = arg;
        if (in == NSLOTS) in = 0;
        sema_inc(&s_lock);

        // finally, signal consumers
        sema_inc(&s_full);
    }
}

static void consumer(void *arg){
    unsigned int i;

    for (i = 0; i < 5; i++) {
        // first make sure there’s something in the buffer
        sema_dec(&s_full);

        // now grab an entry to the queue
        sema_dec(&s_lock);
        void *x = slots[out++];
        printf("%s: got ’%s’\n", arg, x);
        if (out == NSLOTS) out = 0;
        sema_inc(&s_lock);

        // finally, signal producers
        sema_inc(&s_empty);
    }
}

int main(int argc, char **argv){
    thread_init();
    sema_init(&s_lock, 1);
    sema_init(&s_full, 0);
    sema_init(&s_empty, NSLOTS);

    thread_create(consumer, "consumer 1", 16 * 1024);
    producer("producer 1");
    // Code should never reach here since producer is an infinite loop
    thread_exit();
    return 0;
}
```

Implement a producer-consumer with 3 semaphores.

Hints for `struct sema`

- Each semaphore maintains a queue of waiting threads.
  - consider the waiting producer/consumer just mentioned
- In P1, you need to implement more tests, such as
  - multi-reader/writer lock
  - dining philosophers
  - etc.

- 5 steps of `thread_create`
- More on these 5 steps
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- Semaphores for testing

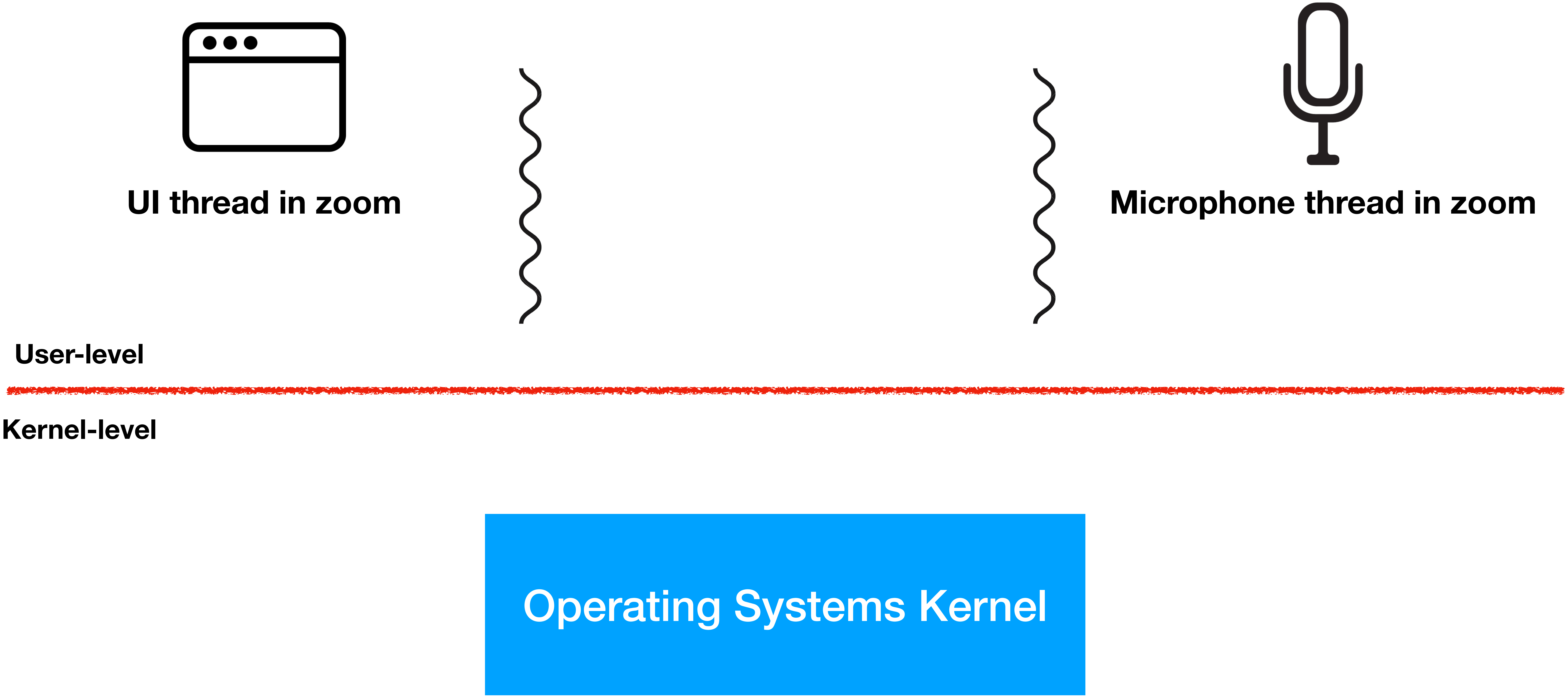
➡ Inter-process communication (IPC)

UNIX System V IPC

`System V IPC is the name given to three interprocess communication mechanisms that are widely available on UNIX systems: message queues, semaphore, and shared memory.`

https://man7.org/linux/man-pages/man7/svipc.7.html

Message queue example



UI thread in zoom

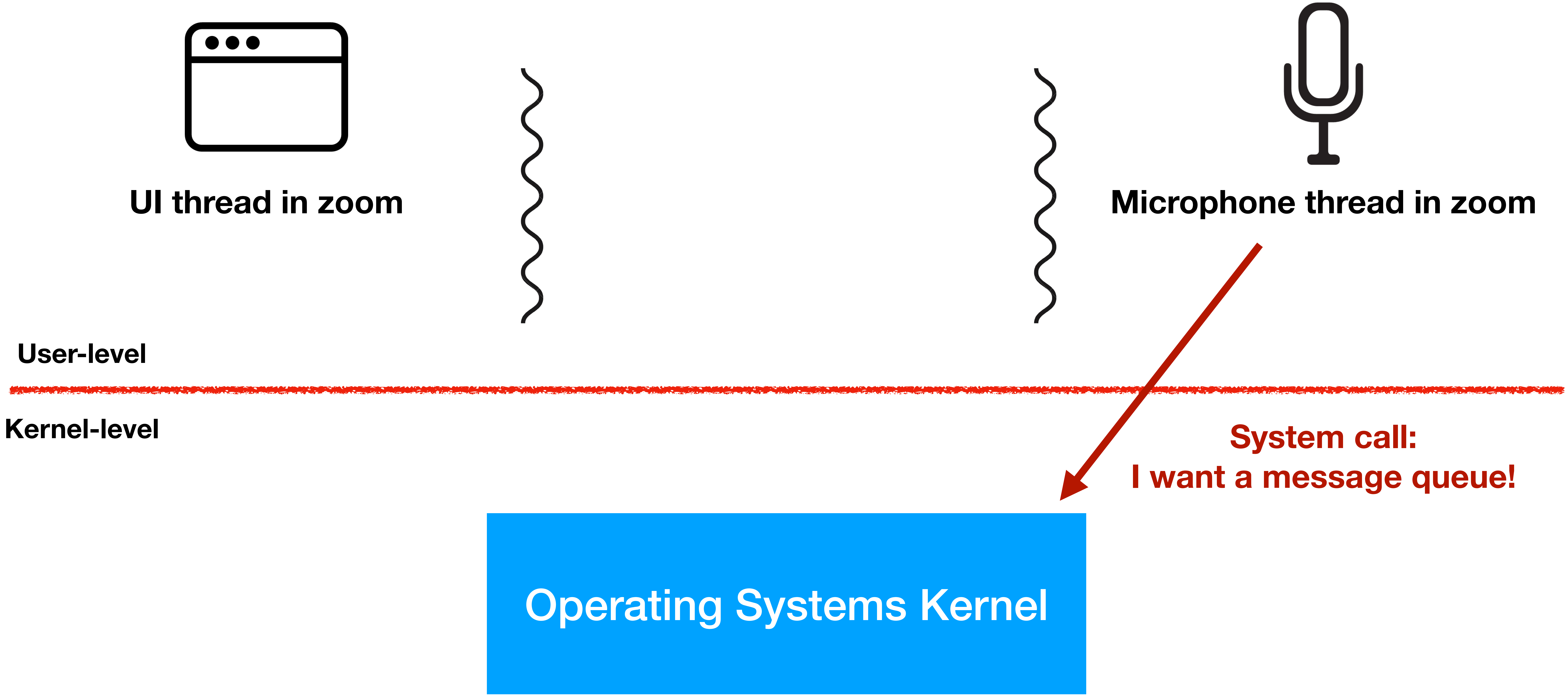
Microphone thread in zoom

User-level

Kernel-level

Operating Systems Kernel

Message queue example



UI thread in zoom

Microphone thread in zoom

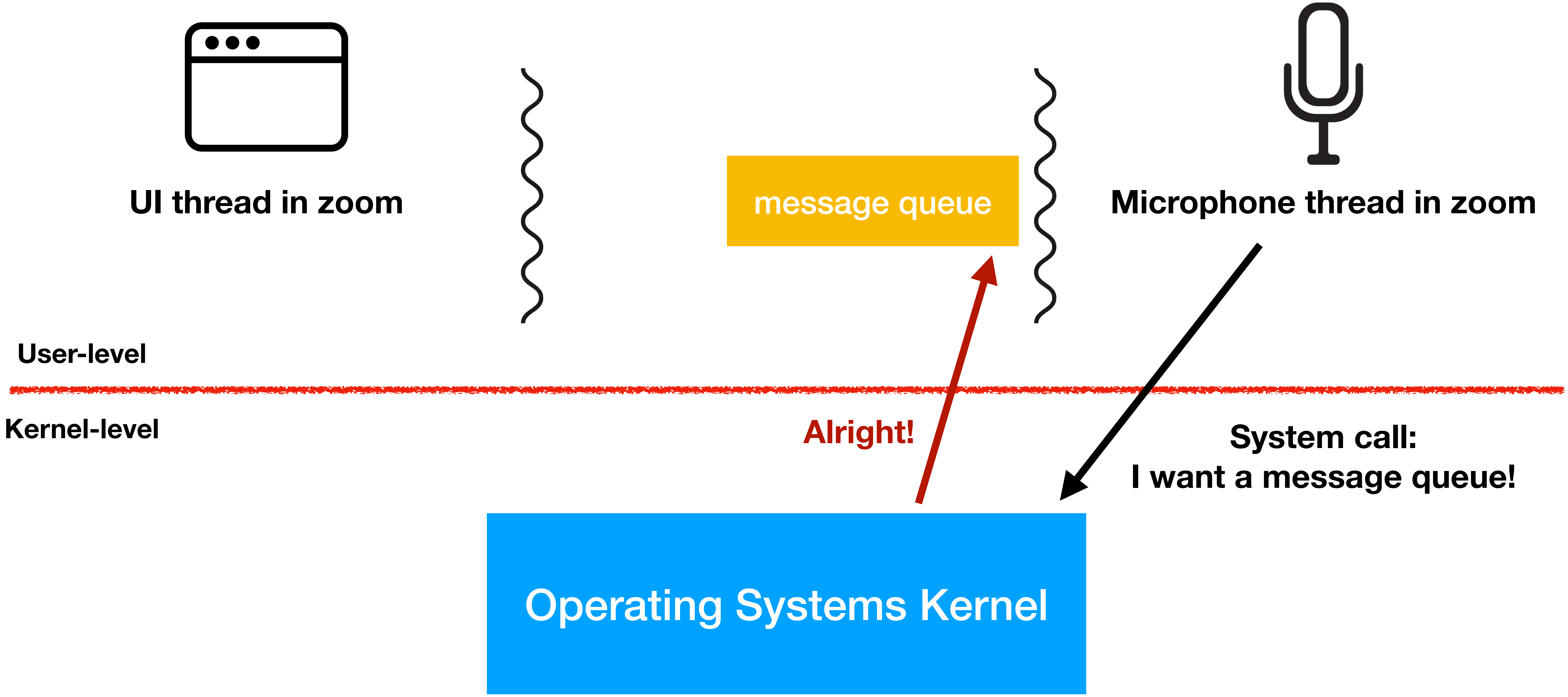
User-level

Kernel-level

System call:
I want a message queue!

Operating Systems Kernel

Message queue example



UI thread in zoom

message queue

Microphone thread in zoom

User-level

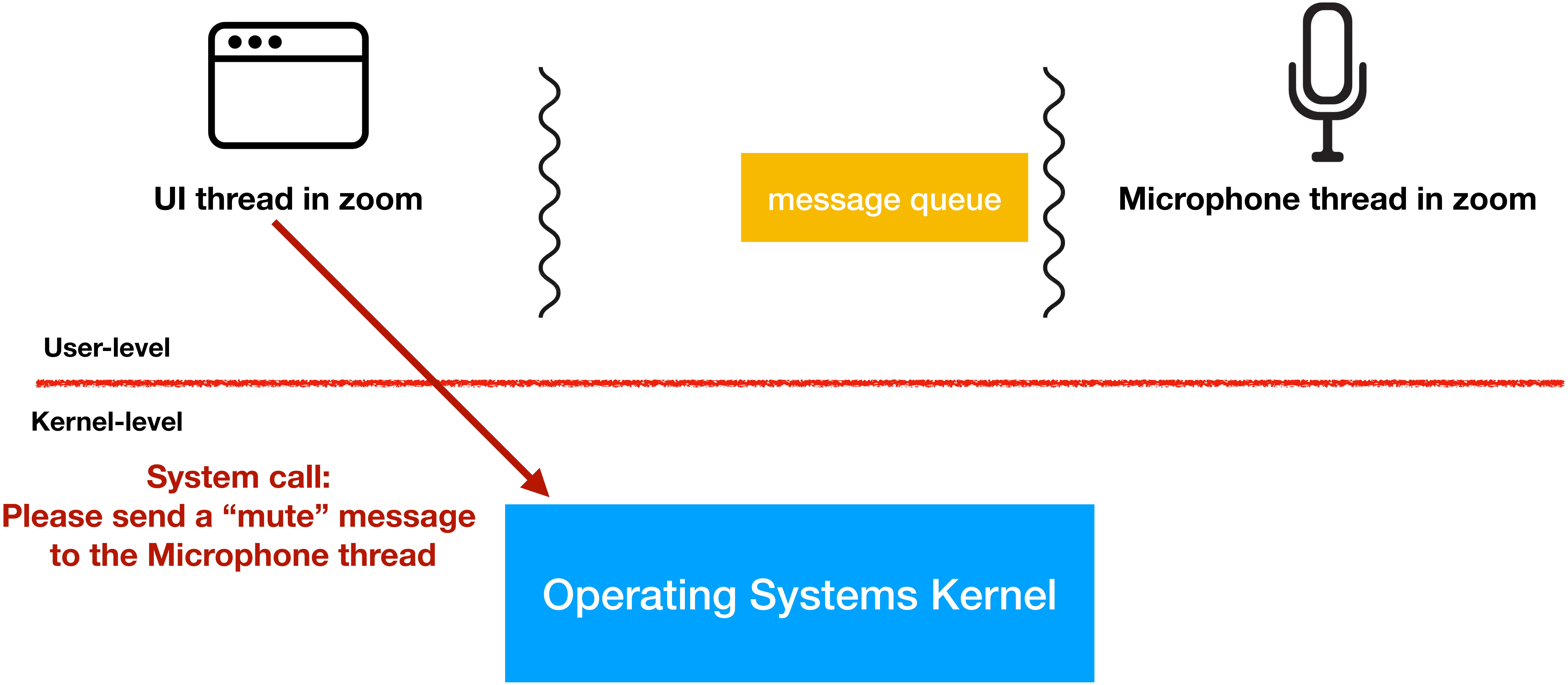
Kernel-level

Alright!

System call:
I want a message queue!

Operating Systems Kernel

Message queue example



UI thread in zoom

message queue

Microphone thread in zoom

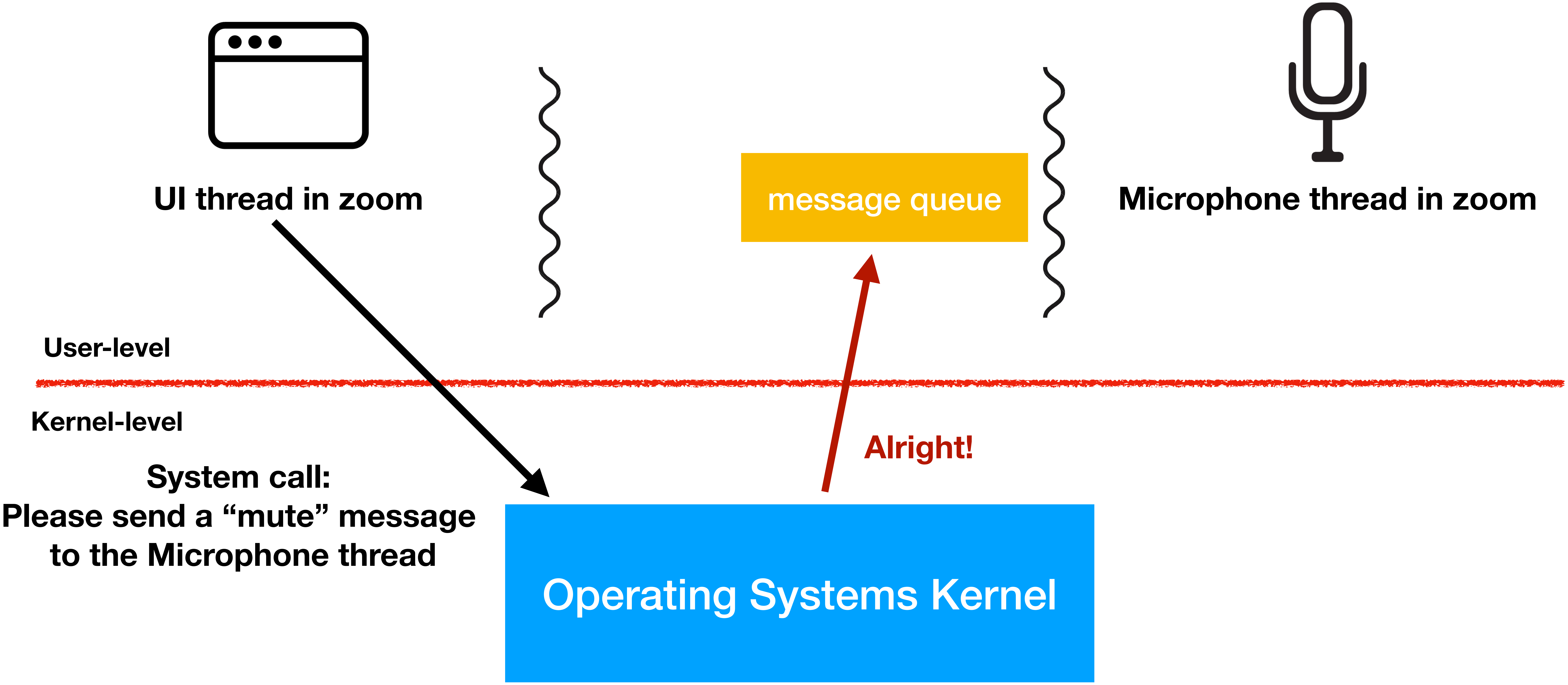
User-level

Kernel-level

System call:
Please send a “mute” message
to the Microphone thread

Operating Systems Kernel

Message queue example



UI thread in zoom

message queue

Microphone thread in zoom

User-level

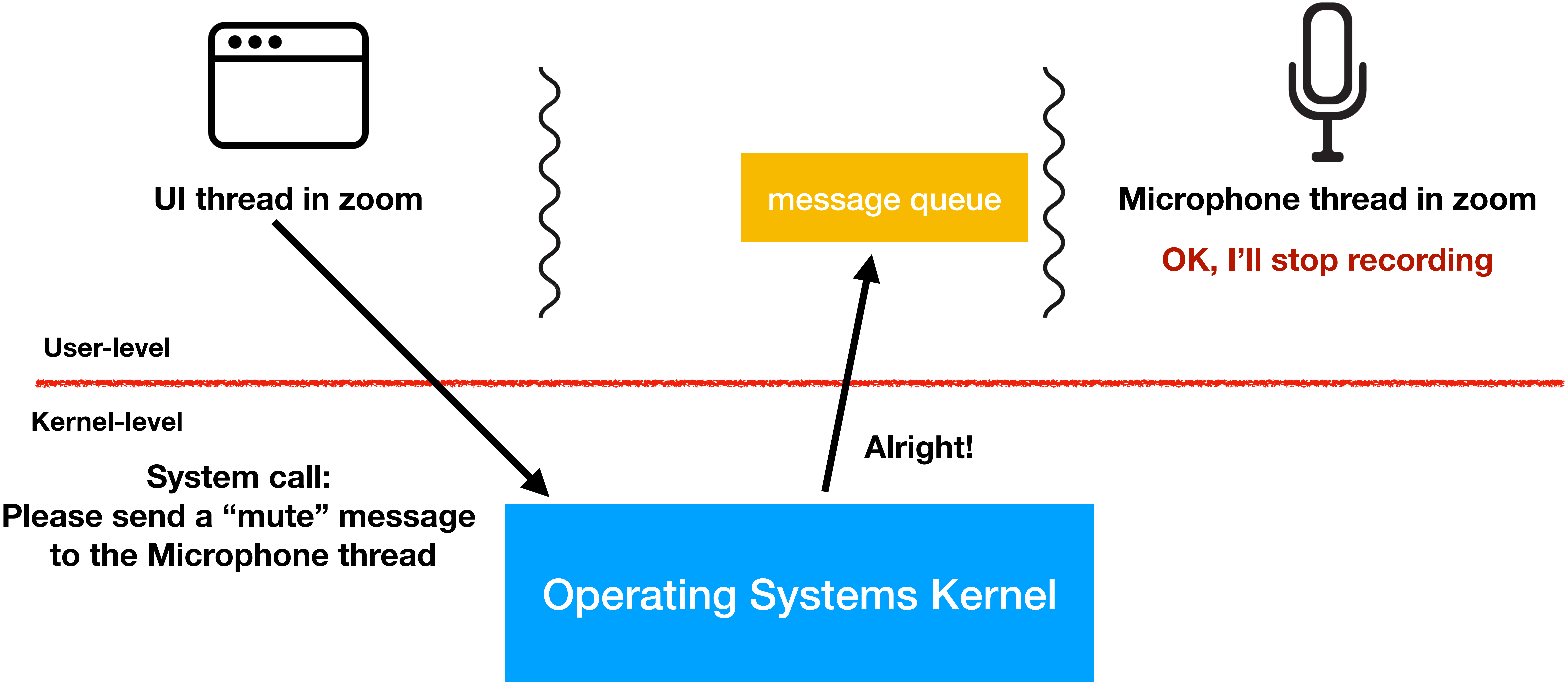
Kernel-level

Alright!

System call:
Please send a “mute” message
to the Microphone thread

Operating Systems Kernel

Message queue example



UI thread in zoom

message queue

Microphone thread in zoom

OK, I’ll stop recording

User-level

Kernel-level

Alright!

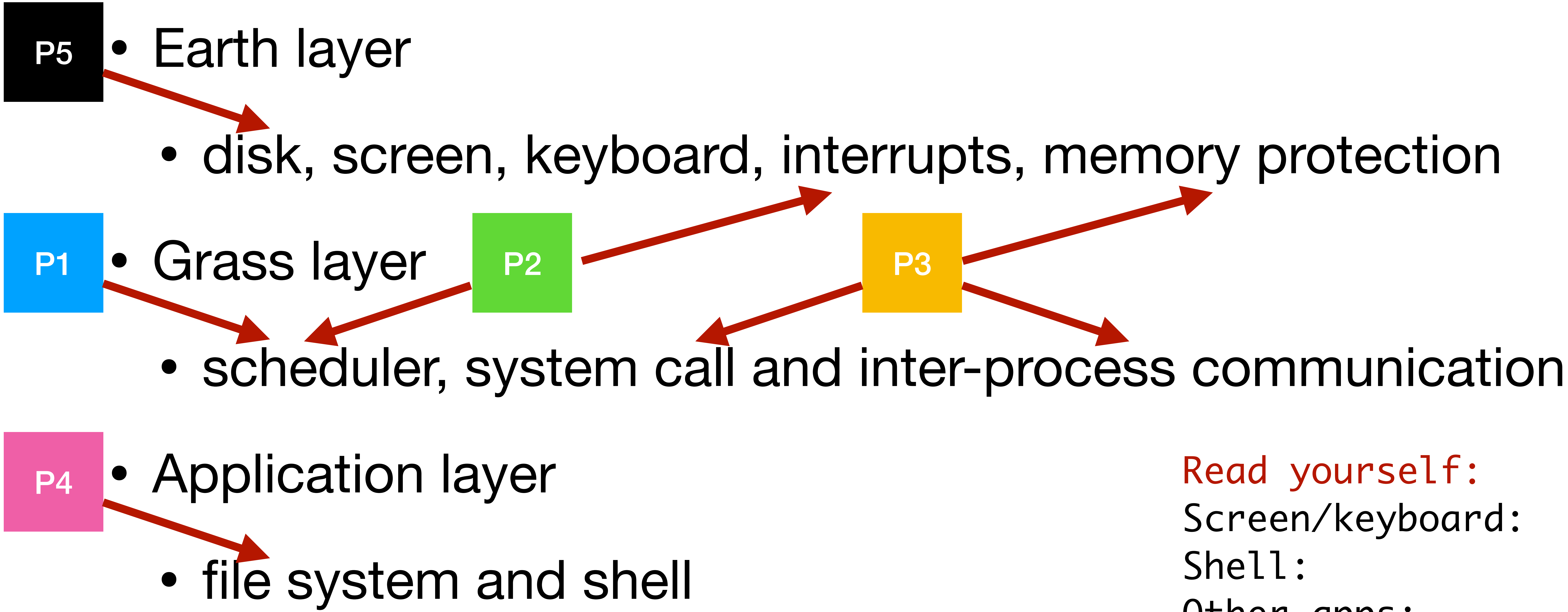
System call:
Please send a “mute” message
to the Microphone thread

Operating Systems Kernel

Message queues in EGOS

- Earth layer
  - disk, screen, keyboard, interrupts, memory protection
- Grass layer
  - scheduler, system call and inter-process communication (IPC)
- Application layer
  - file system and shell (communicate through message queues)
  - shell commands: ls, mkdir, echo, cat, …

4411 projects design



- Earth layer
  - disk, screen, keyboard, interrupts, memory protection
- Grass layer
  - scheduler, system call and inter-process communication
- Application layer
  - file system and shell
  - shell commands: ls, mkdir, echo, cat, …

Read yourself:

Screen/keyboard:	~80 LOC
Shell:	~50 LOC
Other apps:	~150 LOC

High-level roadmap

- ➡ [basic RISC-V CPU] non-preemptive multi-threading
- [+ timer interrupt] preemptive scheduling
- [+ privilege levels] protection and isolation for processes
- [+ I/O bus controllers] disk driver and file systems

Homework

- P1 is due on Sep 28.
    - multi-threading
    - semaphore
    - testing suite using semaphores