TOSThreads

Thread-Safe and Non-Invasive Preemption in TinyOS

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November 5, 2009

SenSys 2009

Events vs. Threads

- Event-Based Execution
  - Single thread of control
    - No context switch overheads
    - Less RAM usage (no per thread stacks)
  - Manually managed continuations
  - Good model for highly event driven code
- Thread-Based Execution
  - Multiple threads of control
    - Context switch overheads
    - More RAM usage (one stack per thread)
  - System manages continuations automatically
  - Good model for code with many sequential operations

Events vs. Threads

- Event-Based Model

```
int i = 0;
uint8_t val[3*NUM_ITERS];

void ReadSensors() {
   readTemp();
}
void readTempDone(uint8_t v) {
   val[ i++ ] = v;
   readHumidity();
}
void readHumidityDone(uint8_t v) {
   val[ i++ ] = v;
   readLight();
}
void readLightDone(uint8_t v) {
   val[ i++ ] = v;
   readLight();
   if ( i < NUM_ITERS)
     readTemp();
}
```

- Thread-Based Model

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- Thread-Based Model

```
uint8_t val[3*NUM_ITERS];

void ReadSensors() {
   for (int i=0; i<NUM_ITERS; i+=3) {
      val[i]     = readTemp();
      val[i+1] = readHumidity();
      val[i+2] = readLight);
   }
}
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Events vs. Threads

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TOSThreads aims to resolve this tension for TinyOS-based applications

TOSThreads Goals

- Thread Safety
  - Building a thread library is easy – ensuring thread safety is not
  - Introduces thread-safe preemption through message passing
- Non-Invasiveness
  - Requires minimal changes to existing TinyOS code
  - 100% backwards compatible with TinyOS
  - Minimal overheads (energy, memory footprint, performance)

TOSThreads Goals

- Ease of Extensibility
  - Ability to leverage future innovations in TinyOS
  - TinyOS service wrappers for system calls
- Flexible Application Development
  - Easily customizable system call API
  - Mixed use of events and threads
  - Dynamic linking and loading
  - C and nesC based APIs

Outline

- **The Challenge of Preemption**
- TOSThreads Architecture
- Interesting Results
- Conclusion

The Challenge of Preemption

- Concurrently running threads need the ability to invoke kernel functions
- Concurrency of kernel invocations must be managed in some way
- Three basic techniques
  - Cooperative threading
  - Kernel Locking
  - Message Passing

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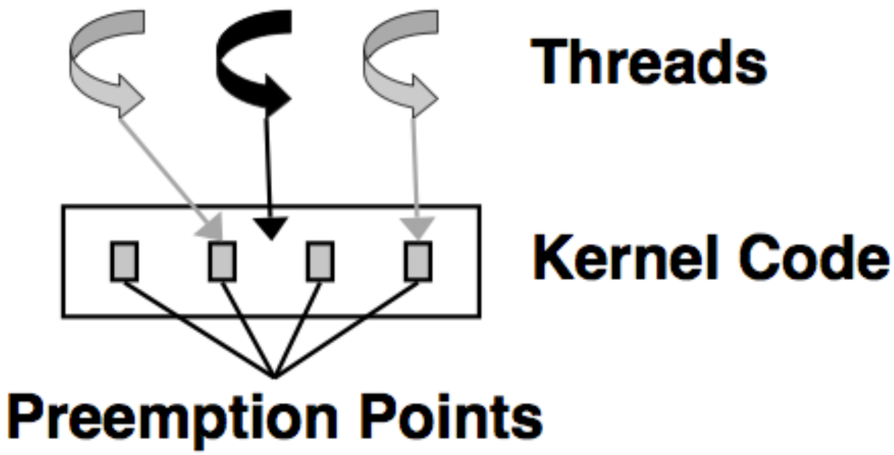
Contiki (EmNets ’04)

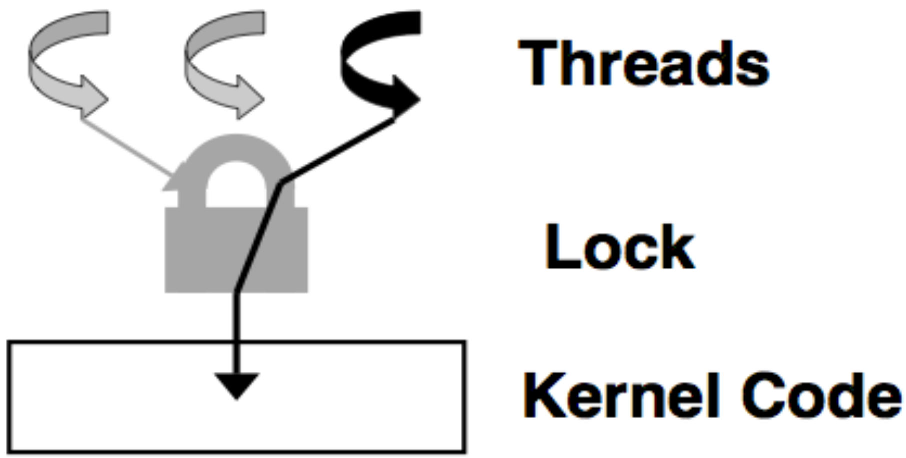
Cooperative Threading



- Advantages:
  - Simple Kernel
- Disadvantages:
  - Complex applications
  - No Preemption

- Avoids challenge of kernel reentrancy
- Kernel only context switches on pre-defined functions (blocking I/O, yields)
- TinyThreads (Sensys ’06)

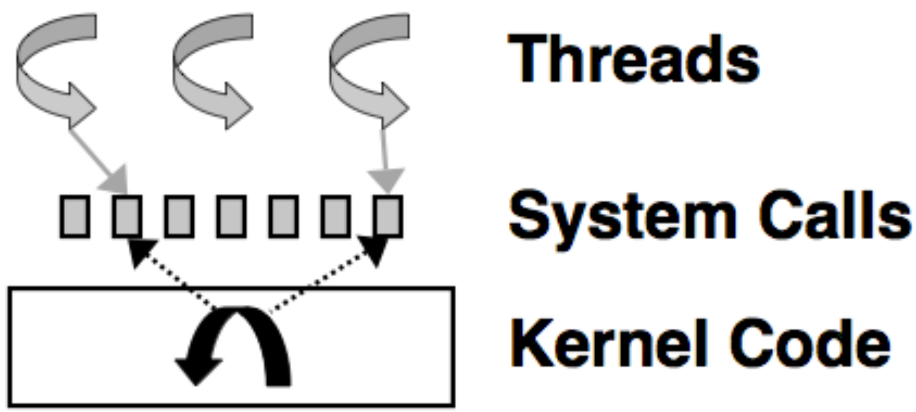
Kernel Locking



- Advantages:
  - Simple applications
- Disadvantages:
  - Limits concurrency
  - Complex kernel

- All kernel accesses explicitly locked enabling re-entrancy
- Coarse vs. Fine grained locks
- TinyMOS (EmNets '06)

Message Passing



- Advantages:
  - Simple kernel
  - Simple applications
- Disadvantages:
  - Context Switch on every kernel operation

- Applications never invoke kernel code directly
- All kernel accesses through single thin messaging interface
- LiteOS (IPSN '08)

Outline

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Architecture Overview

Thread-Based Applications

- Lower Priority Threads
- Application logic

System Calls

- Message Passing Interface

Event-Based Kernel

- Single High Priority Thread
- Core TinyOS services
- Highly concurrent / timing sensitive application code

Architecture Overview

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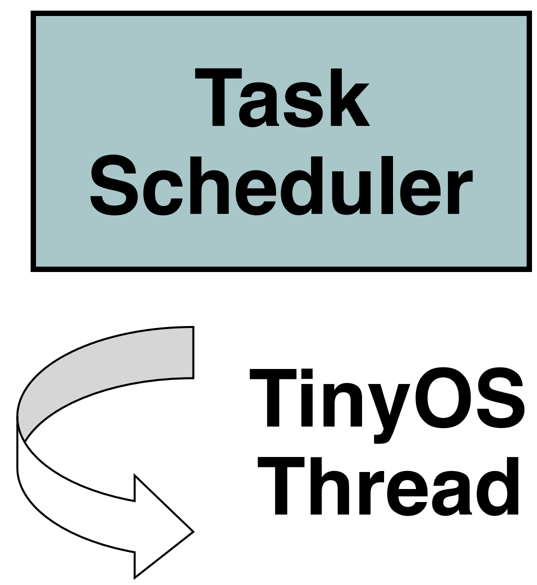

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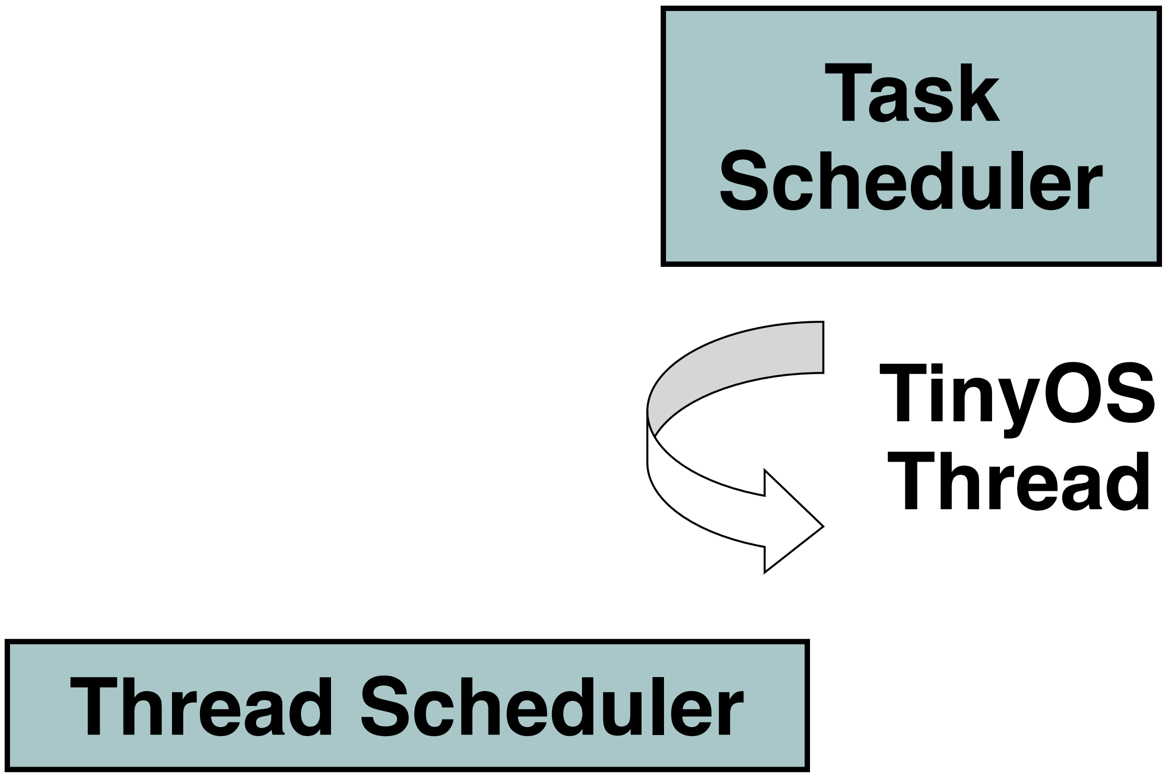

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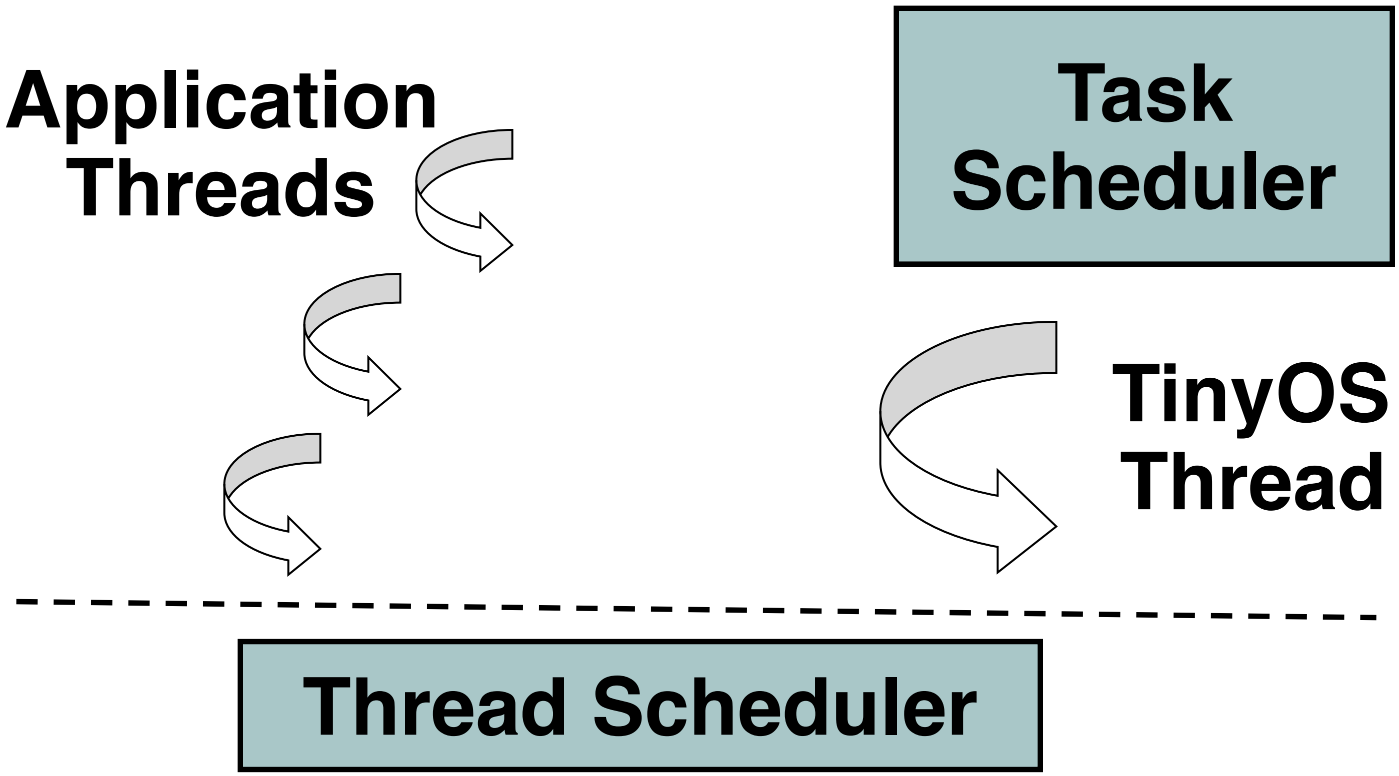

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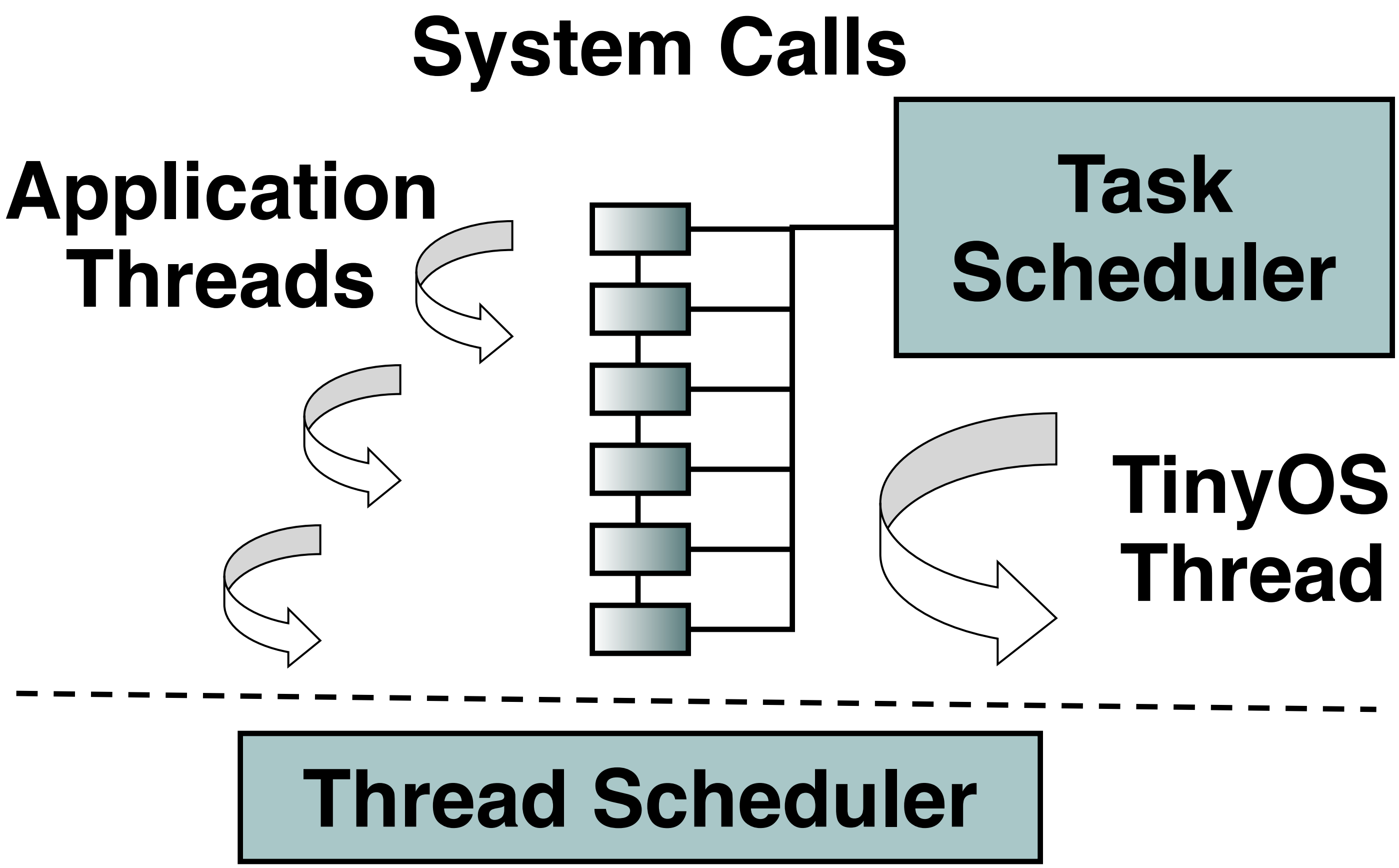

Blink Example (nesC)

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configuration BlinkAppC {
}
implementation {
  components MainC, BlinkC,  LedsC;
  components new ThreadC(STACK_SIZE);

  MainC.Boot <- BlinkC;
  BlinkC.Thread -> ThreadC;
  BlinkC.Leds -> LedsC;
}
```

```
module BlinkC {
  uses {
    interface Boot;
    interface Thread;
    interface Leds;
  }
}
implementation {
  event void Boot.booted() {
    call Thread.start(NULL);
  }
  event void Thread.run(void* arg) {
    for(;;) {
      call Leds.led0Toggle();
      call Thread.sleep(BLINK_PERIOD);
    }
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```

Mixed Event / Thread
Application Logic

Blink Example (standard C)

```c
#include "tosthread.h"
#include "tosthread_leds.h"

//Initialize variables associated with a thread
tosthread_t blink;
void blink_thread(void* arg);

void tosthread_main(void* arg) {
  tosthread_create(&blink, blink_thread, NULL, STACK_SIZE);
}
void blink_thread(void* arg) {
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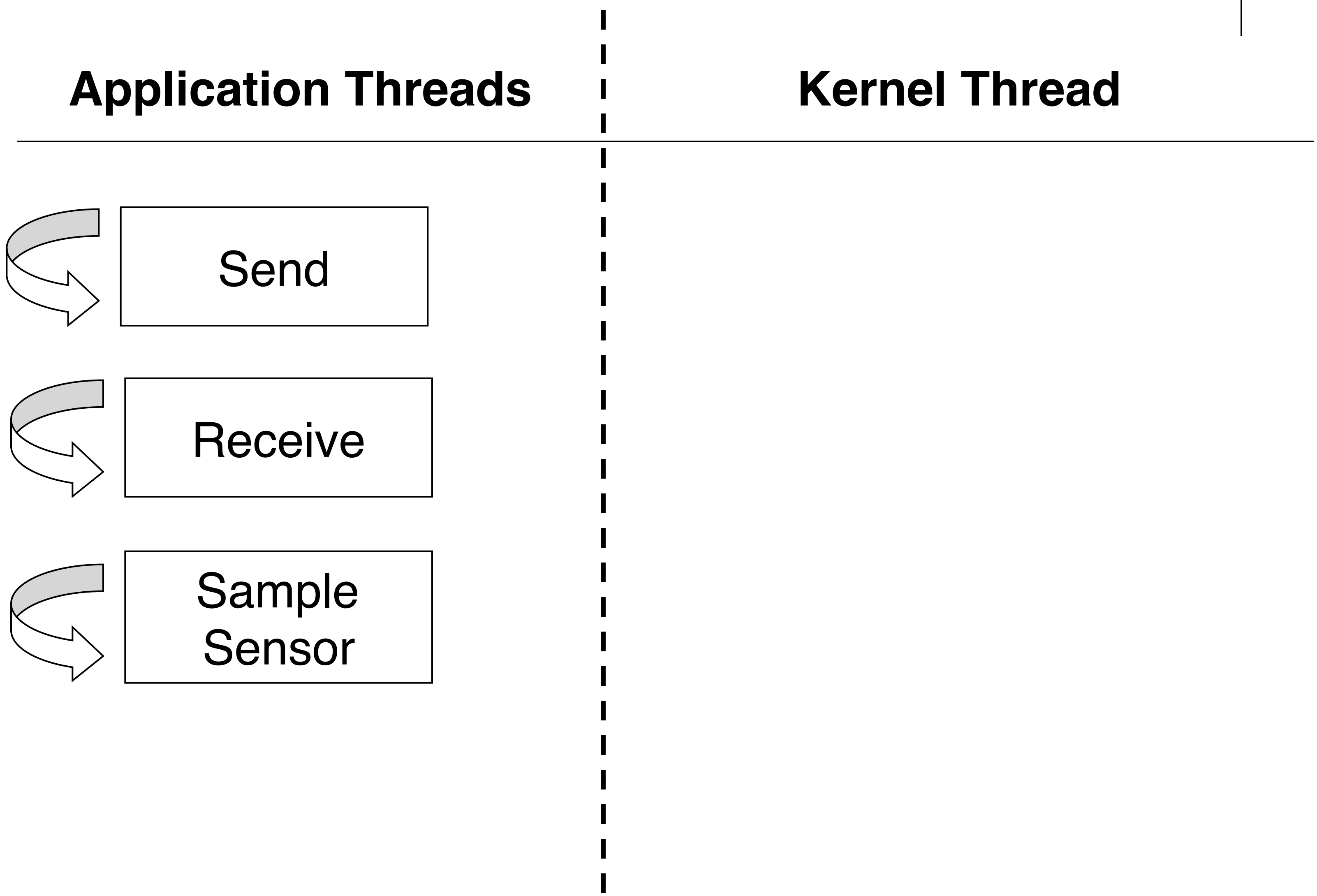
Message Passing System Calls

Application Threads	Kernel Thread

Message Passing System Calls



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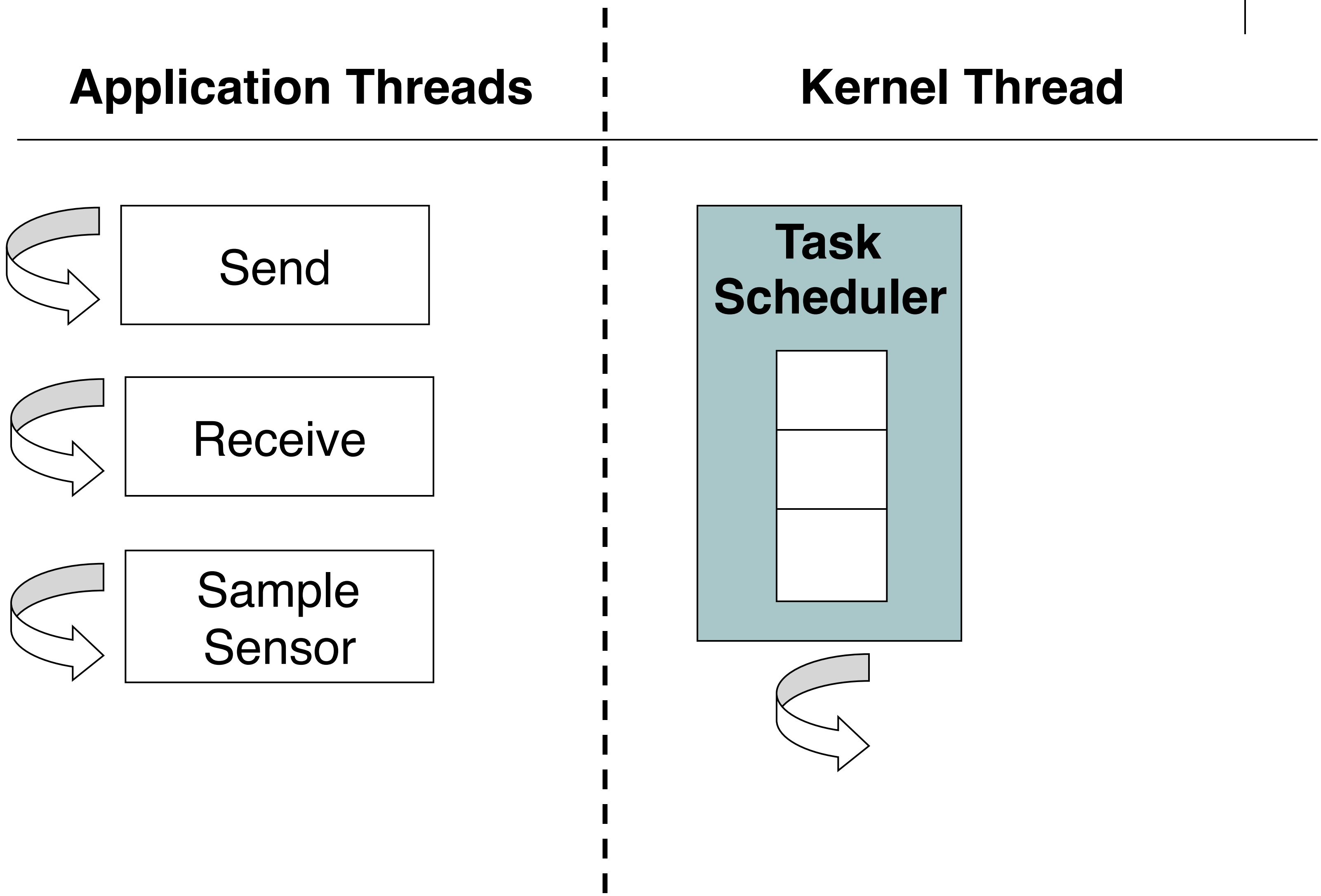

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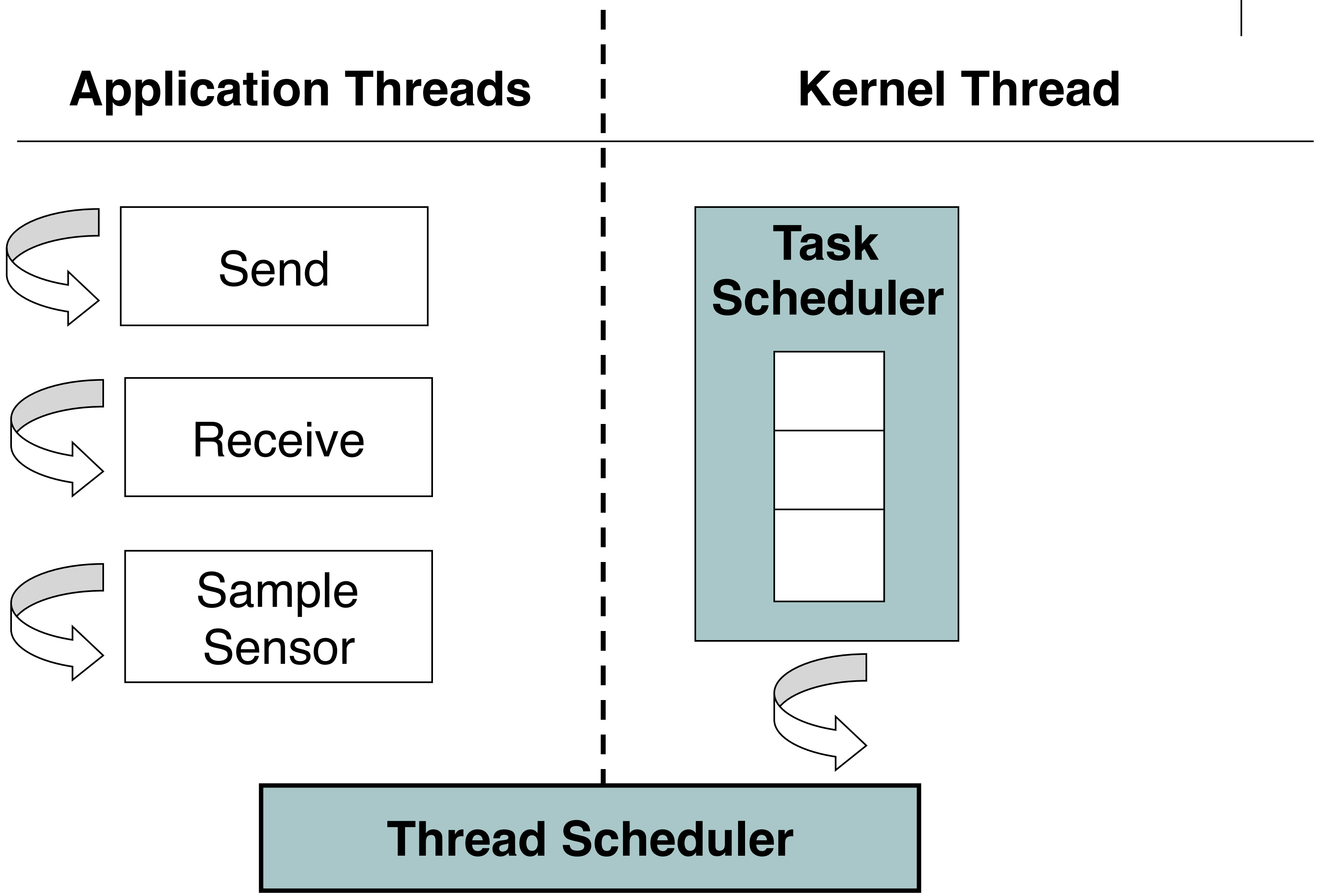

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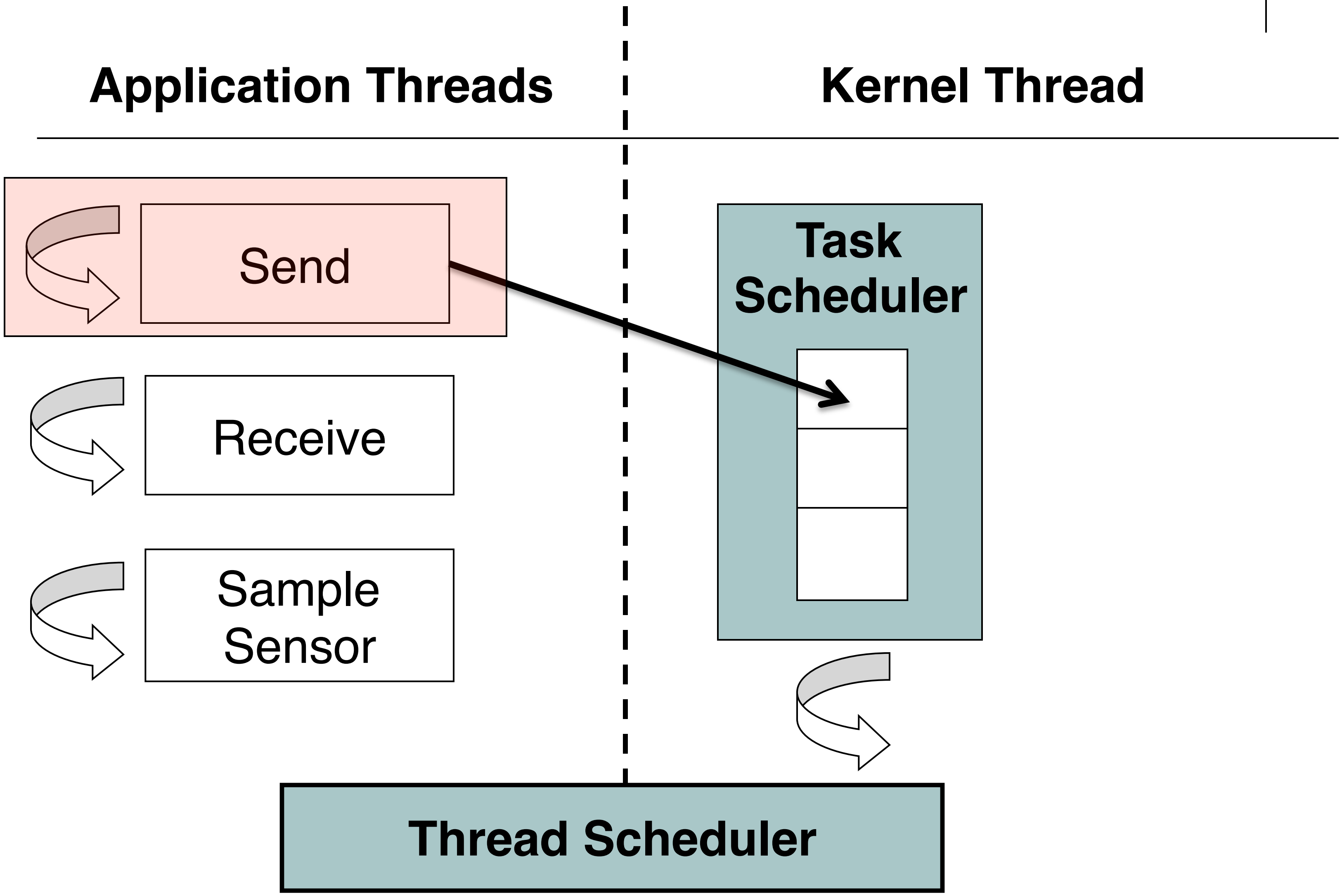

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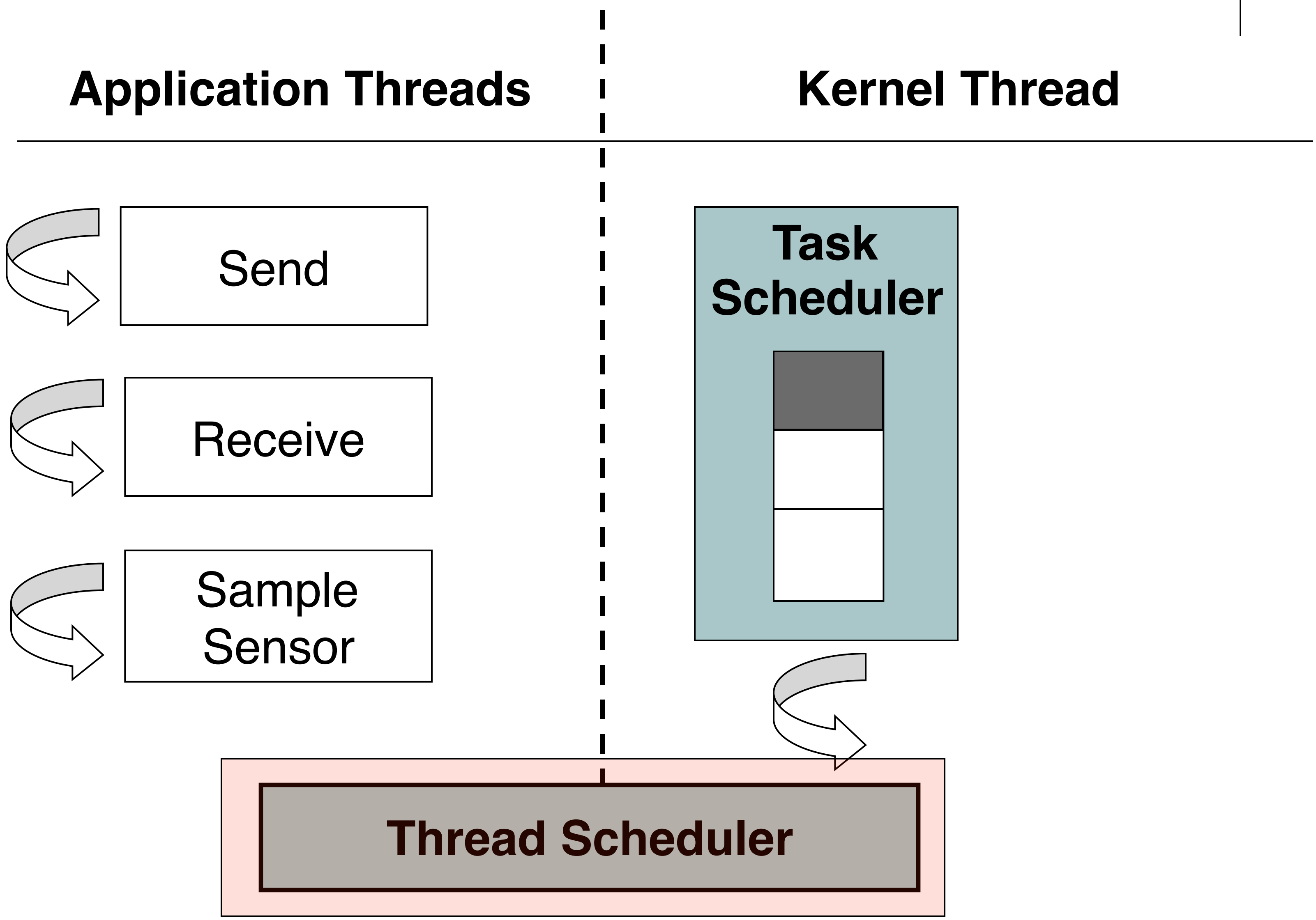

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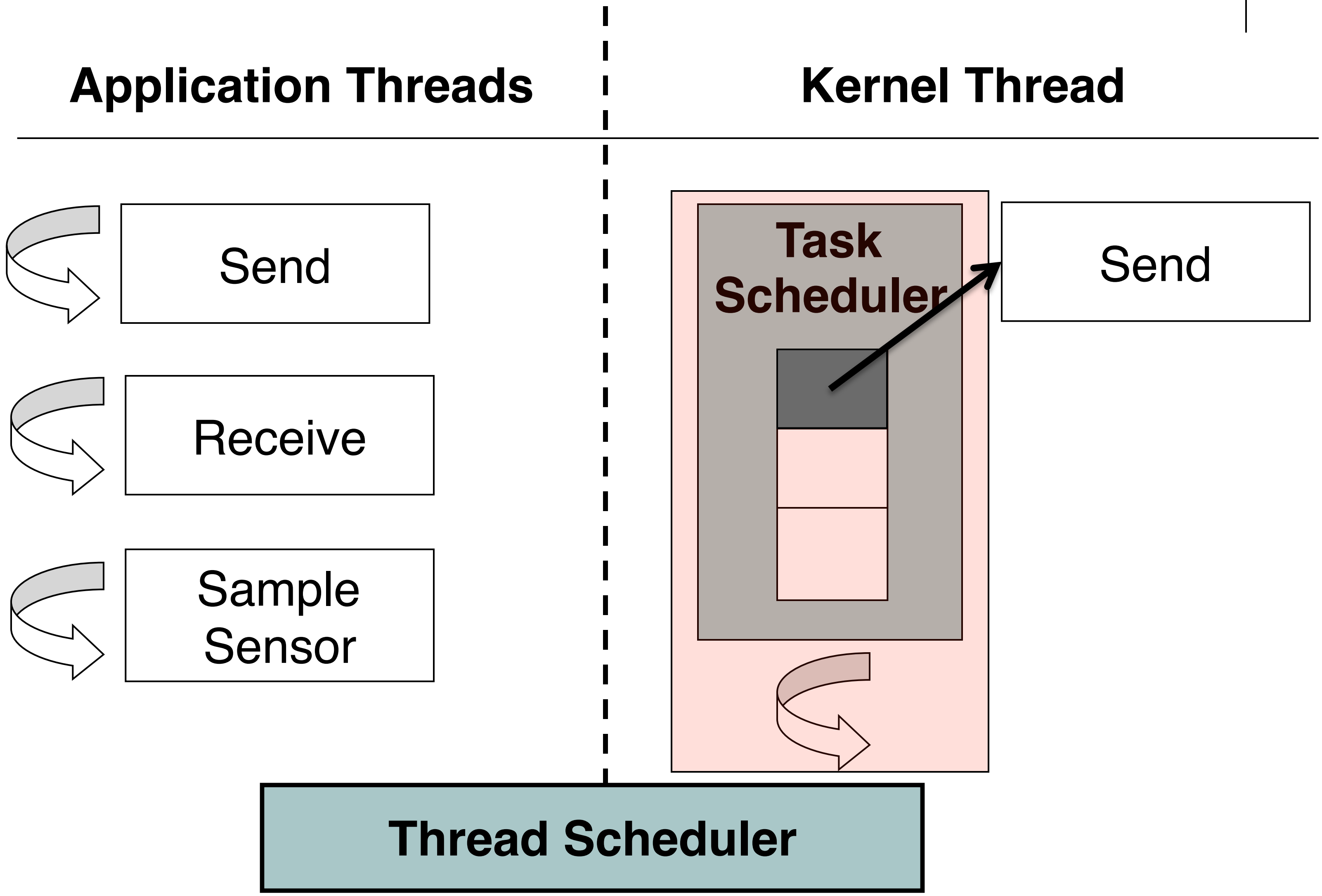

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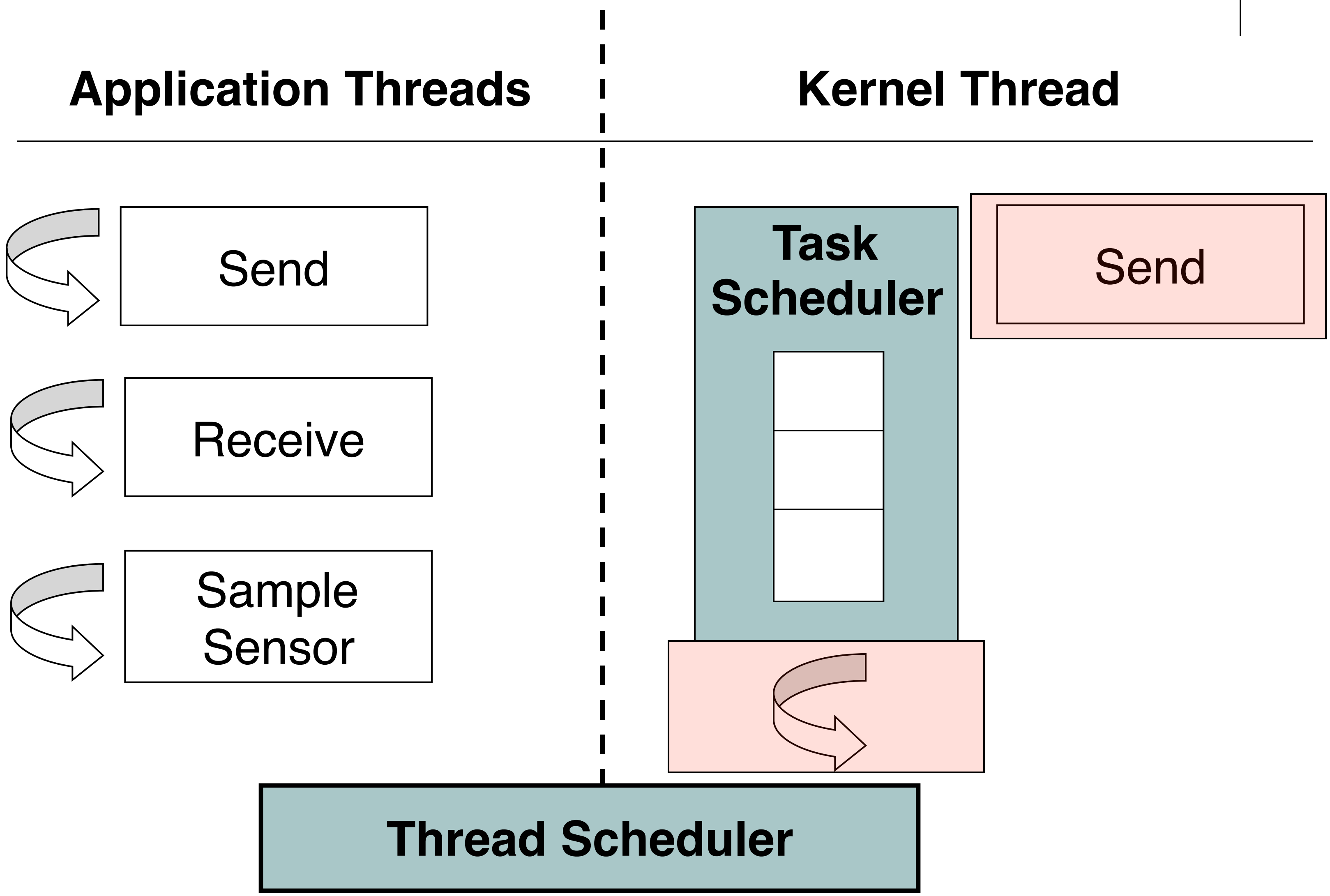

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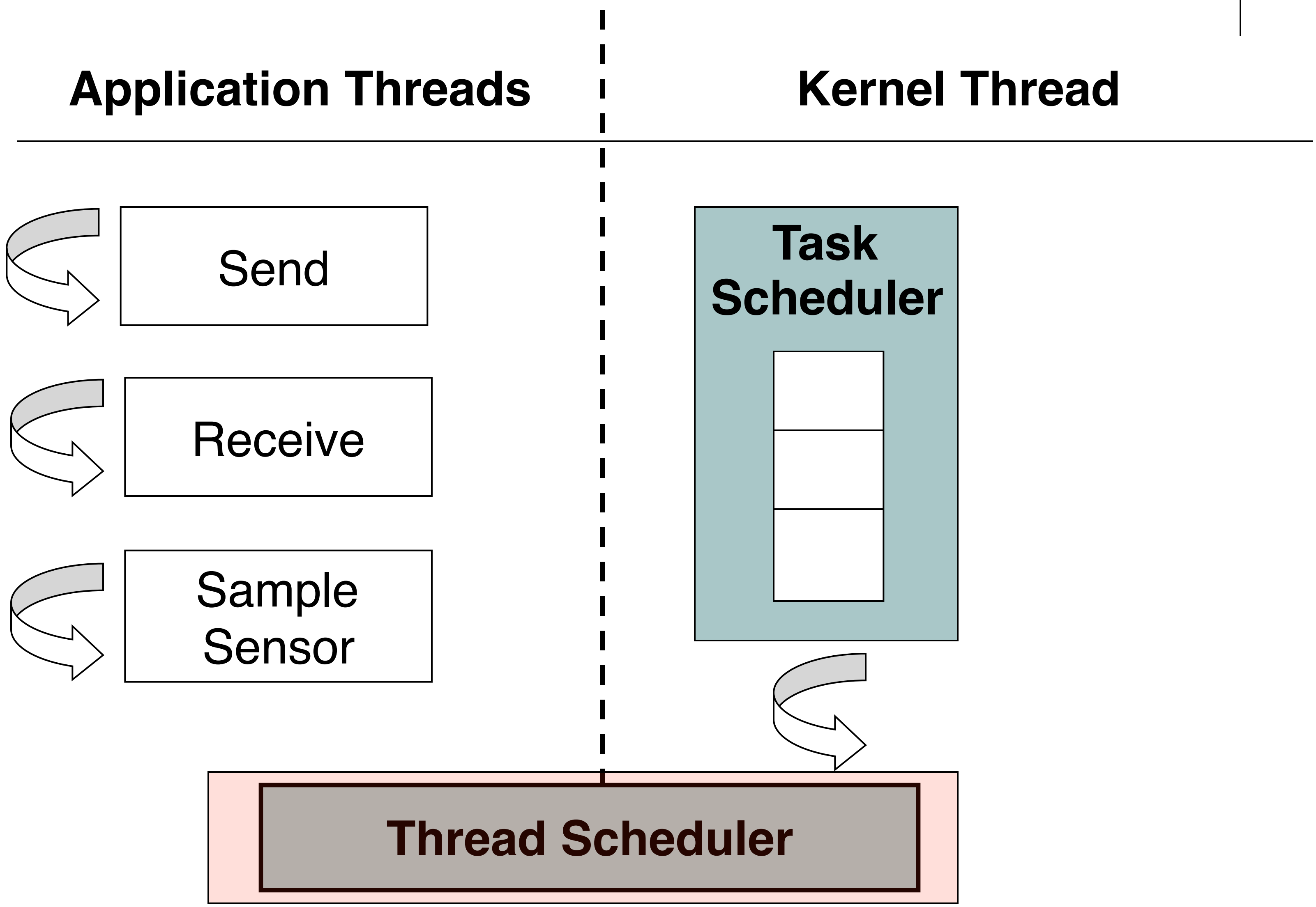

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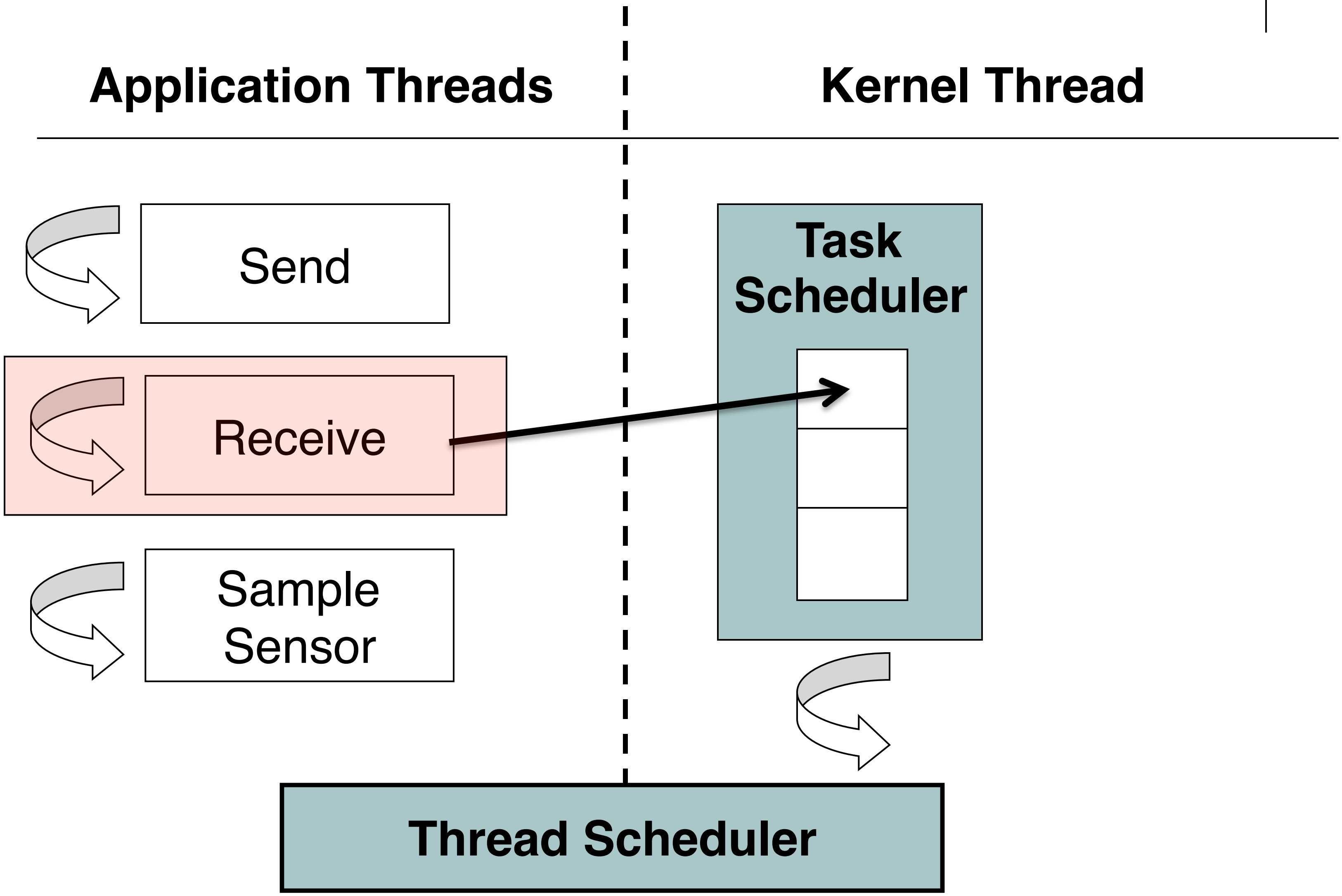

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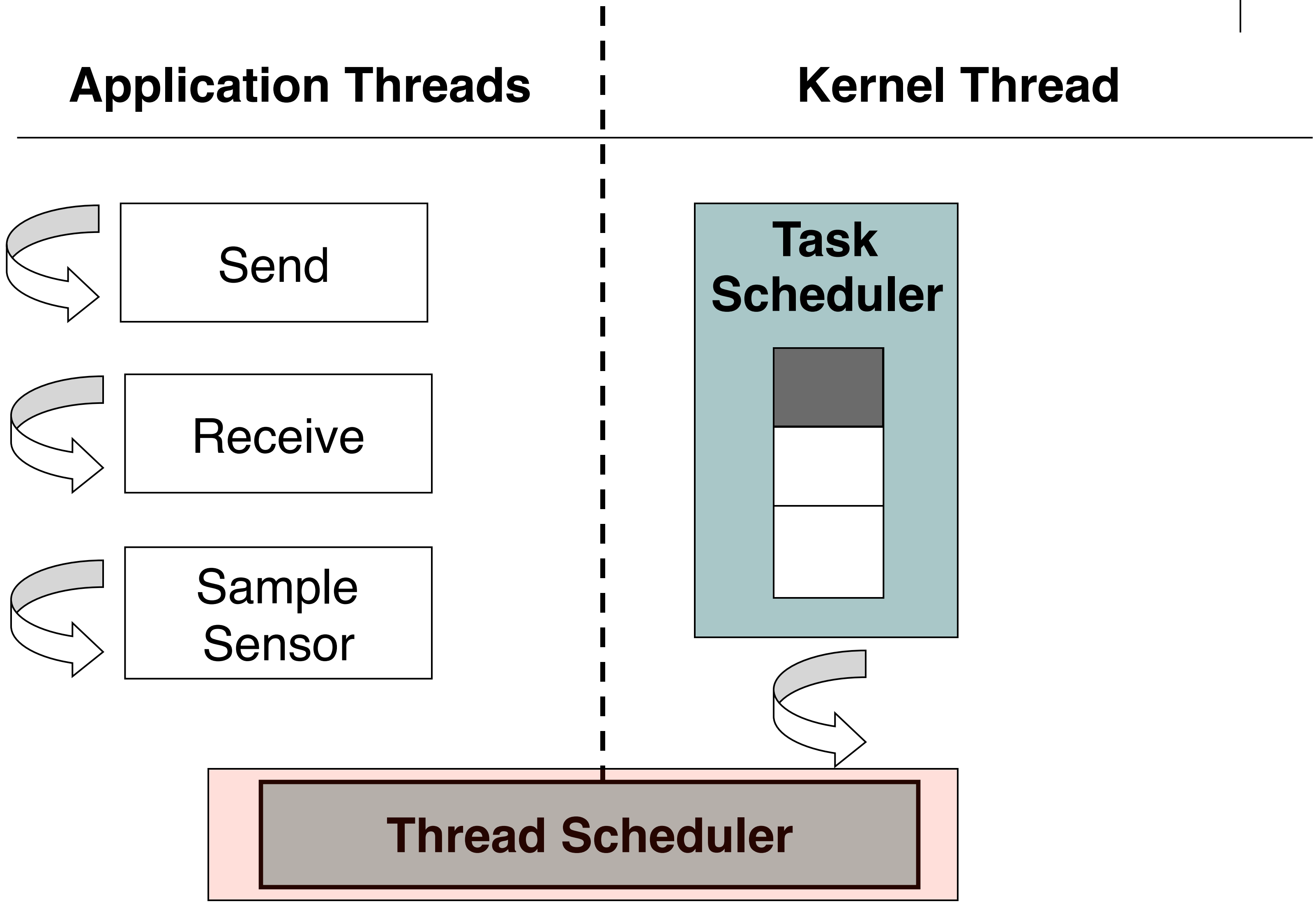

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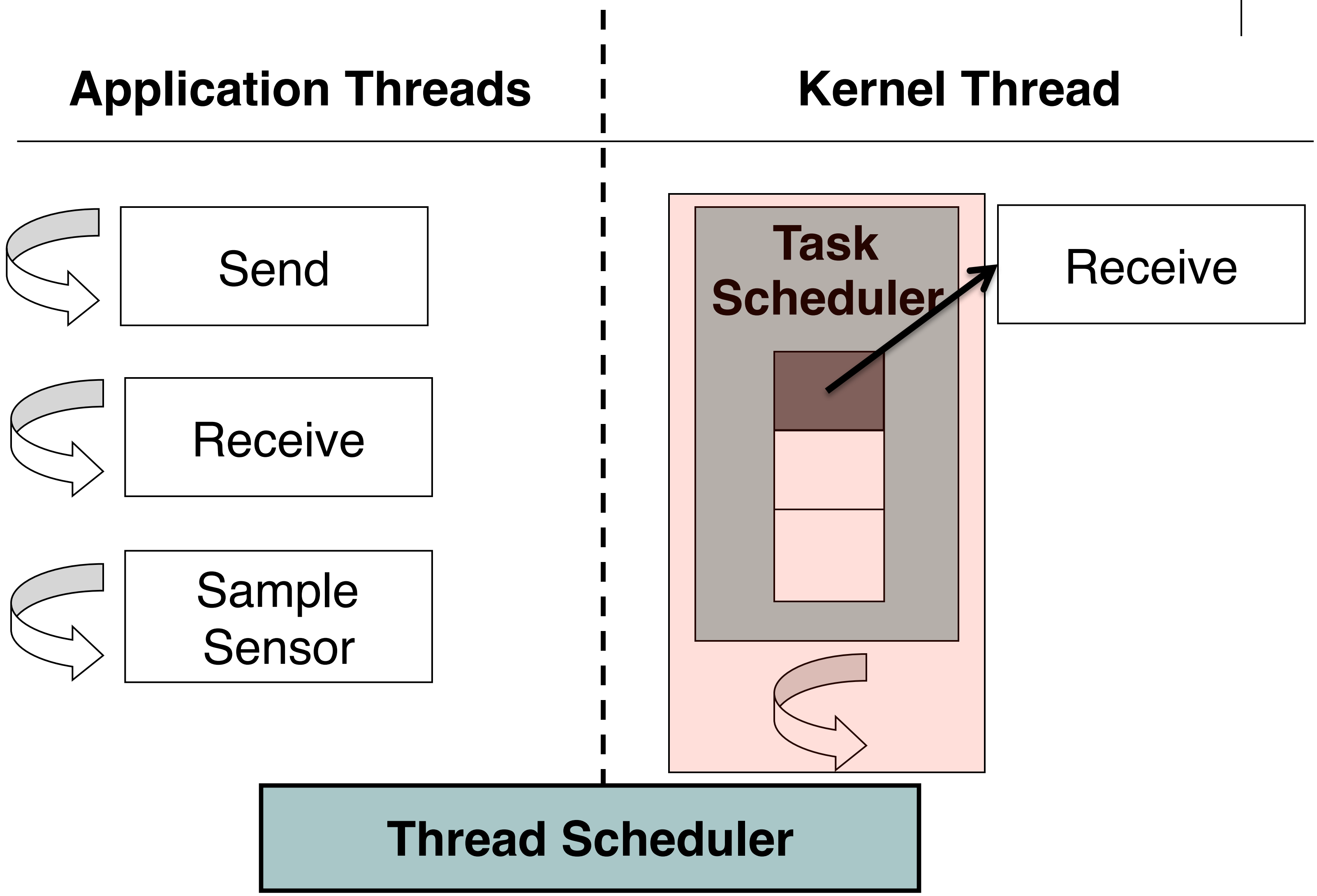

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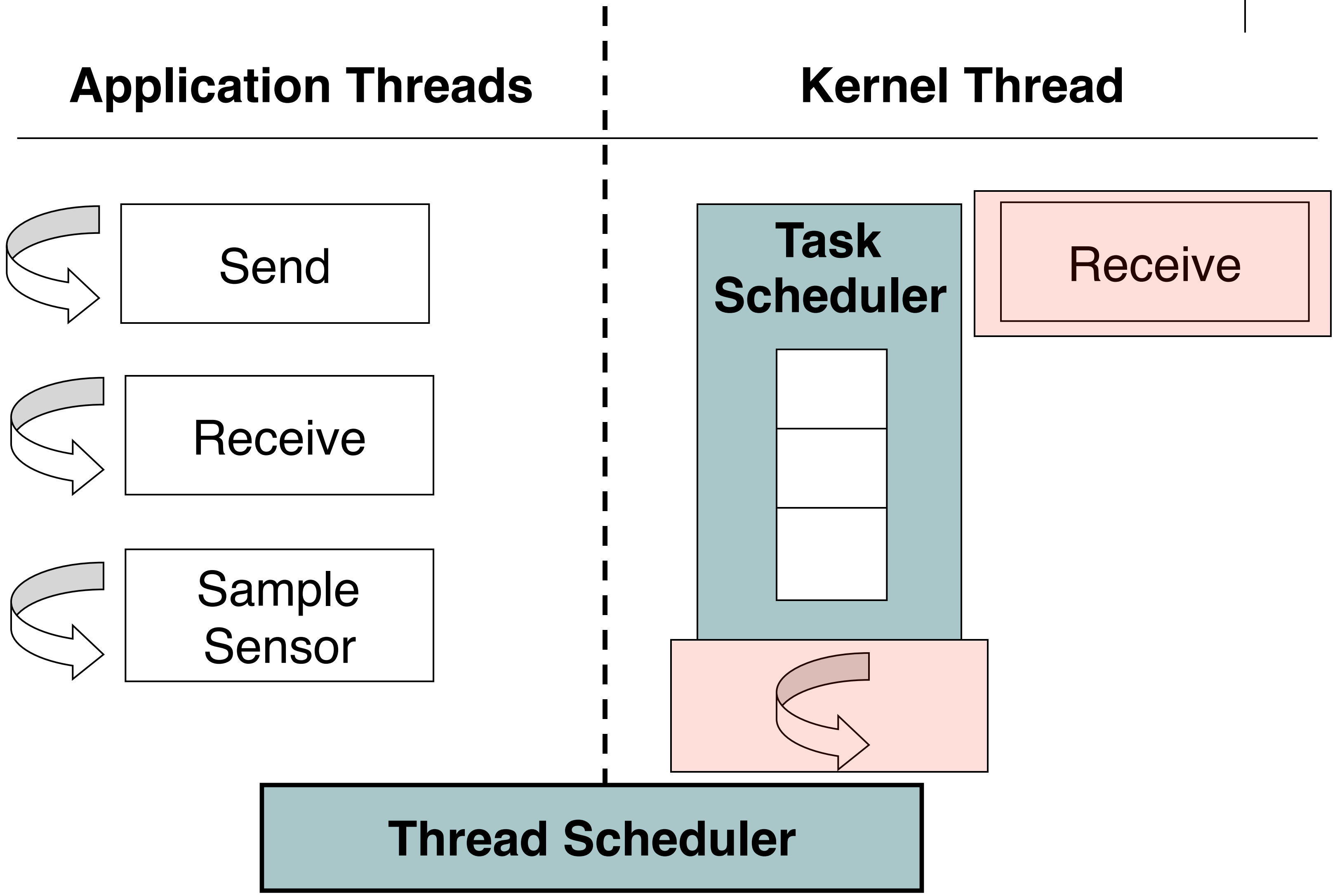

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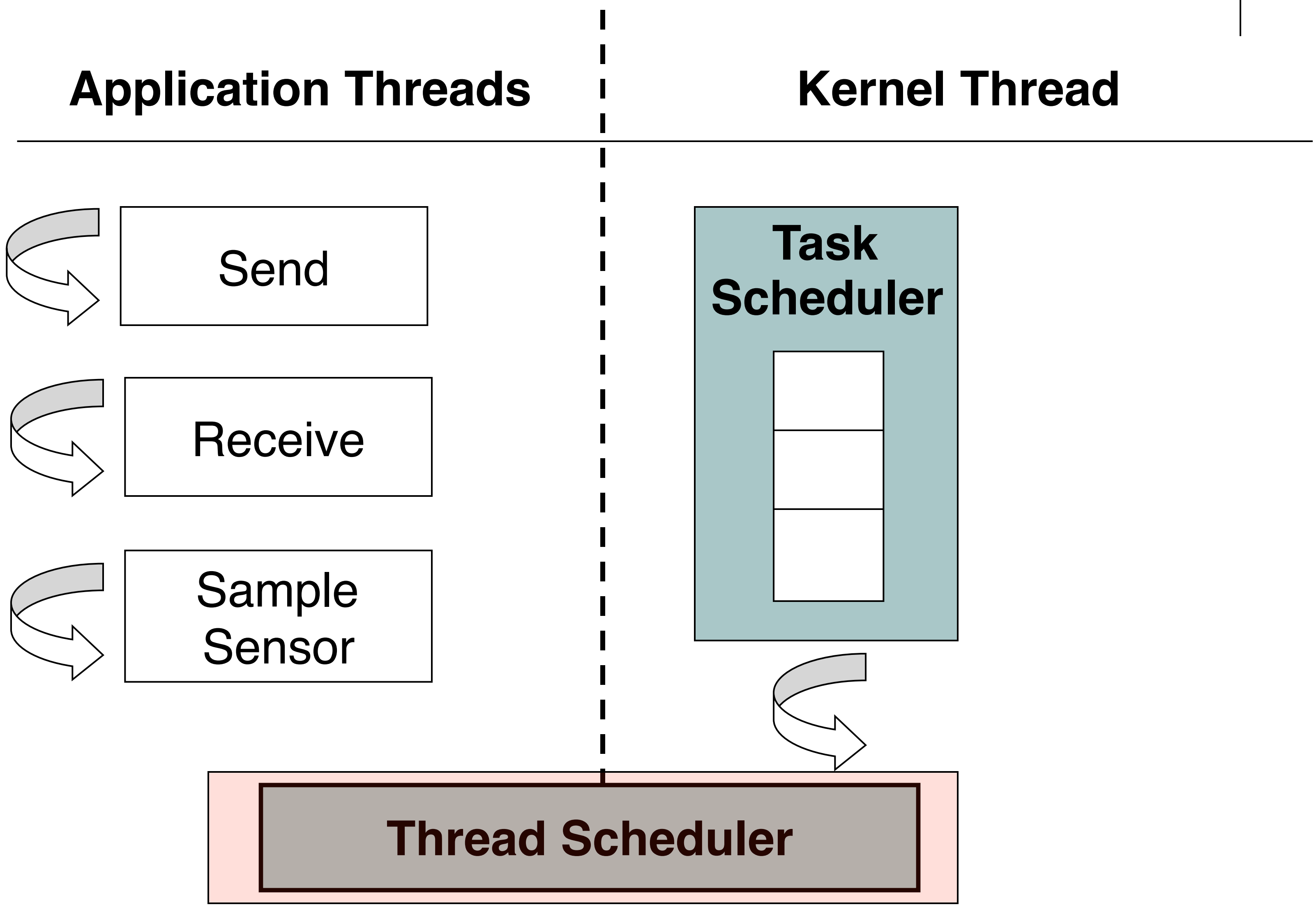

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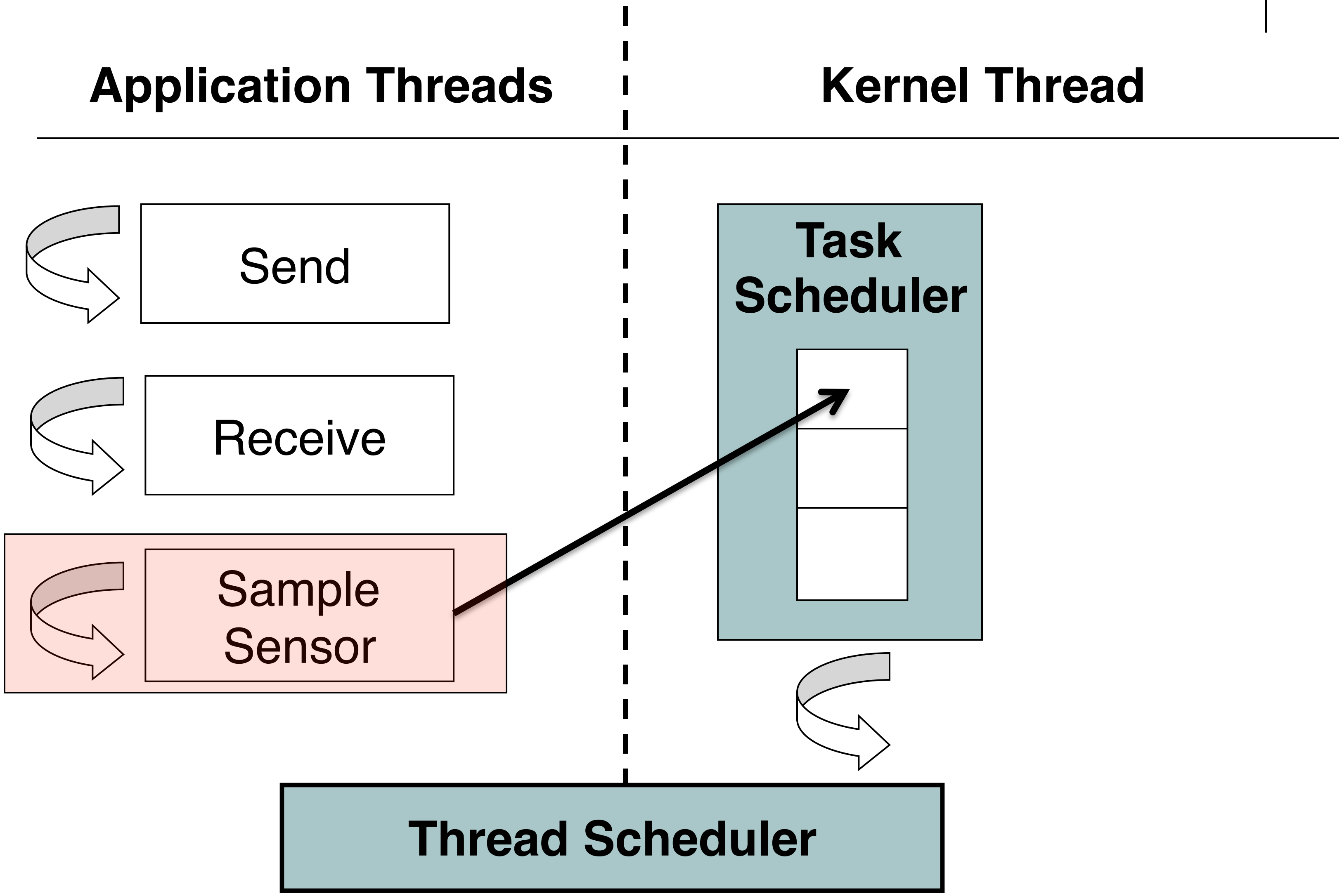

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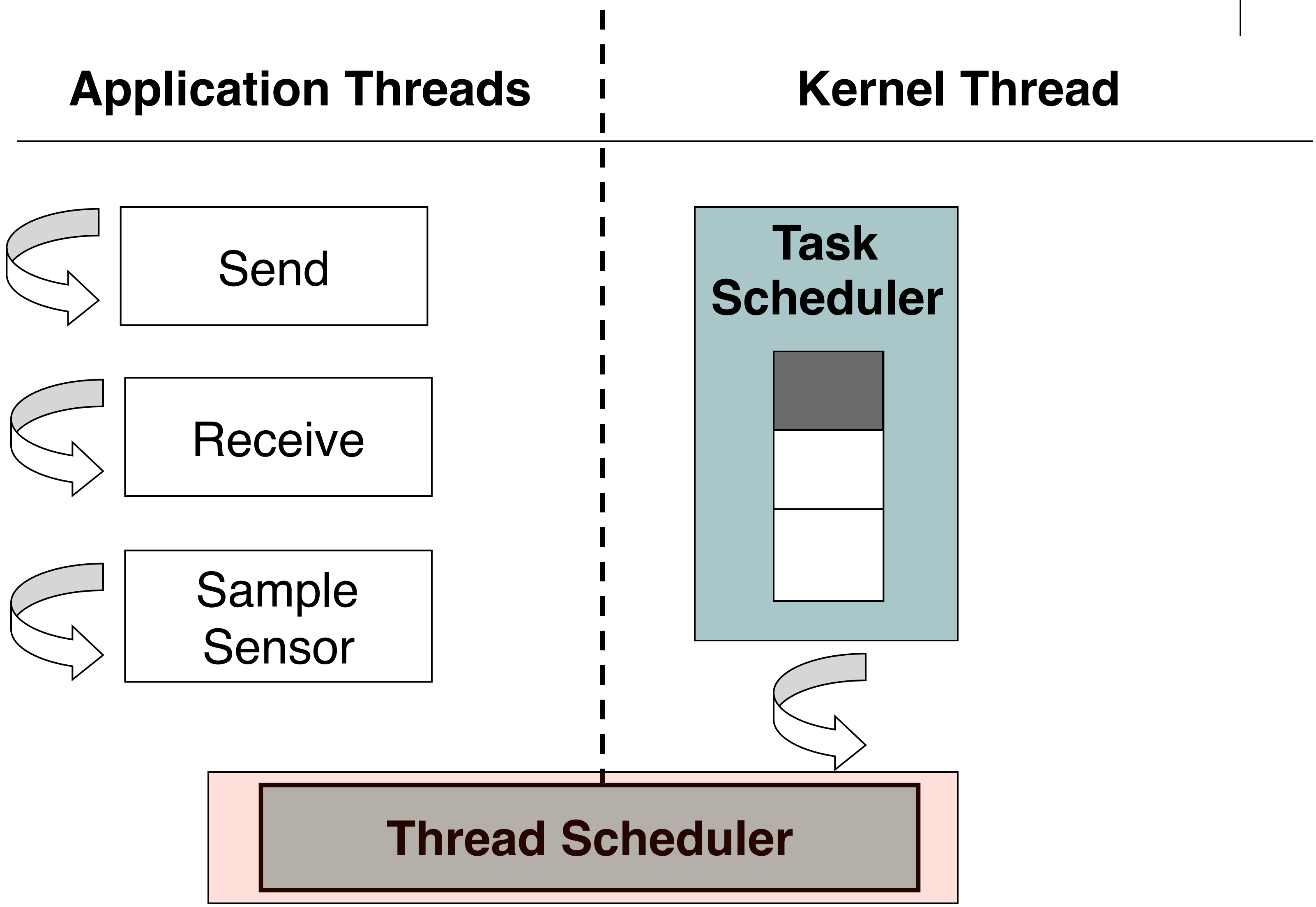

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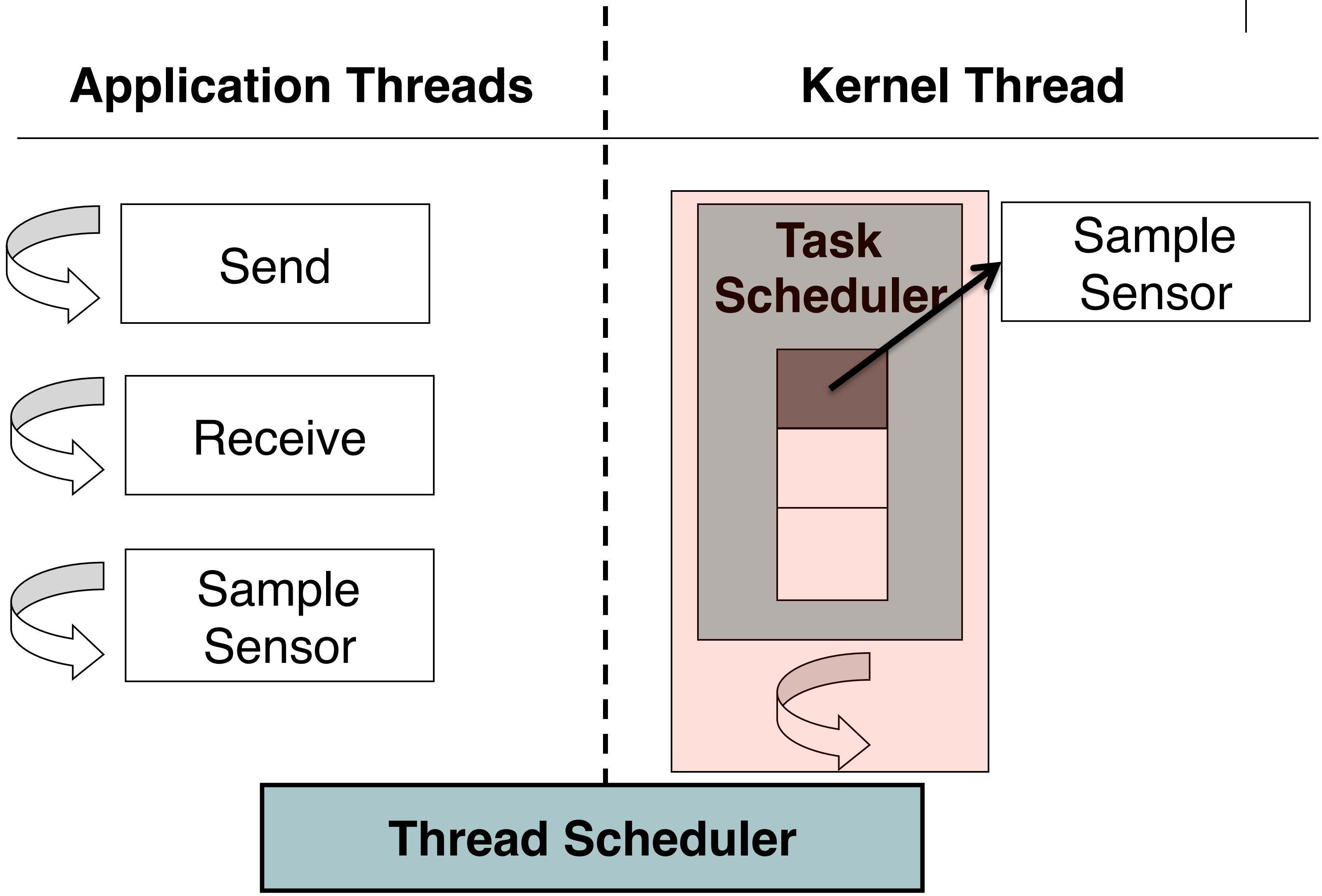

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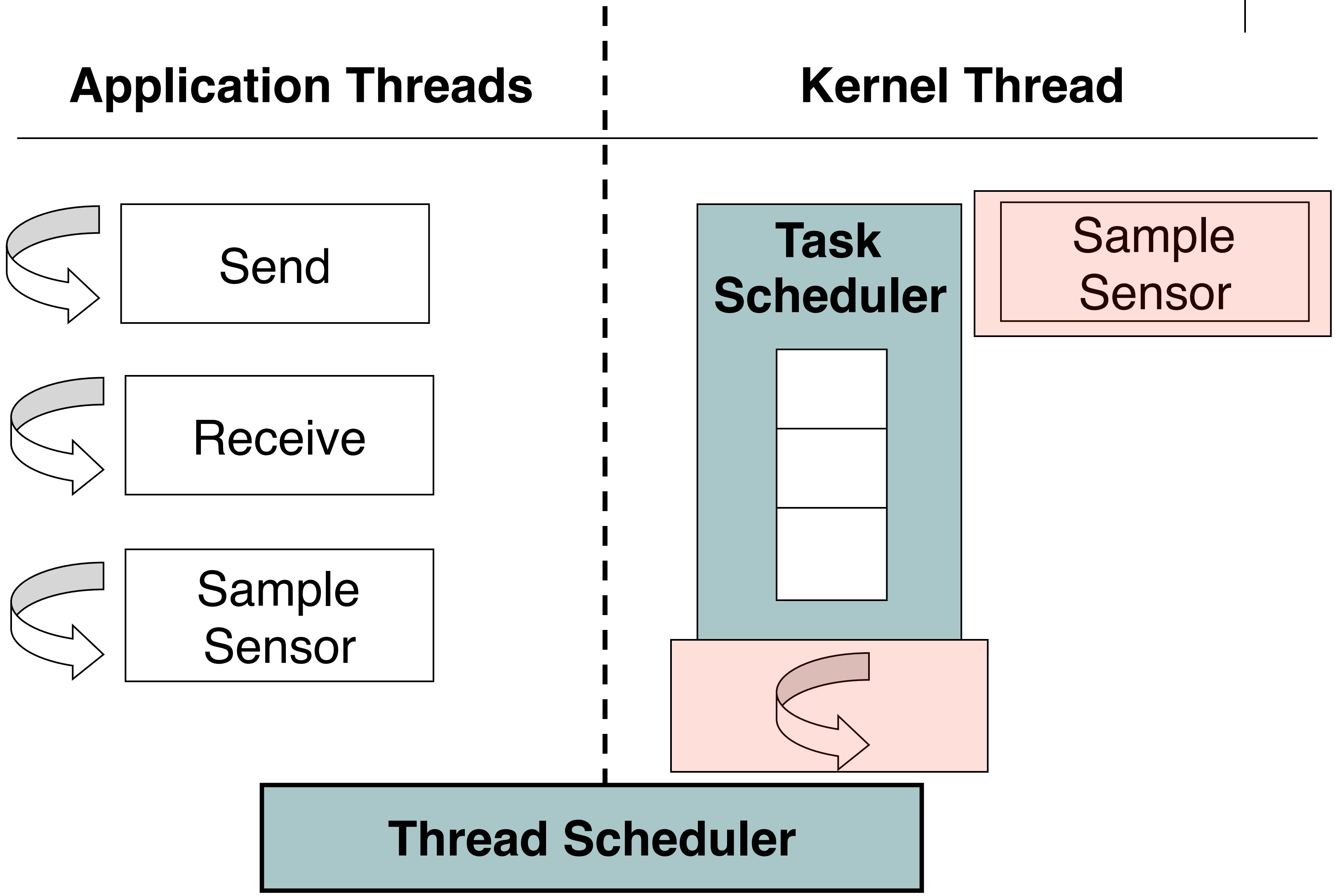

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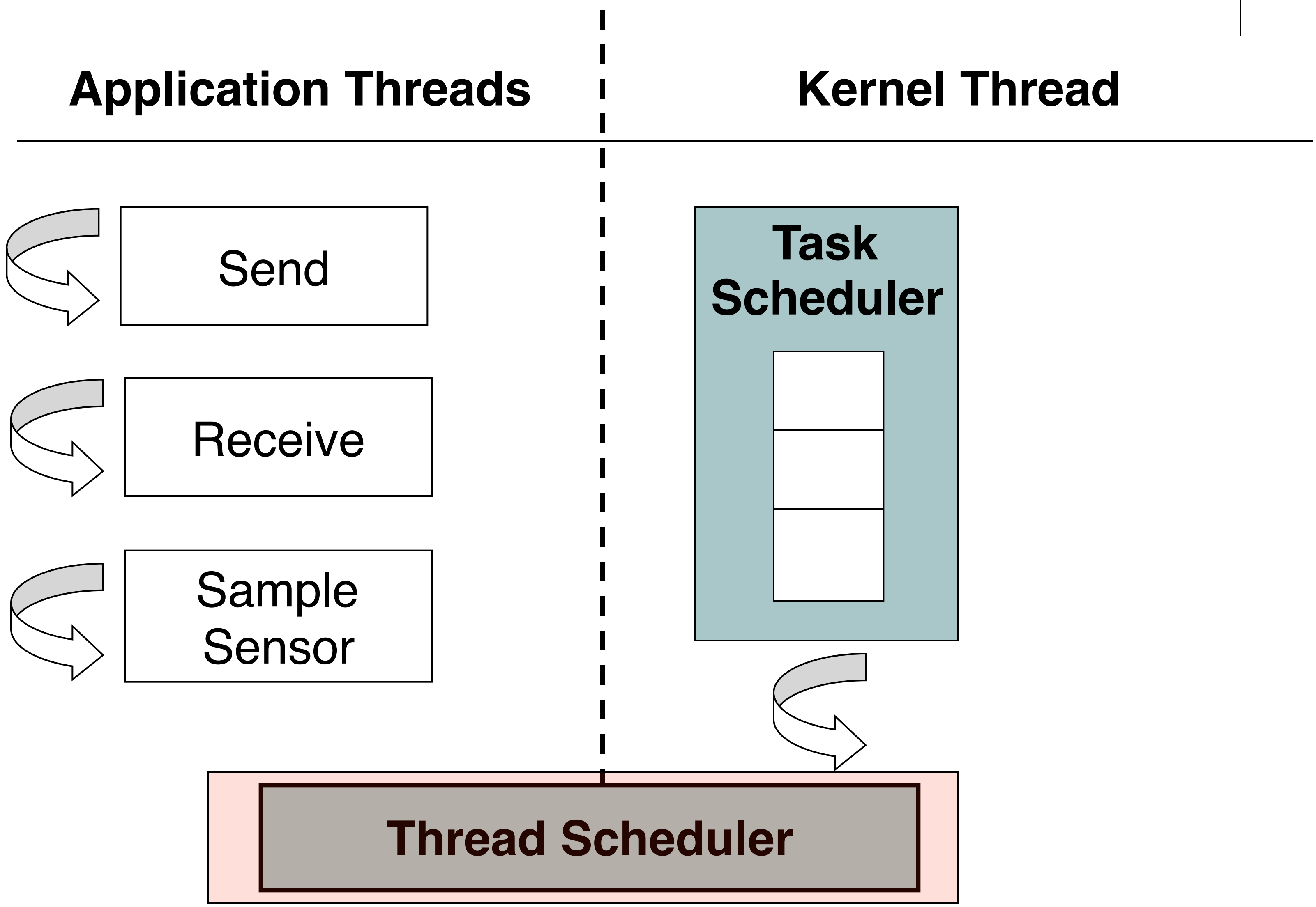

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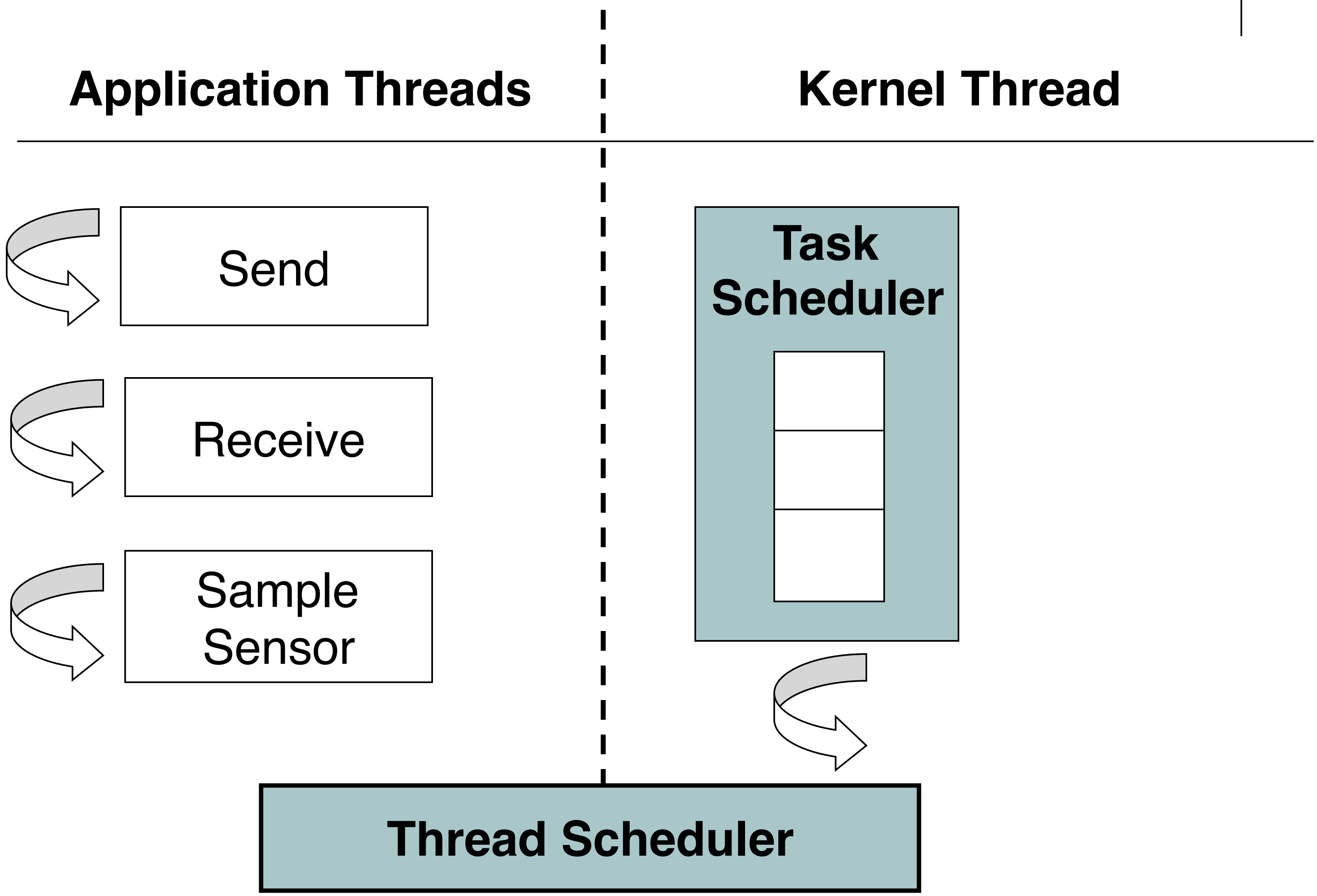

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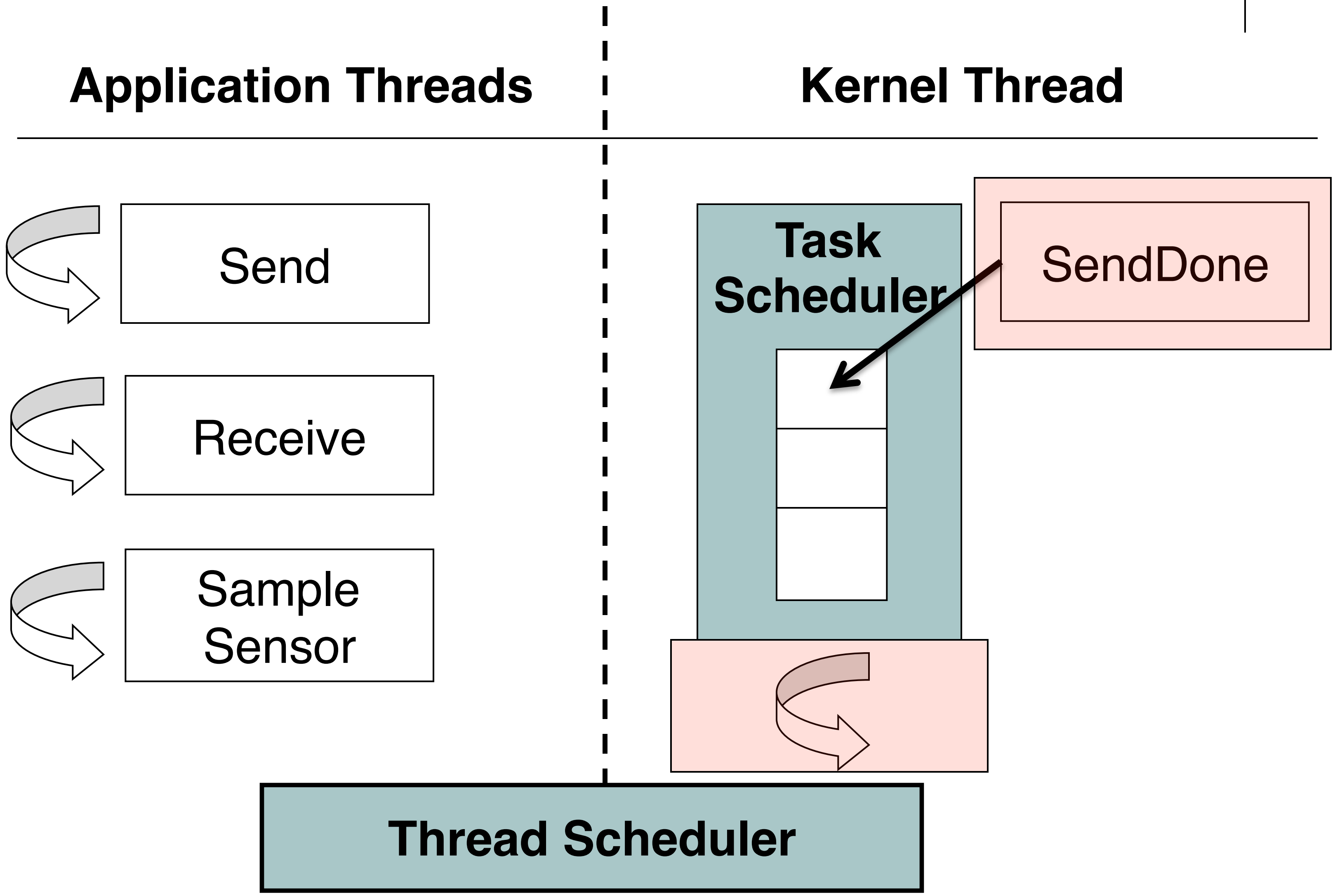

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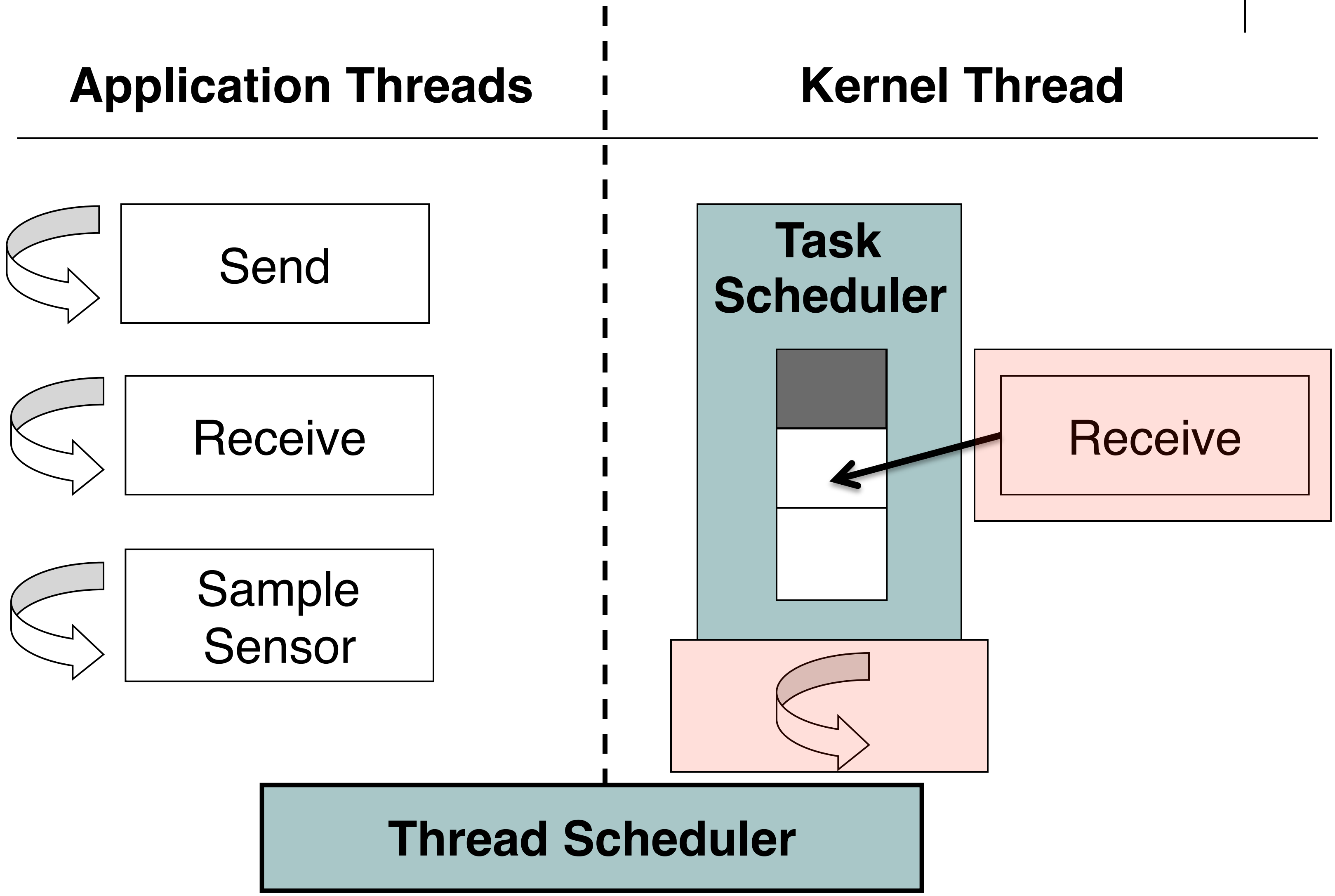

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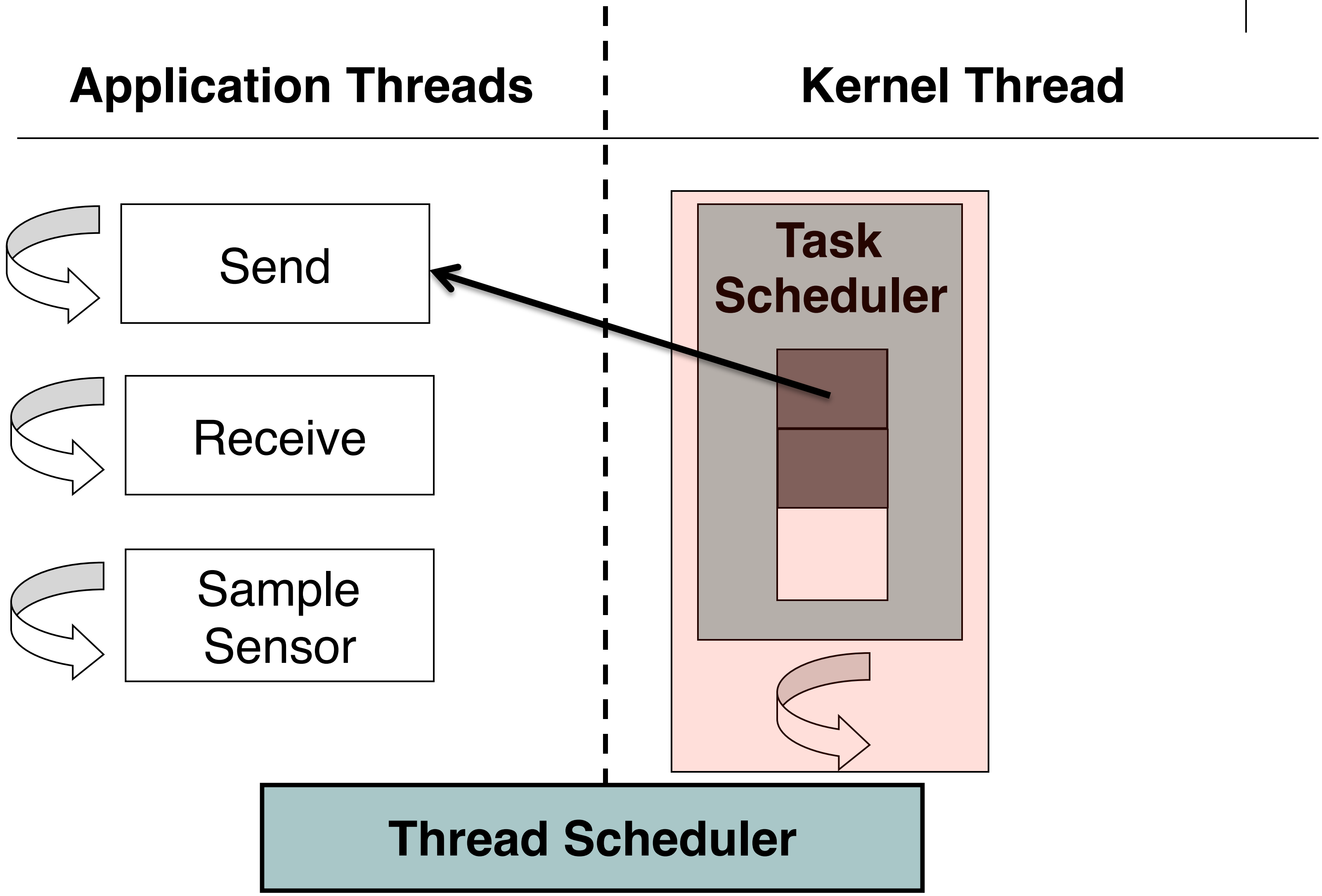

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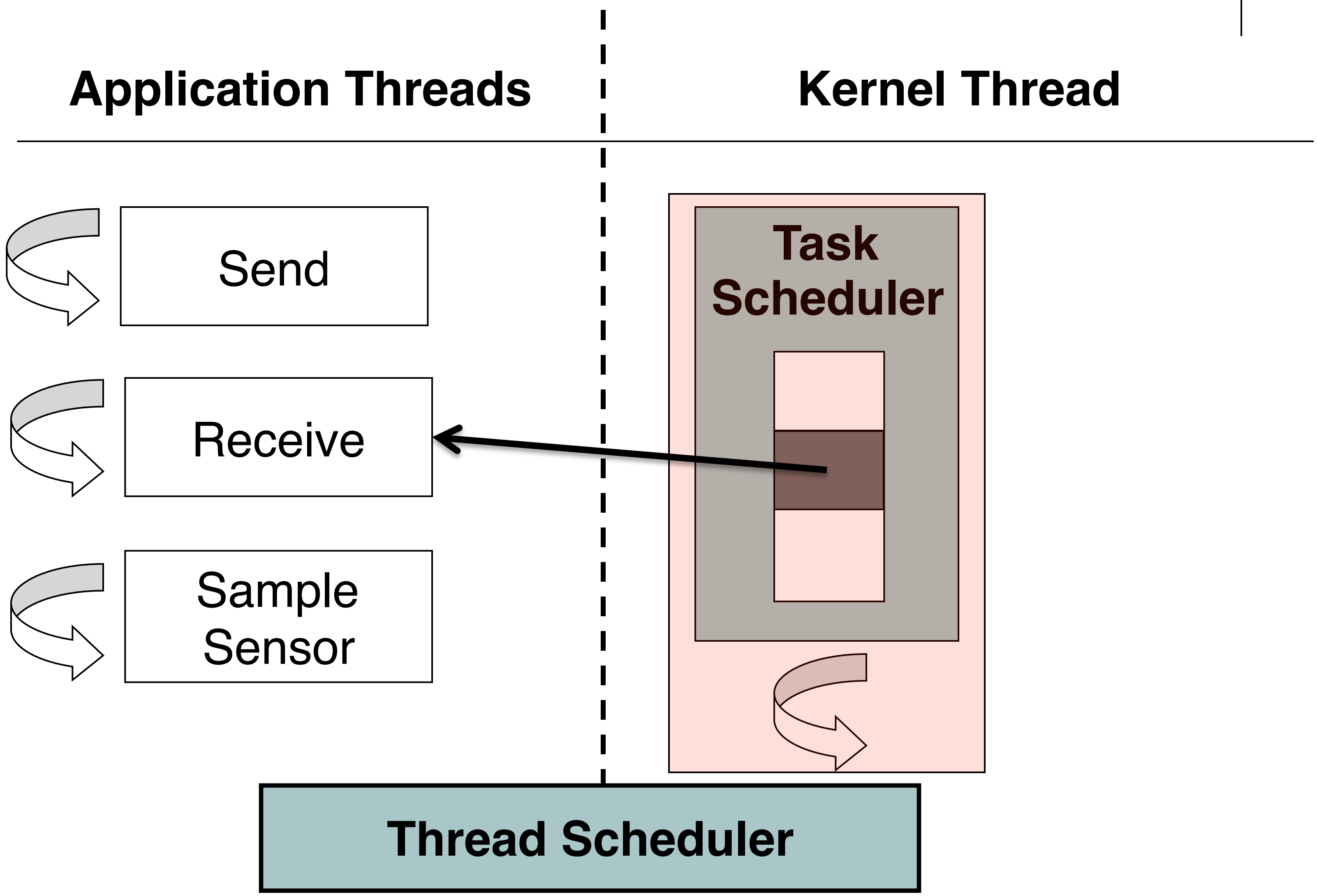

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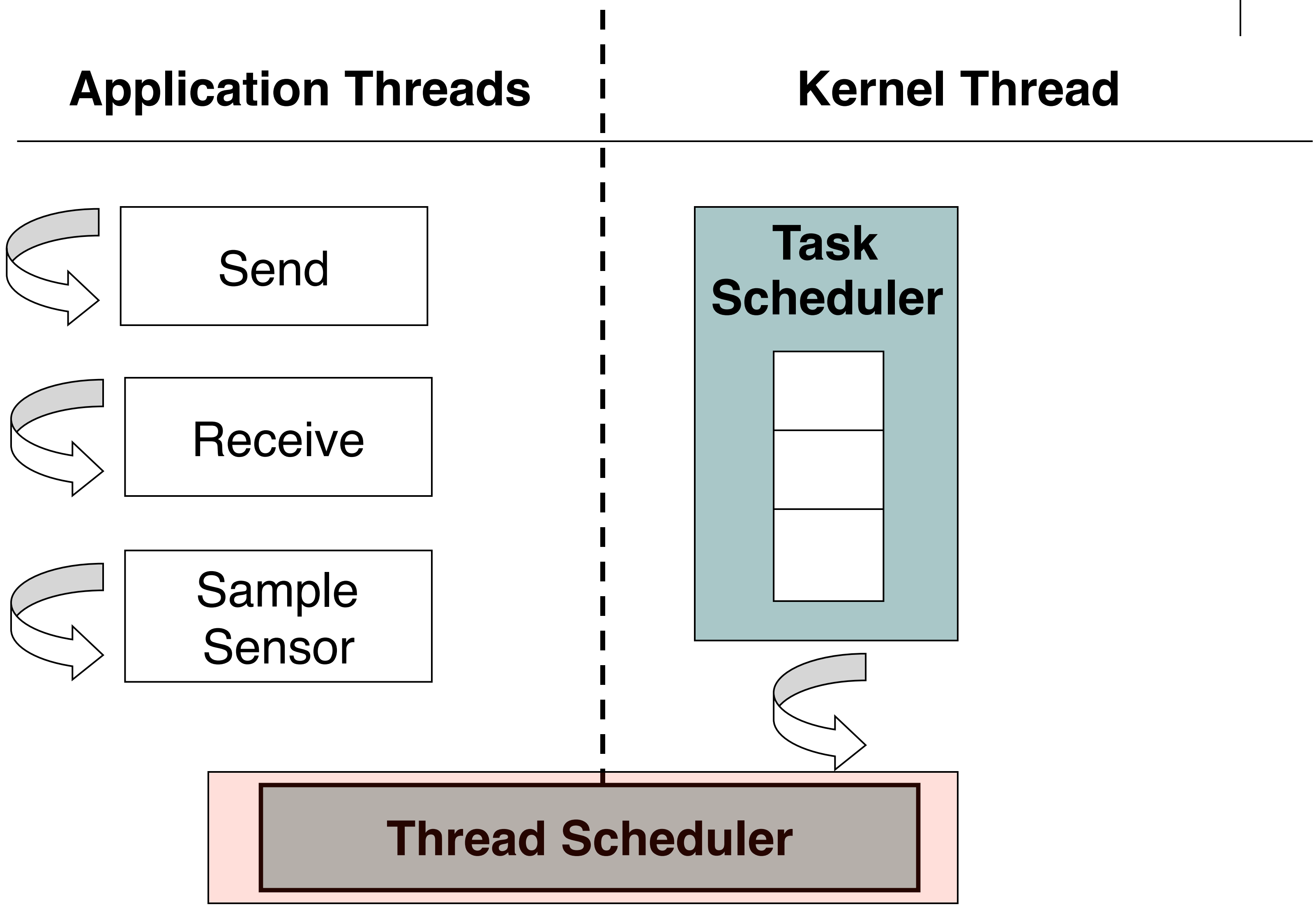

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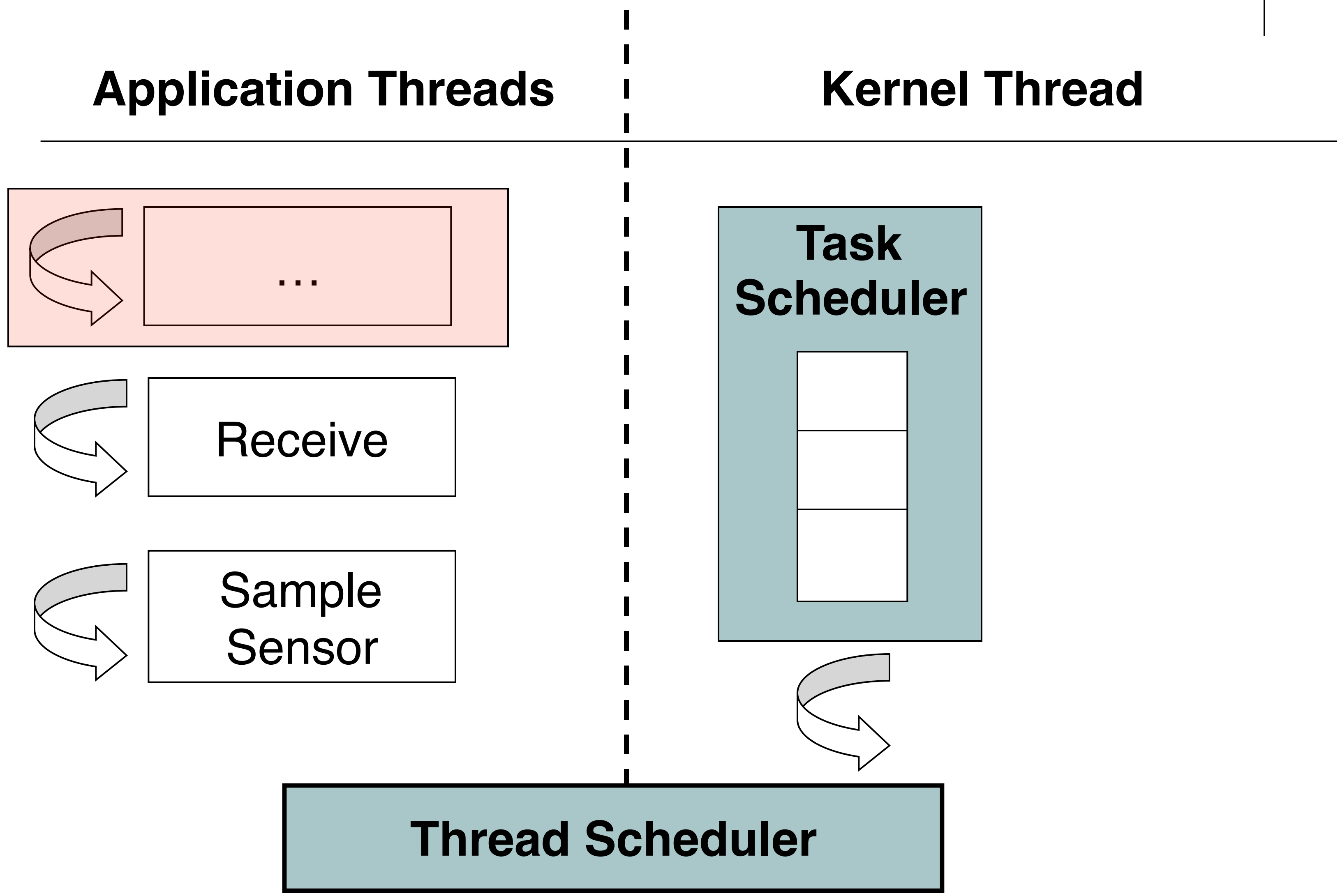

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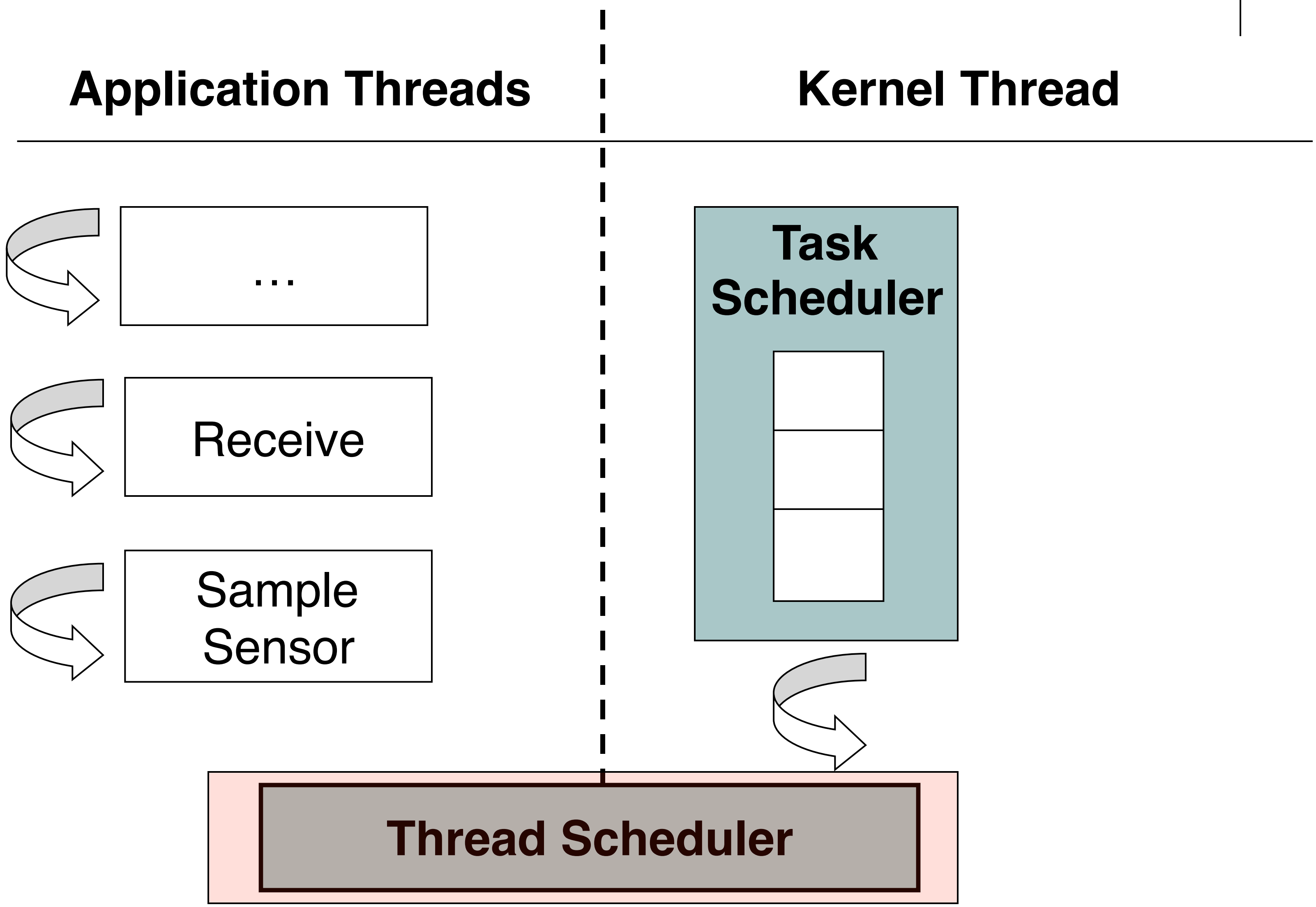

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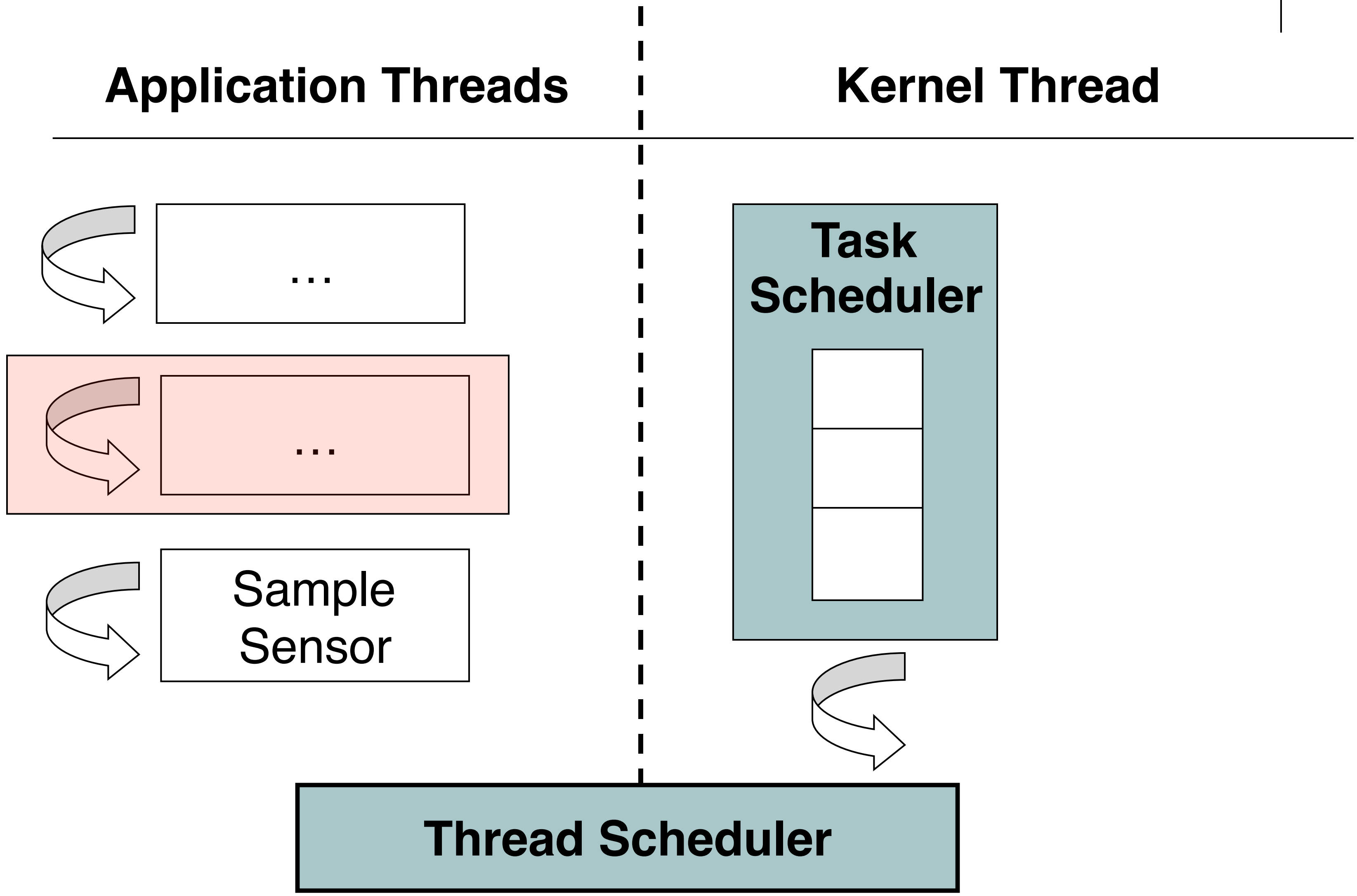

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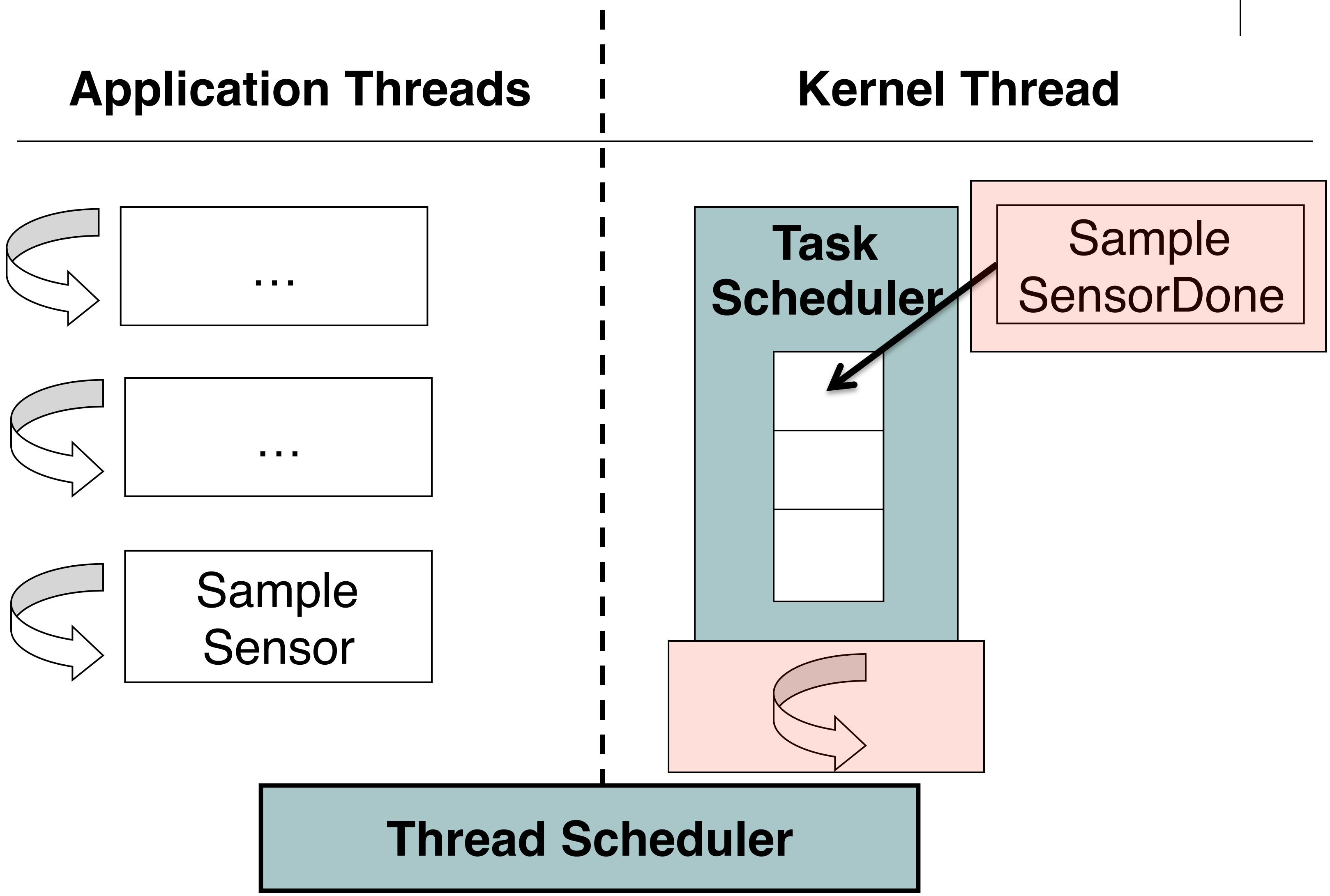

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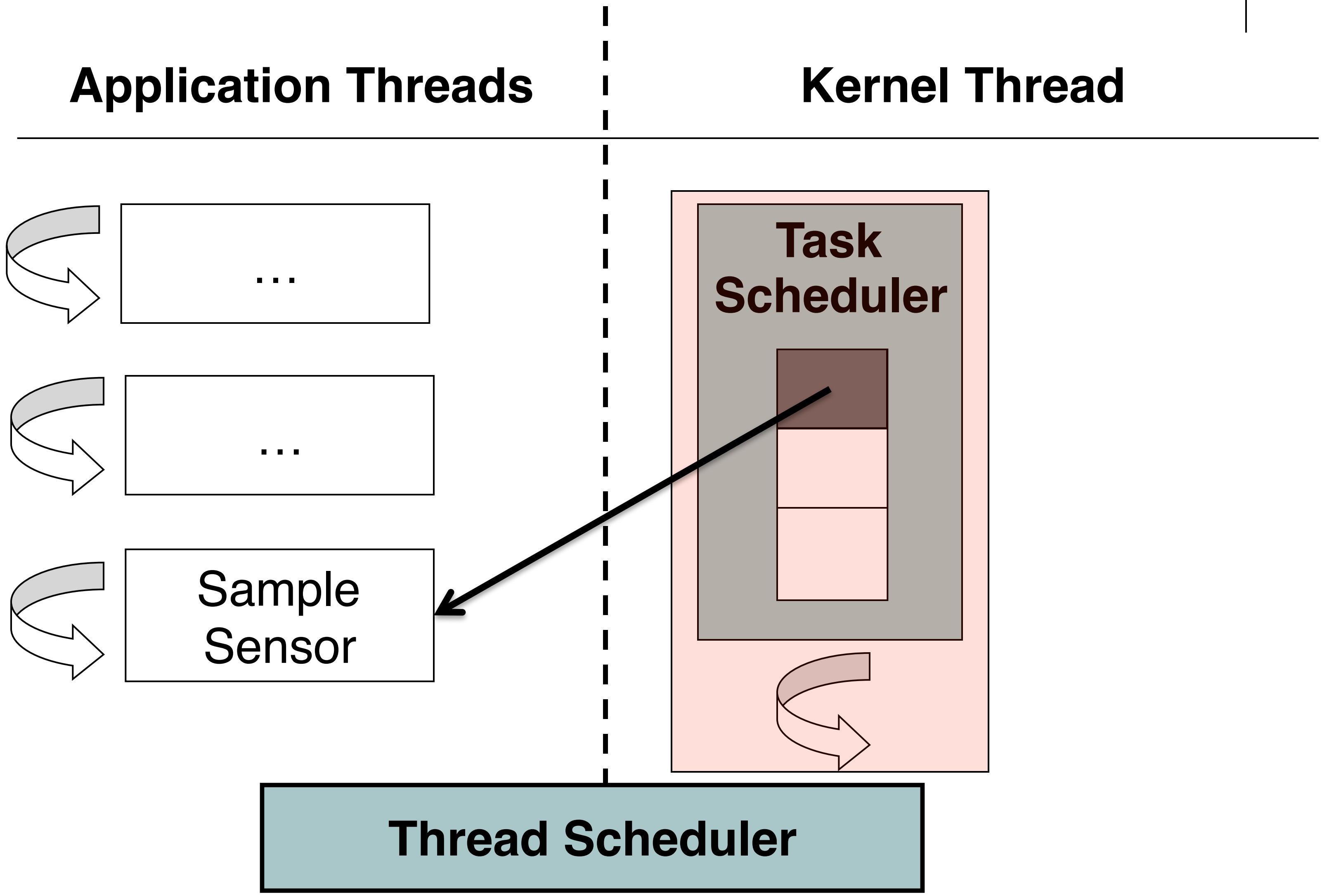

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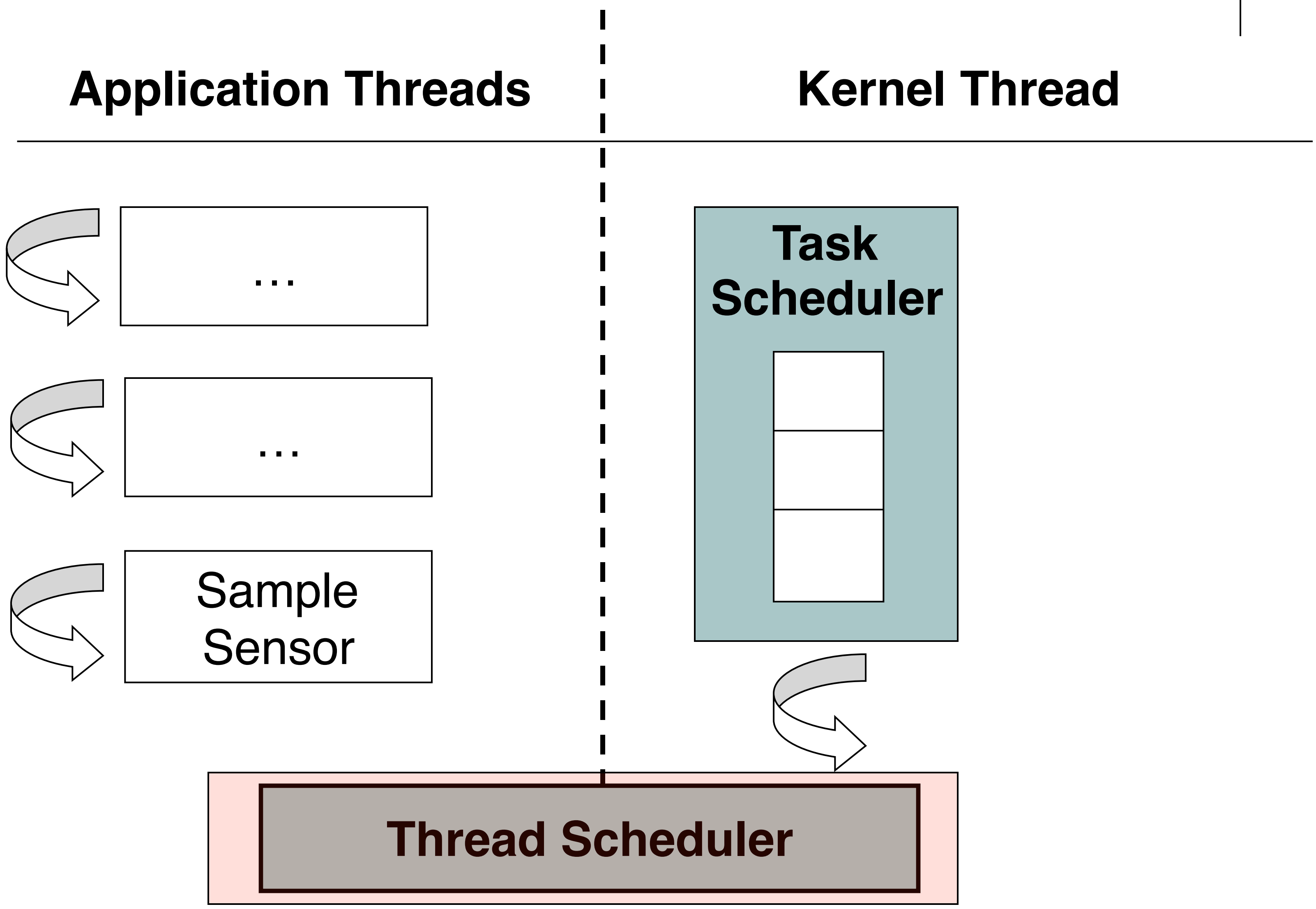

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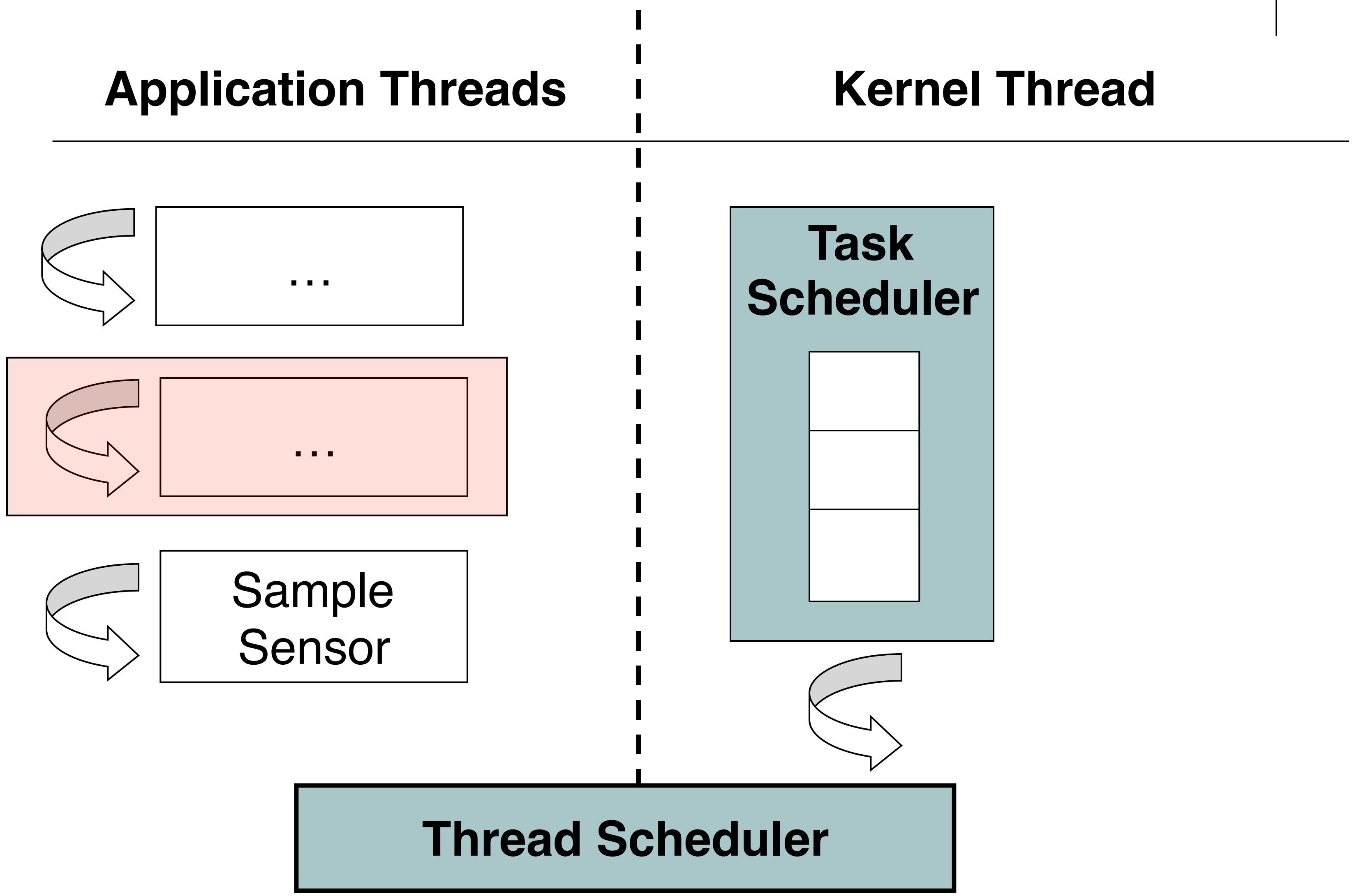

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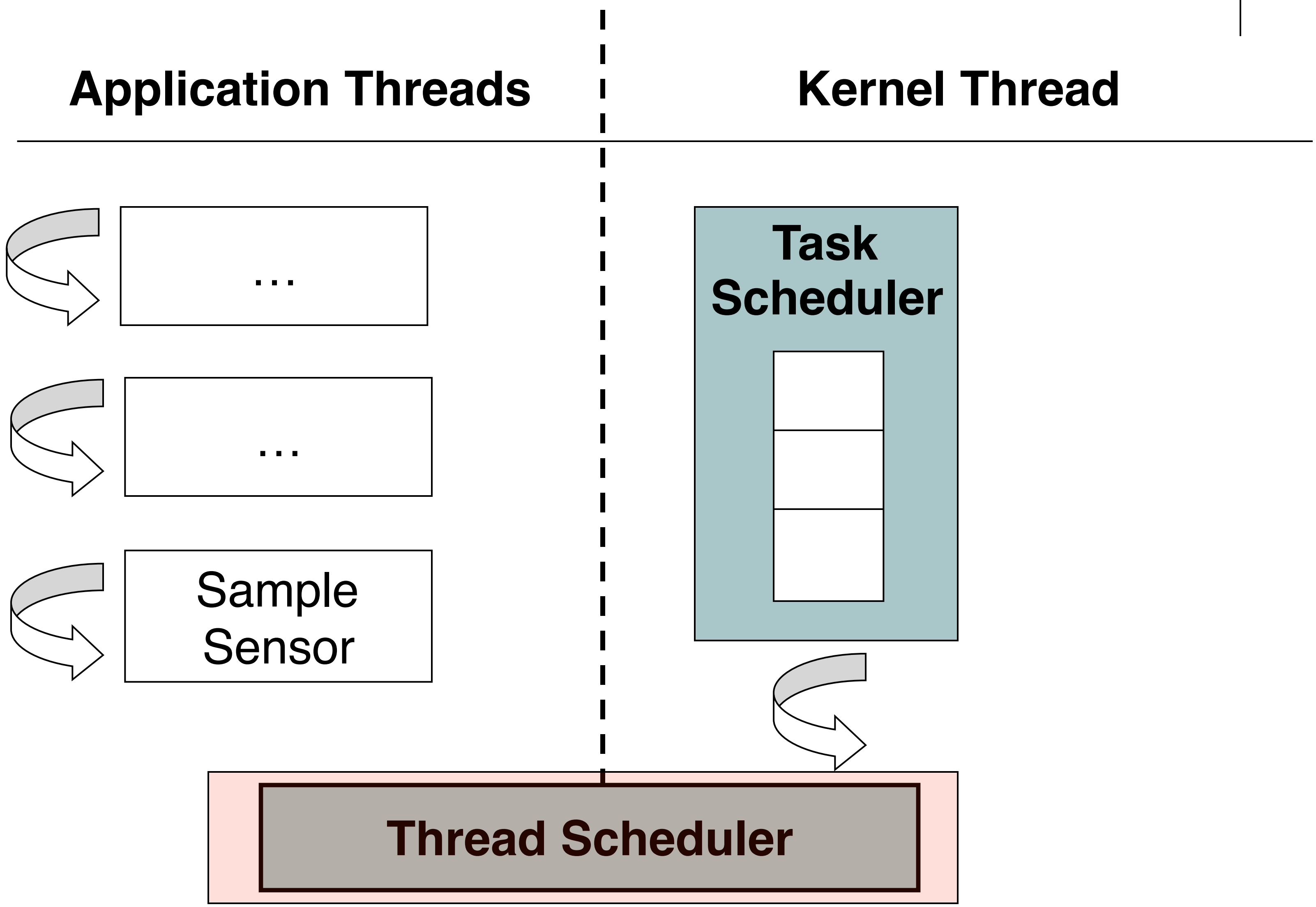

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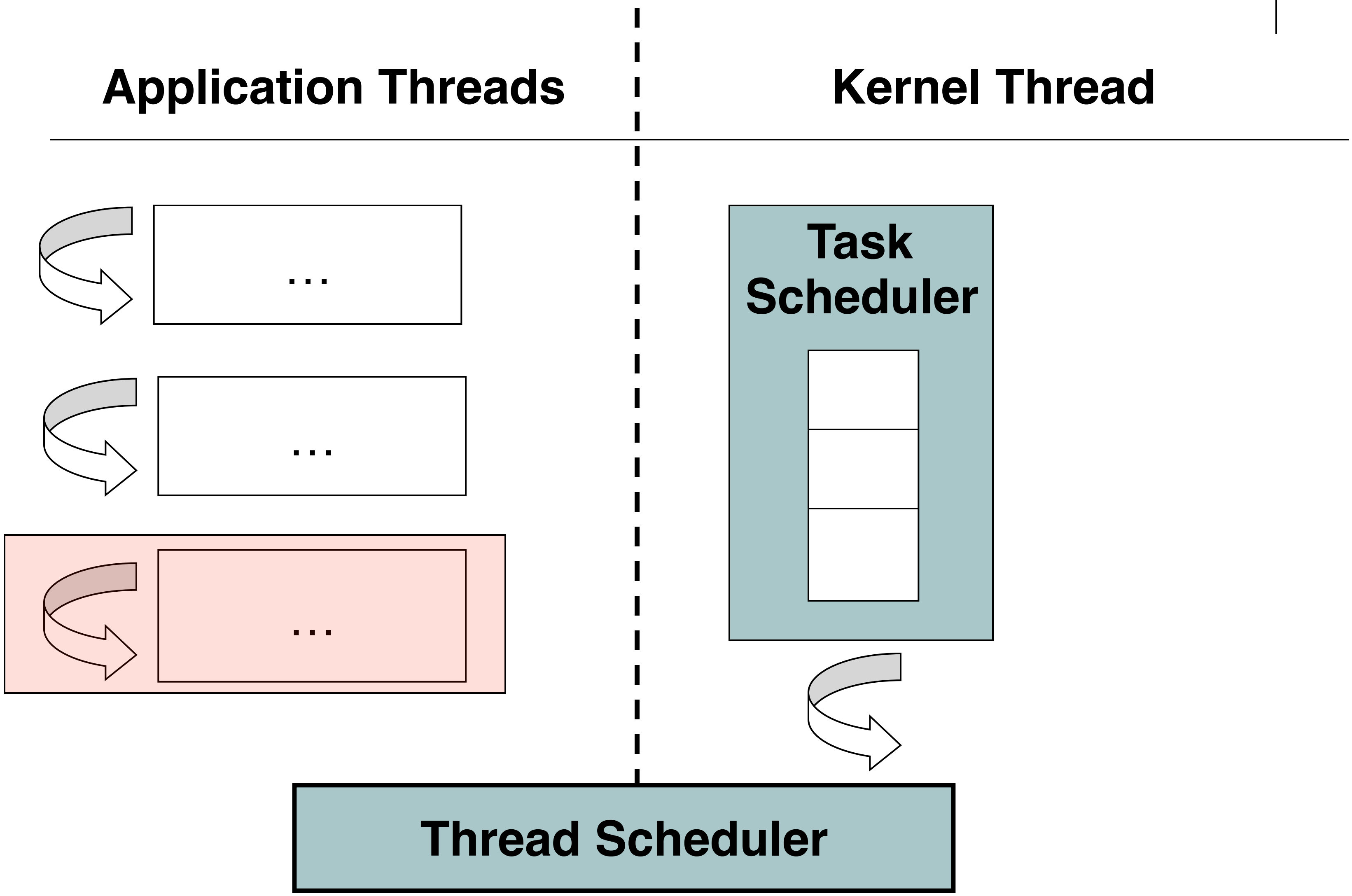

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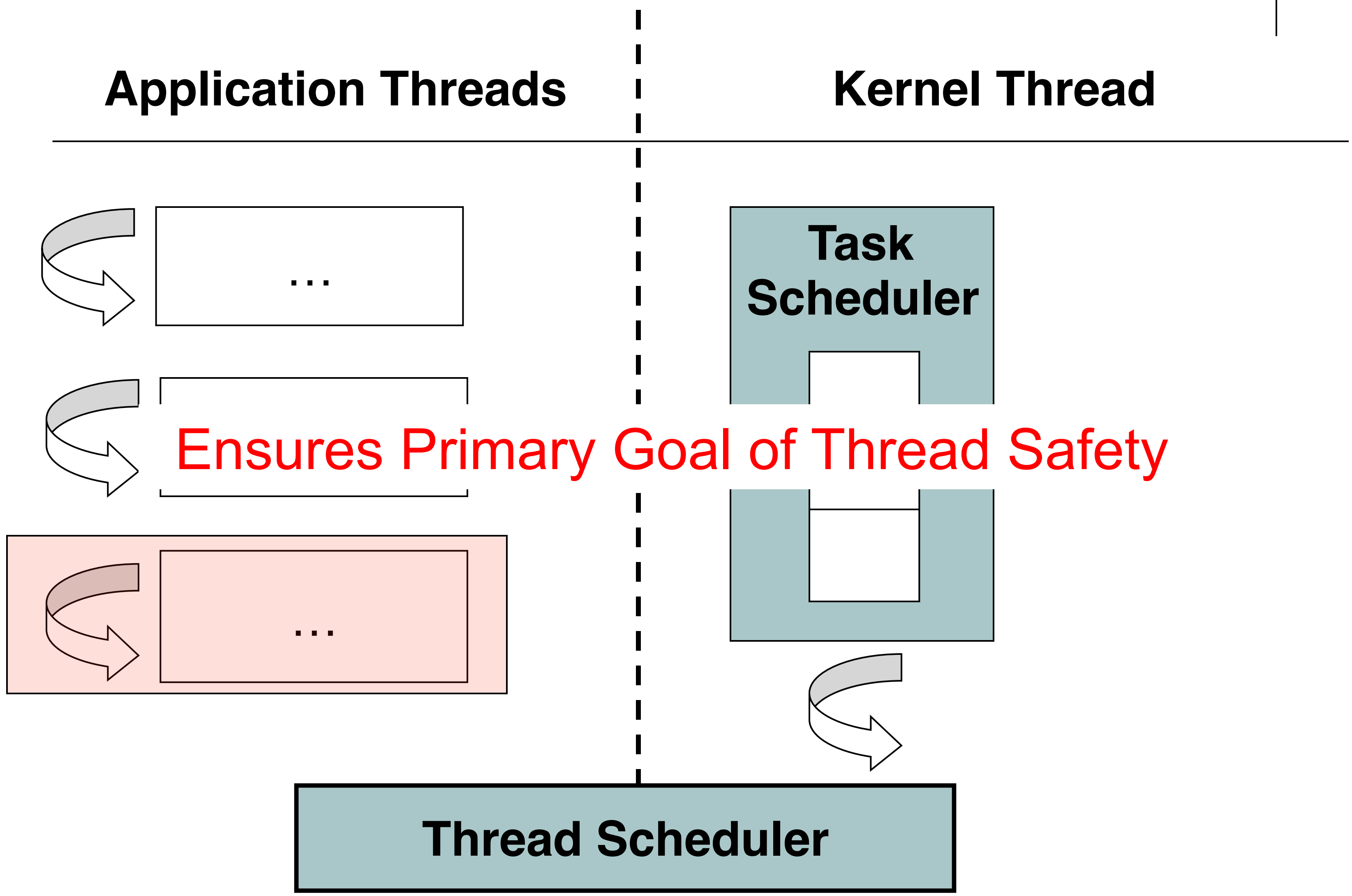

Modifications to TinyOS

- Limited to three small changes
  - Pre-amble in the boot sequence
    - Encapsulates TinyOS inside high priority kernel thread
  - Small change in the TinyOS task scheduler
    - Invokes the thread scheduler when TinyOS thread falls idle
  - Post-ambles in each interrupt handler
    - Ensures TinyOS thread woken up if interrupt handler posts tasks

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  - Post-ambles in each interrupt handler
    - Ensures TinyOS thread woken up if interrupt handler posts tasks

Ensures Primary Goal of Non-Invasiveness

Boot Sequence

<u>Standard TinyOS Boot</u>

<u>TOSThreads TinyOS Boot</u>

```
int main()
{
   /* Initialize the hardware */
   call Hardware_init();

   /* Initialize the software */
   call Software_init();

   /* Signal boot to the application */
   signal Boot.booted();

   /* Spin in the Scheduler */
   call Scheduler.taskLoop();
}
```

Boot Sequence

Standard TinyOS Boot

```
command void TinyOS.boot()
{
   /* Initialize the hardware */
   call Hardware_init();

   /* Initialize the software */
   call Software_init();

   /* Signal boot to the application */
   signal Boot.booted();

   /* Spin in the Scheduler */
   call Scheduler.taskLoop();
}
```

TOSThreads TinyOS Boot

```
int main()
{
   /* Encapsulate TinyOS inside a thread */
   call setup_TinyOS_in_kernel_thread();

   /* Boot up TinyOS*/
   call TinyOS.boot();
}
```

Task Scheduler

Standard TinyOS Task Scheduler

```
command void Scheduler.taskLoop() {
  for (;;) {
    uint8_t nextTask;
    atomic {
          while ((nextTask = popTask()) == NO_TASK))
          call McuSleep.sleep();
    }
    signal TaskBasic.runTask[nextTask]();
  }
}
```

TOSThreads TinyOS Task Scheduler

```
command void Scheduler.taskLoop() {
  for (;;) {
    uint8_t nextTask;
    atomic {
          while ((nextTask = popTask()) == NO_TASK)
          call ThreadScheduler.suspendThread(TOS_THREAD_ID);
    }
    signal TaskBasic.runTask[nextTask]();
  }
}
```

Interrupt Handlers

```
TOSH_SIGNAL(ADC_VECTOR) {
   signal SIGNAL_ADC_VECTOR.fired();
   atomic interruptCurrentThread();
  }
TOSH_SIGNAL(DACDMA_VECTOR) {
   signal SIGNAL_DACDMA_VECTOR.fired();
   atomic interruptCurrentThread();
  }
….
….
```

Interrupt Handlers

```
TOSH_SIGNAL(ADC_VECTOR) {
  signal SIGNAL_ADC_VECTOR.fired();
  atomic interruptCurrentThread();
 }
TOSH_SIGNAL(DACDMA_VECTOR) {
  signal SIGNAL_DACDMA_VECTOR.fired();
  atomic interruptCurrentThread();
 }
….
….
```

```
void interruptCurrentThread() {
  if (call TaskScheduler.hasTasks() ) {
    call ThreadScheduler.wakeupThread(TOS_THREAD_ID);
    call ThreadScheduler.interruptCurrentThread();
  }
}
```

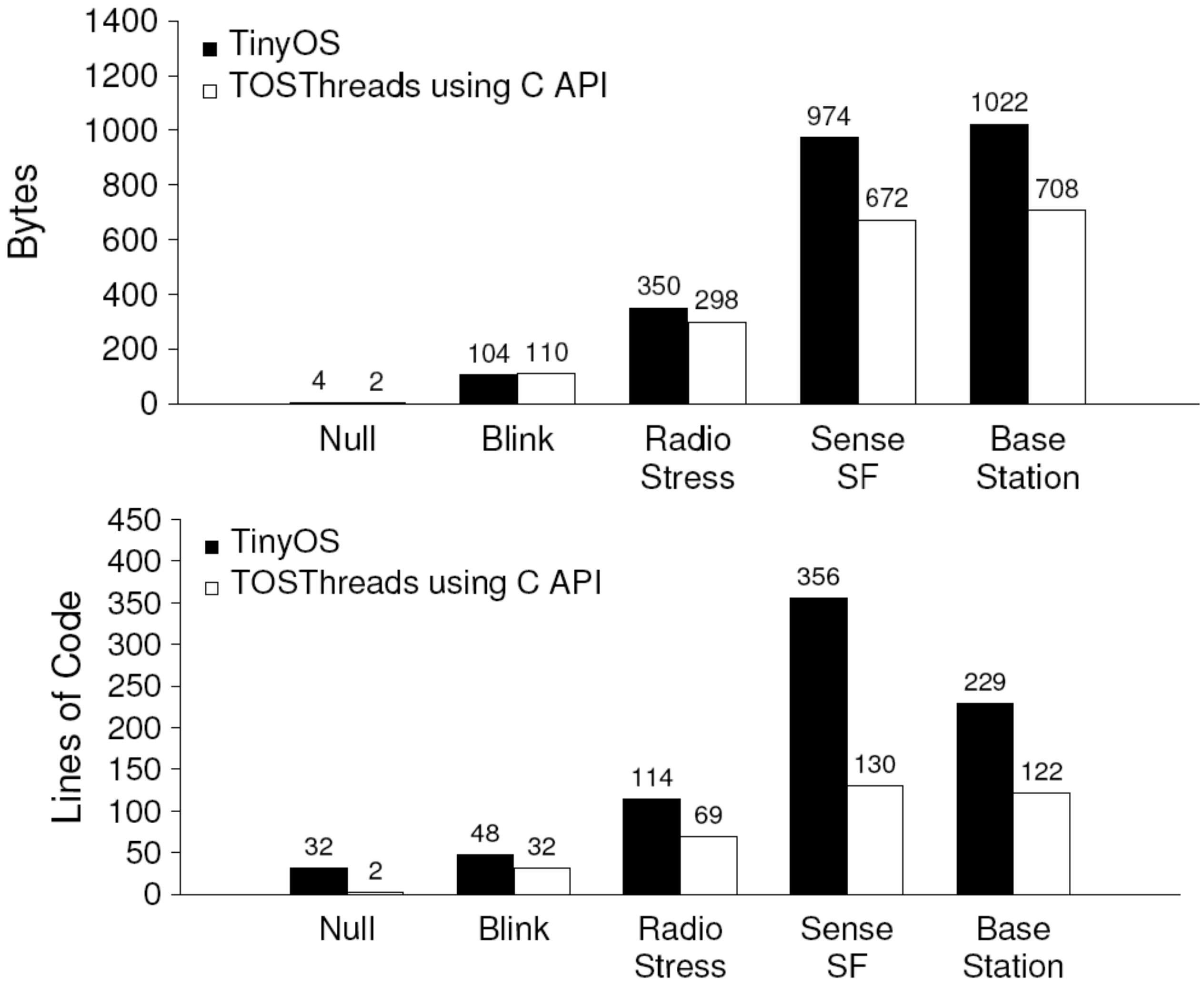
Outline

- The Challenge of Preemption
- TOSThreads Architecture
- **Interesting Results**
- Conclusion

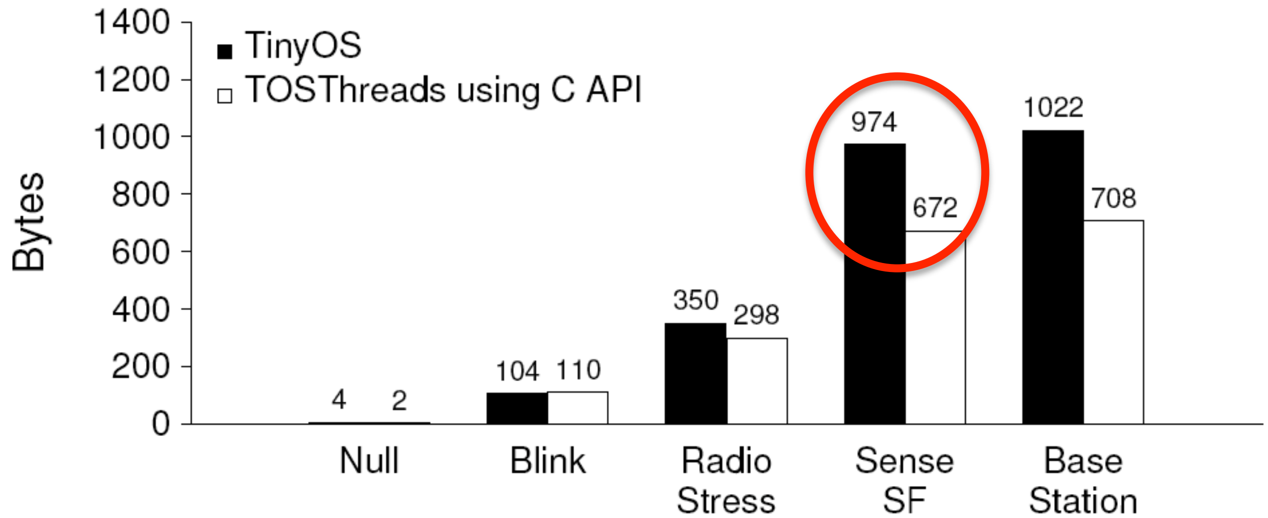
Microbenchmarks

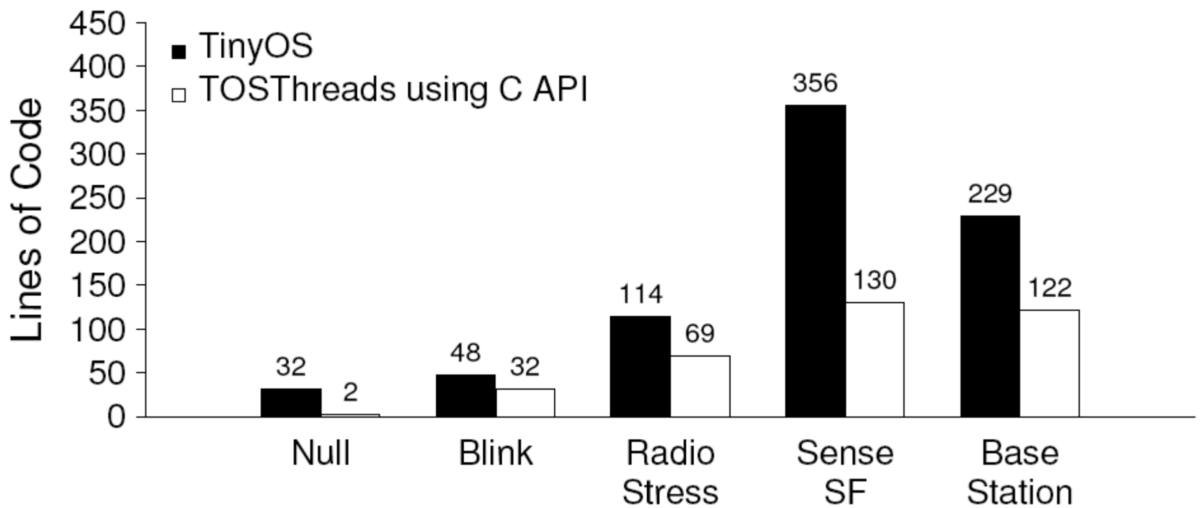
- Overhead of thread operations
  - Less than 1% on Sense-Store-Forward application
- Linking and loading relatively cheap
  - TinyLD: RAM 100 bytes, ROM 800 bytes
  - 100 ms loading time for sense-store-forward
- Major costs include
  - Extra RAM needed for per thread stacks
  - ROM usage of thread scheduler and API wrappers

Application Comparison

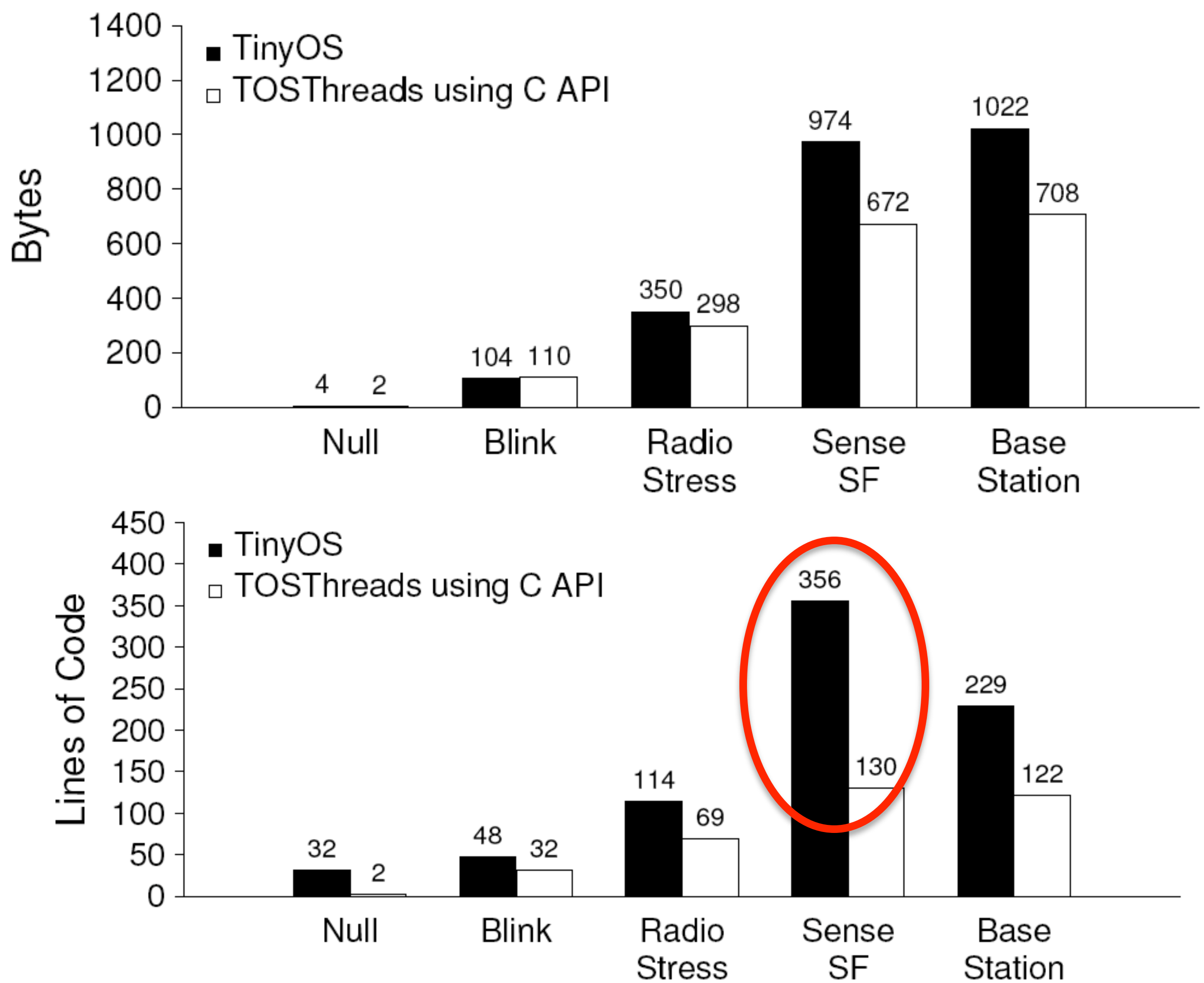


Application Comparison



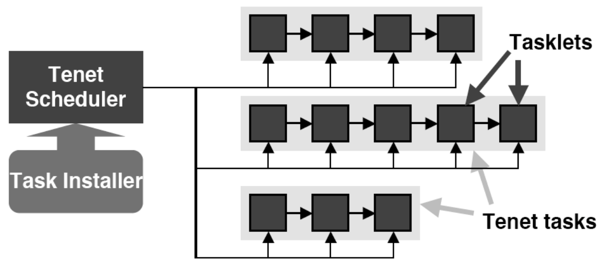


Application Comparison



Reimplementation of Tenet

- Reimplementation of Tenet using TOSThreads
  - Original



  - Tenet Tasks composed of series of static run-to-completion TinyOS tasks

Reimplementation of Tenet

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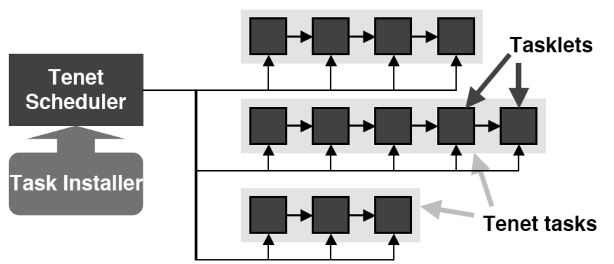
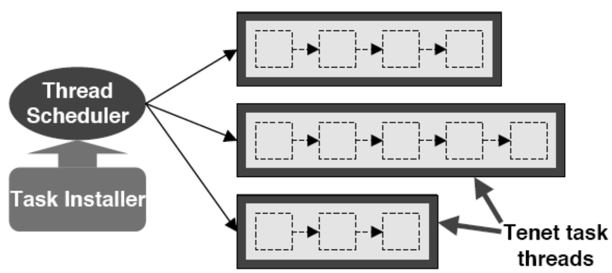


  - Tenet Tasks composed of series of static run-to-completion TinyOS tasks
  - Tenet-T



  - Tenet Tasks implemented as preemptive threads, composed of static code blocks.

Reimplementation of Tenet

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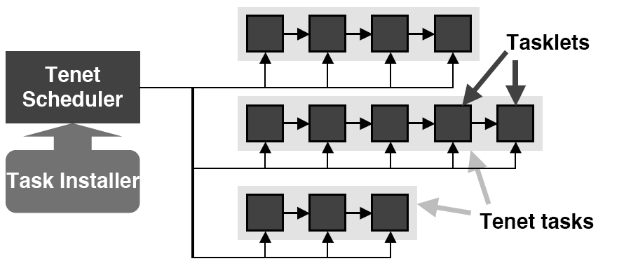

  - Tenet Tasks composed of series of static run-to-completion TinyOS tasks
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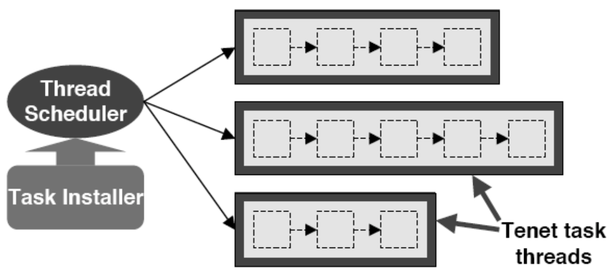
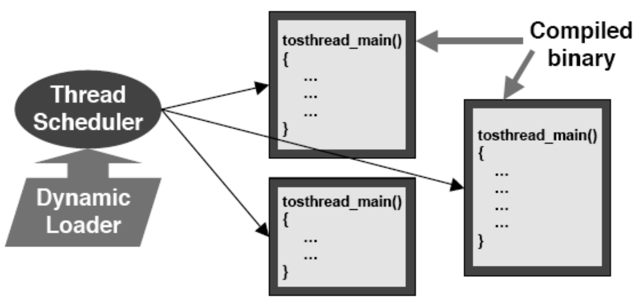
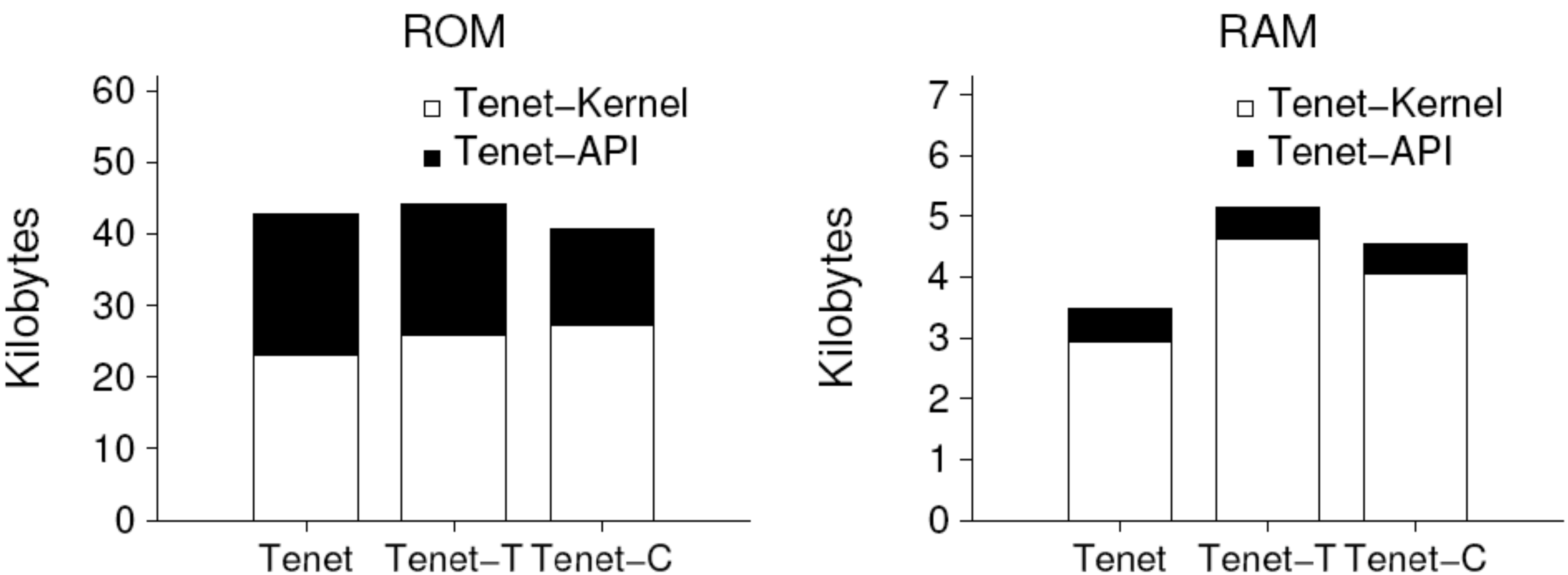


  - Tenet Tasks implemented as preemptive threads, composed of static code blocks.
  - Tenet-C

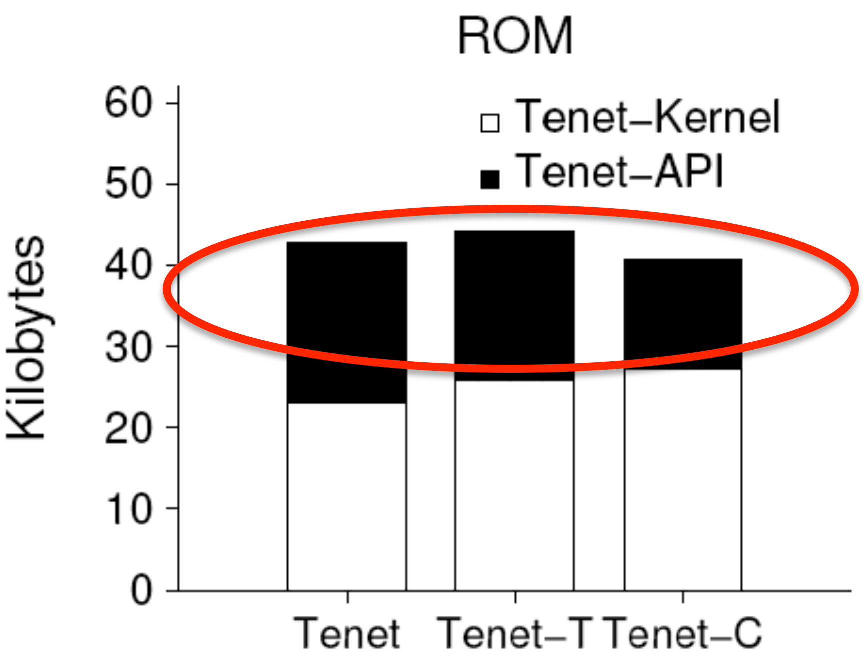


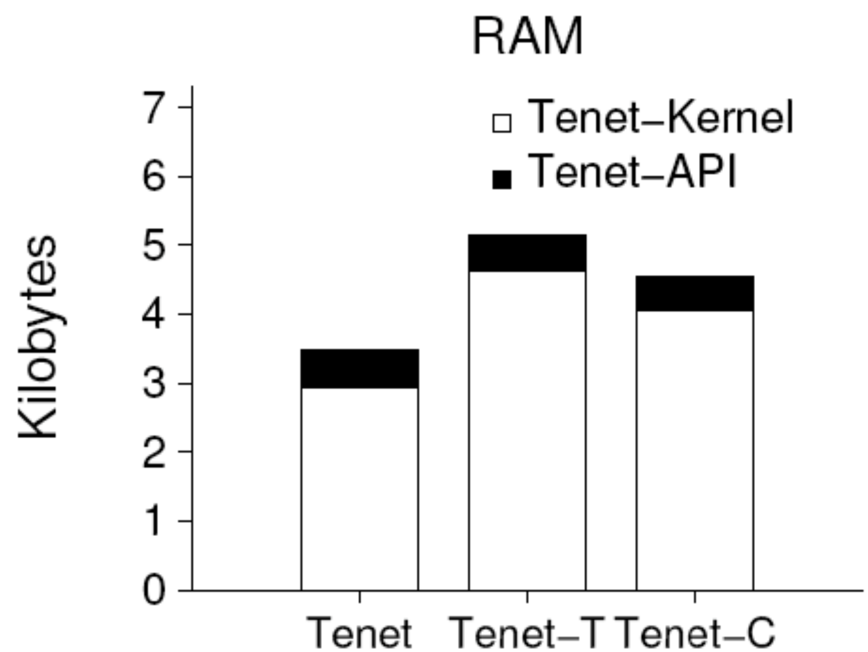
  - Tenet Tasks implemented as dynamically loadable preemptive threads with arbitrary code blocks

Reimplementation of Tenet



Reimplementation of Tenet





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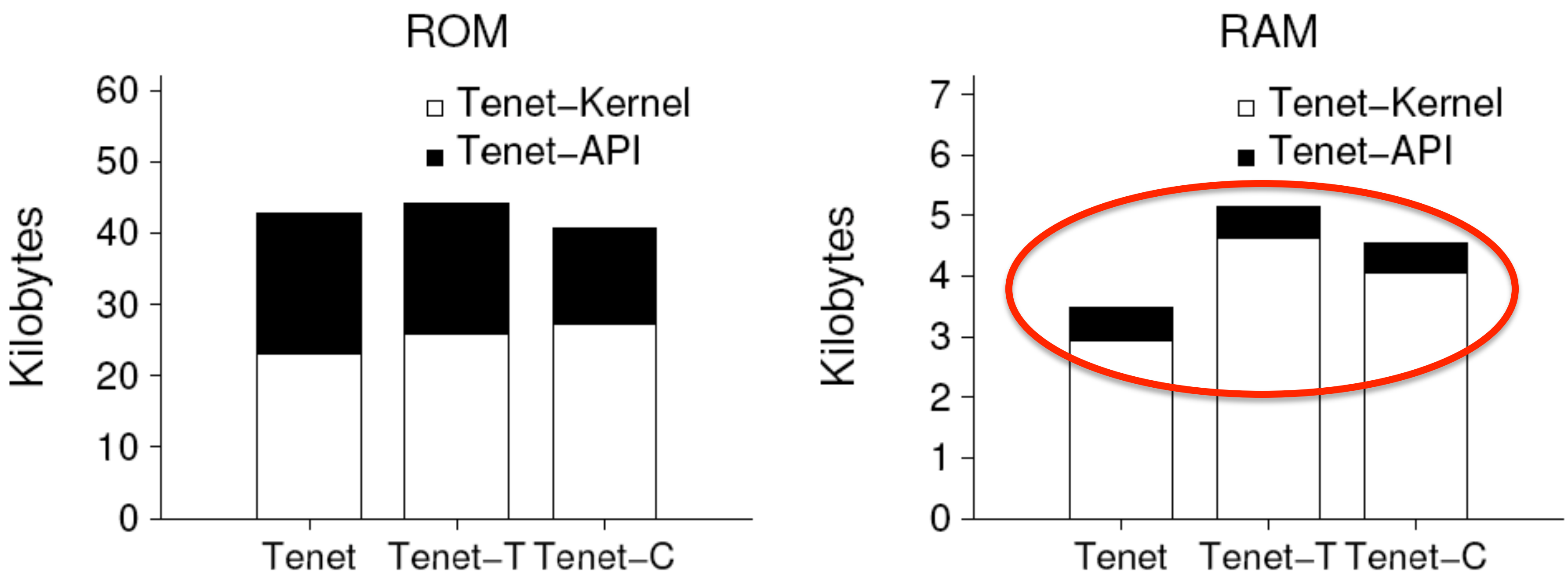
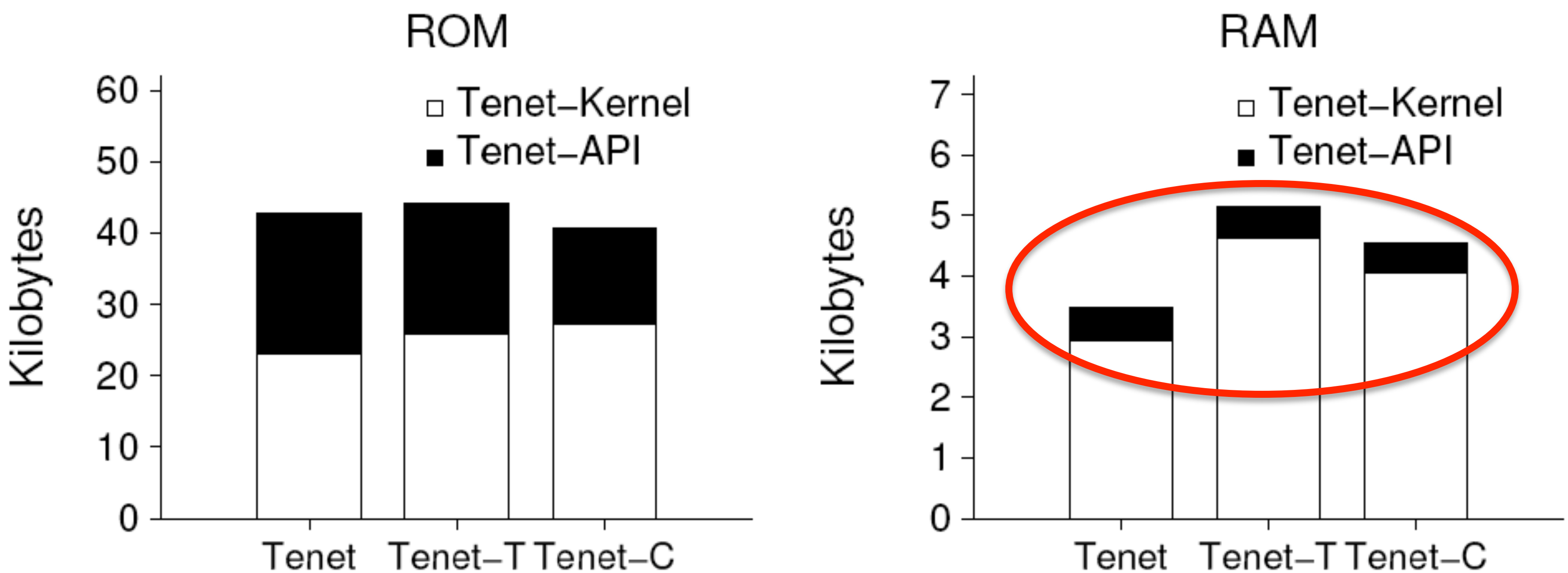


Reimplementation of Tenet



Slight RAM overhead using TOSThreads,
but much less constrained programming model

Conclusion

- TOSThreads Goals
  - Thread Safety
  - Non-Invasiveness
  - Ease of Extensibility
  - Flexible Application Development

Questions & Resources

- Details of Dynamic Linking (slightly outdated)

  http://sing.stanford.edu/klueska/microexe.pdf
- The Latte Programming Language

  http://www.cs.jhu.edu/~razvanm/latte.pdf
- TOSThreads TEP

  http://www.tinyos.net/tinyos-2.x/doc/html/tep134.html
- Source Code

  Library Code - tinyos-2.x/tos/lib/tosthreads

  Apps - tinyos-2.x/apps/tosthreads