Integrating Concurrency Control and Energy Management in Device Drivers

Kevin Klues, Vlado Handziski, Chenyang Lu,
Adam Wolisz,
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Overview

- **Concurrency Control:**
  - Concurrency of I/O operations alone, not of threads in general
  - Synchronous vs. Asynchronous I/O
- **Energy Management:**
  - Power state of devices needed to perform I/O operations
  - Determined by pending I/O requests using Asynchronous I/O

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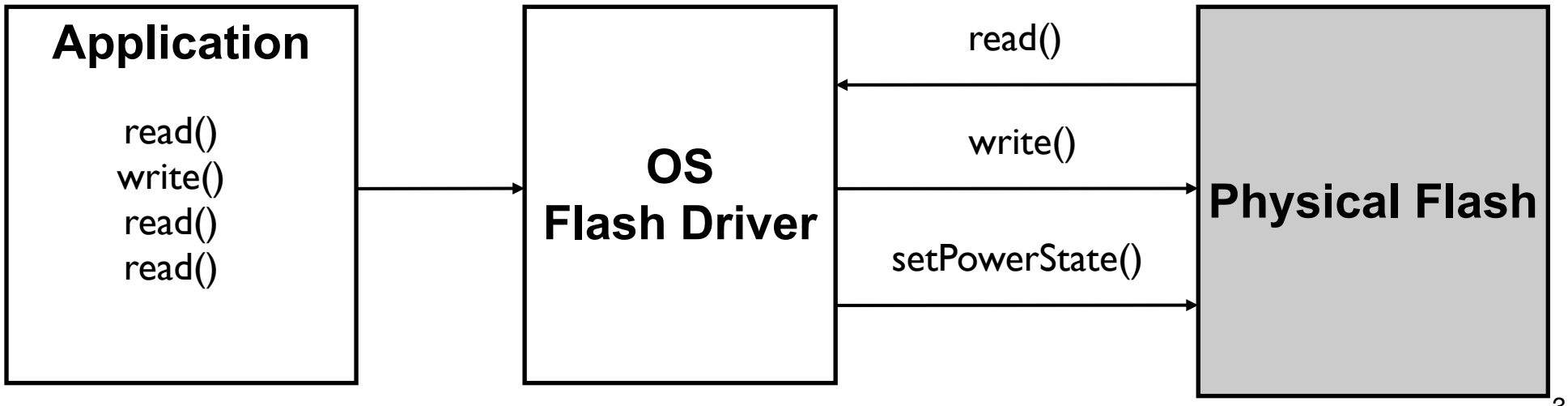

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The more workload information an application can give the OS, the more energy it can save when scheduling that workload

Outline

- Background Information
- Platform and Application
- Driver architecture
- Evaluation
- Conclusion

Motivation

- **Difficult to manage energy in traditional OSs**
  - Hard to tell OS about future application workloads
  - All logic pushed out to the application
  - API extensions for hints?

Existing OS Approaches

- **Dynamic CPU Voltage Scaling**
  - Vertigo - Application workload classes
  - Grace OS - Explicit real-time deadlines
- **Disk Spin Down**
  - Coop-IO - Application specified timeouts

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Saving energy is a complex process

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Saving energy is a complex process

A little application knowledge can help us alot

Sensor Networks

- **Domain in need of unique solution to this problem**
  - Harsh energy requirements
  - Very small source of power (2 AA batteries)
  - Must run unattended from months to years
- **First generation sensornet OSes (TinyOS, Contiki, Mantis, ...)**
  - Push all energy management to the application
  - Optimal energy savings at cost of application complexity

ICEM: Integrated Concurrency and Energy Management

- **A device driver architecture that automatically manages energy**
  - Implemented in TinyOS 2.0 -- all drivers follow it
  - Introduces Power Locks, split-phase locks with integrated energy and configuration management
  - Defines three classes of drivers: dedicated, shared, virtualized
  - Provides a component library for building drivers
- **Advantages of using ICEM**
  - Energy efficient – At least 98.4% as hand-tuned implementation
  - Reduces code complexity – 400 vs. 68 lines of code
  - Enables natural decomposition of applications

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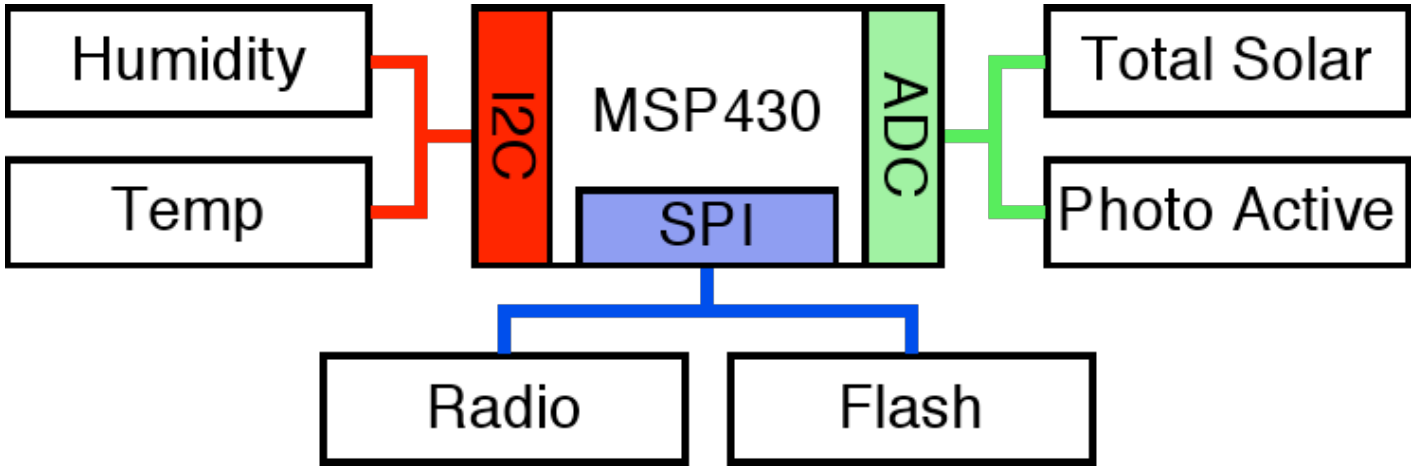
The Tmote Platform

- **Six major I/O devices**
- **Possible Concurrency**
  - I2C, SPI, ADC
- **Energy Management**
  - Turn peripherals on only when needed
  - Turn off otherwise



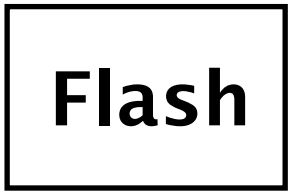
Representative Logging Application

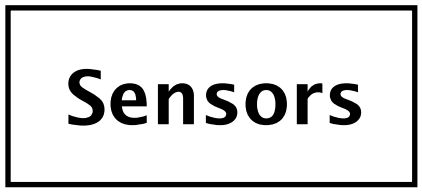
Producer

```
Every 5 minutes:
  Write prior samples
  Sample photo active
  Sample total solar
  Sample temperature
  Sample humidity
```

Consumer

```
Every 12 hours:
  For all new entries:
    Send current sample
    Read next sample
```





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Sensors

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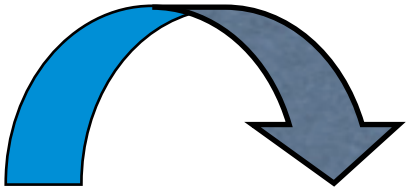

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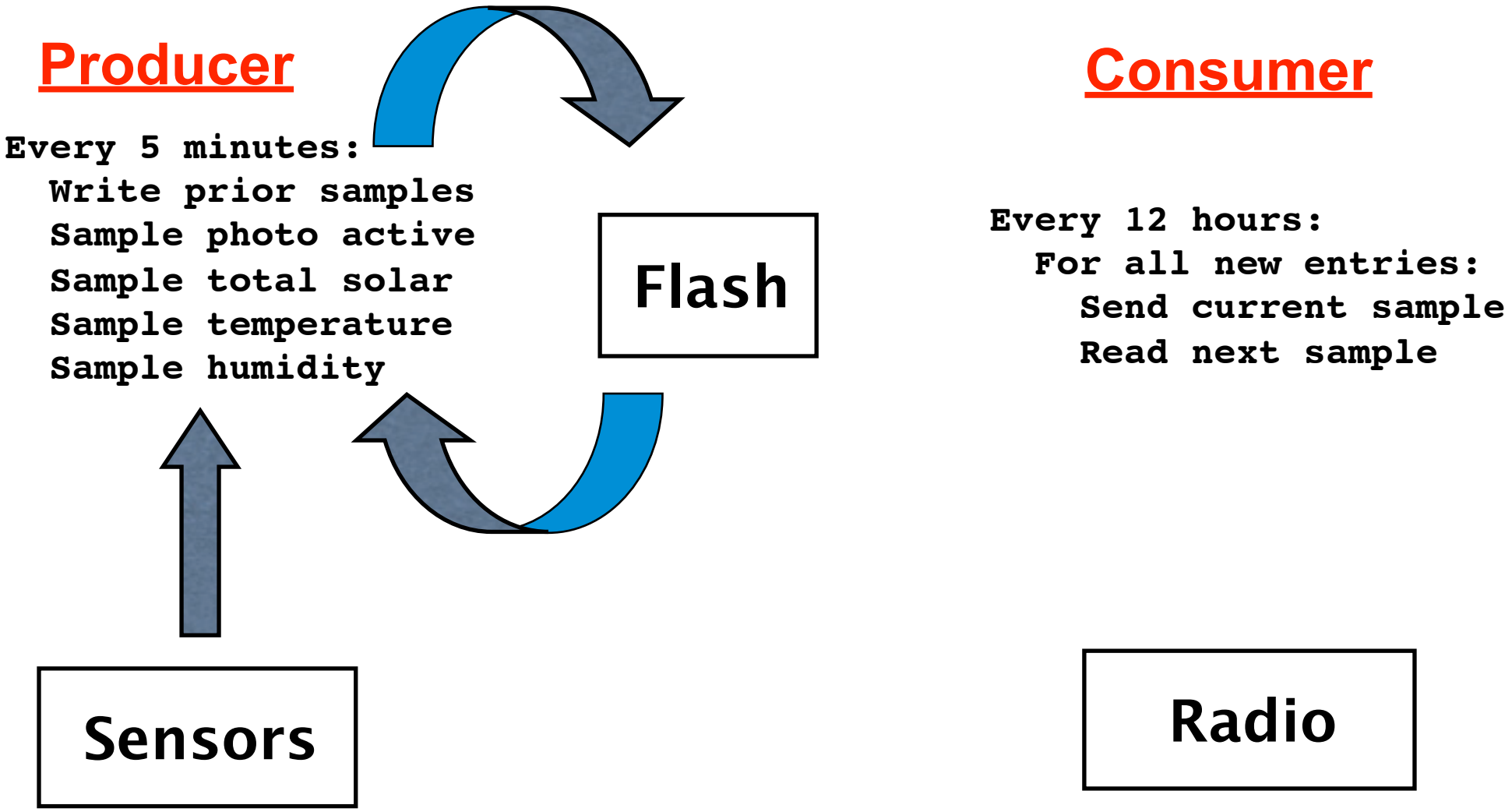

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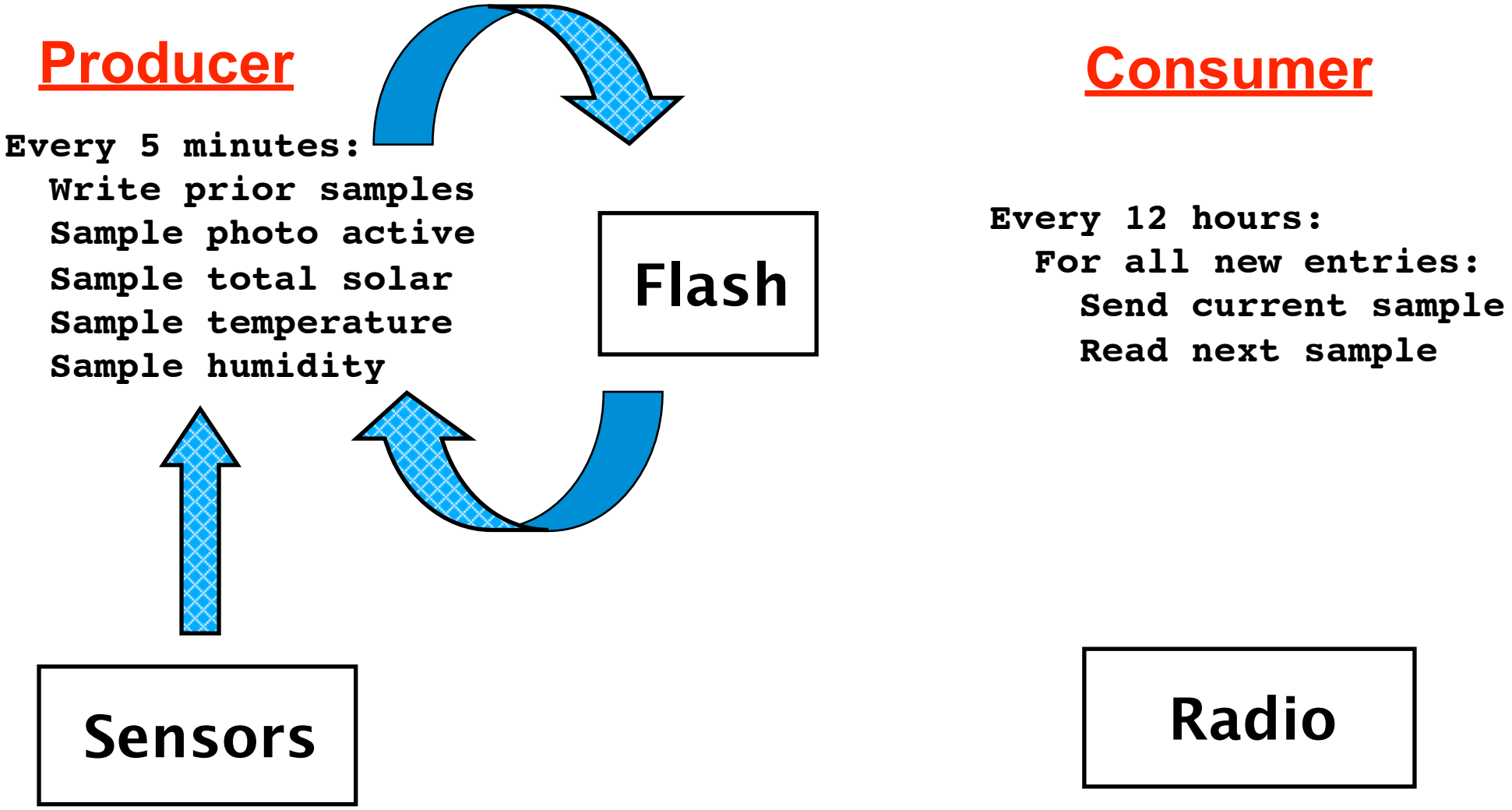

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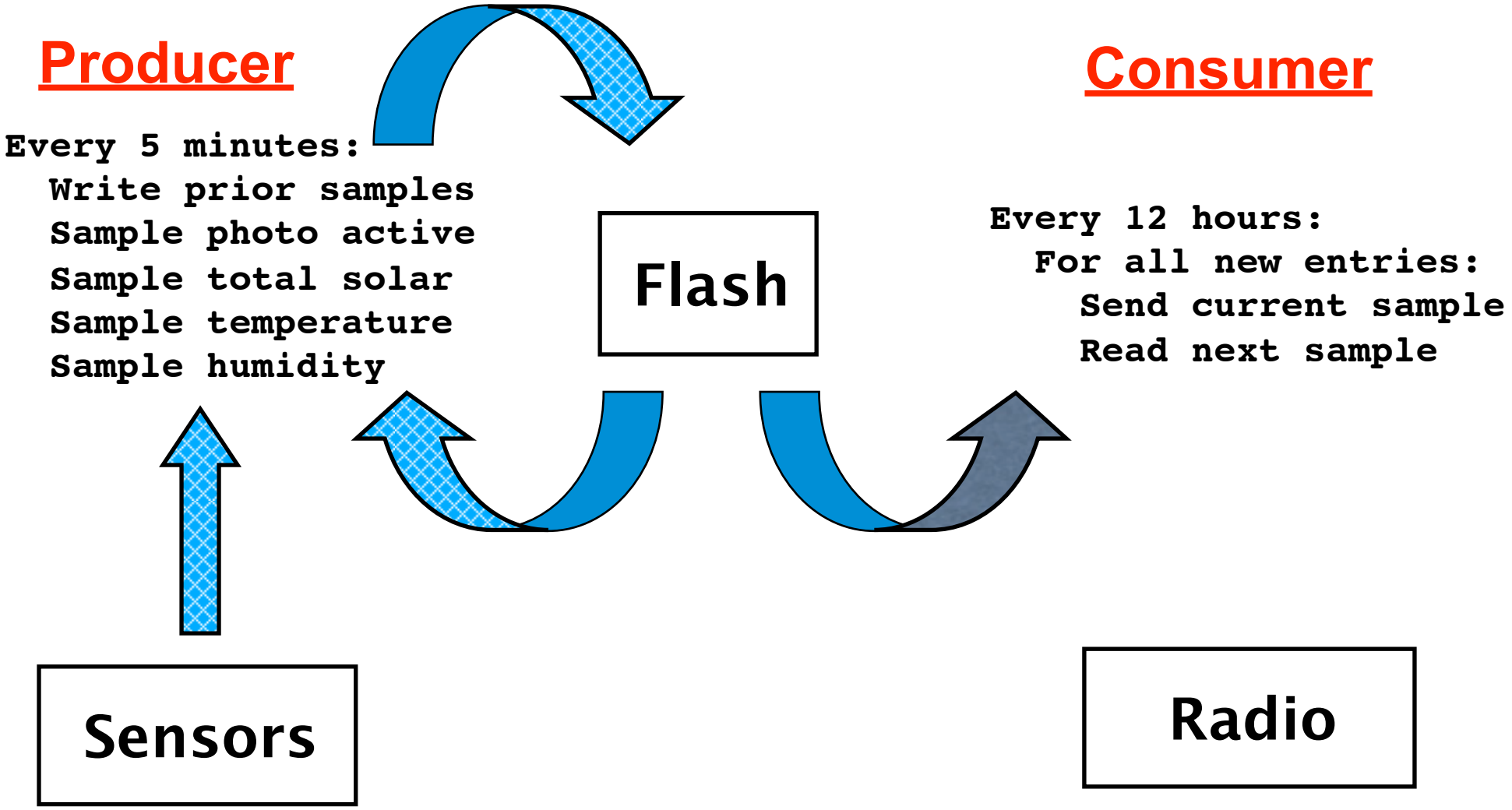

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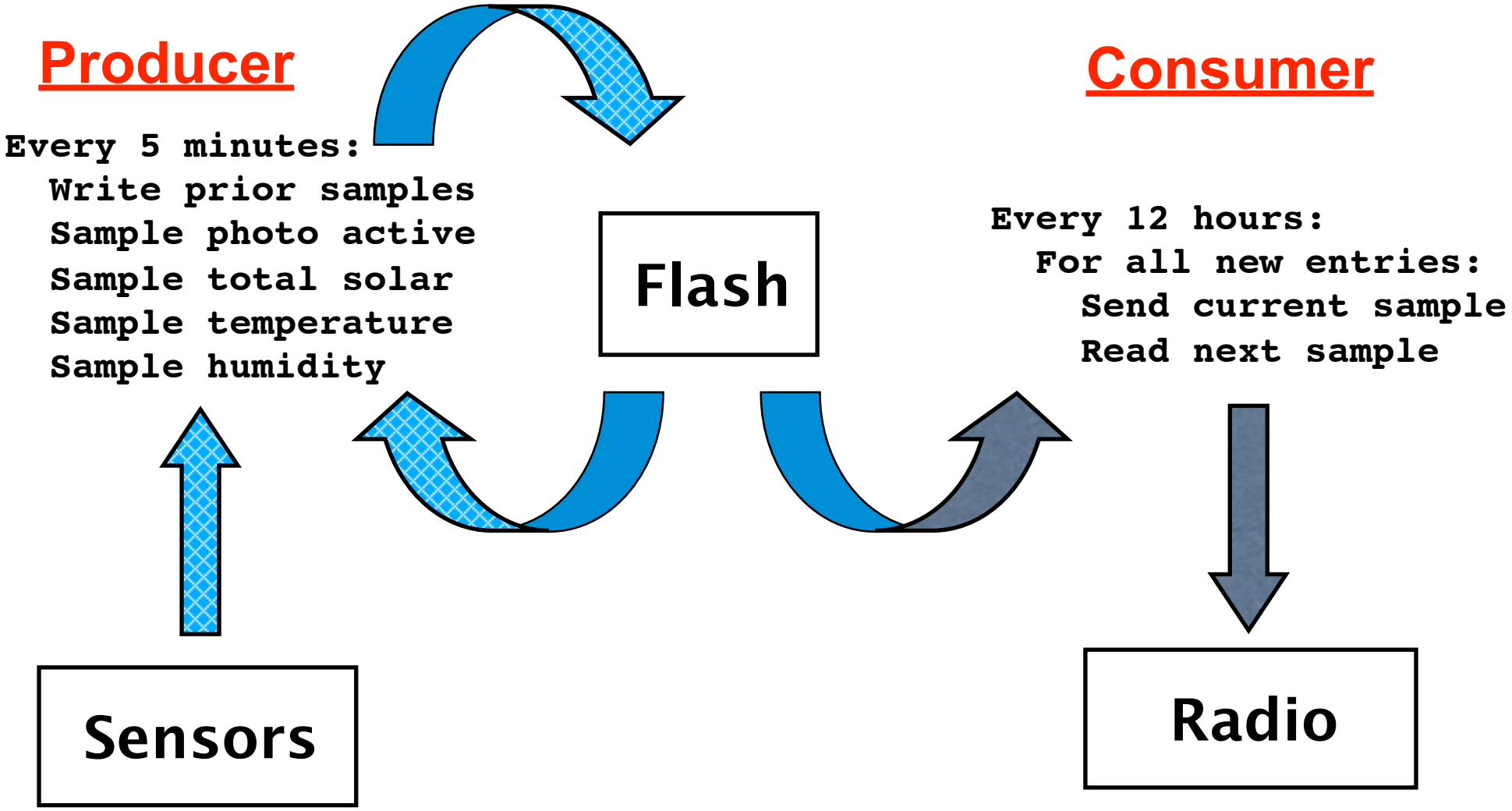

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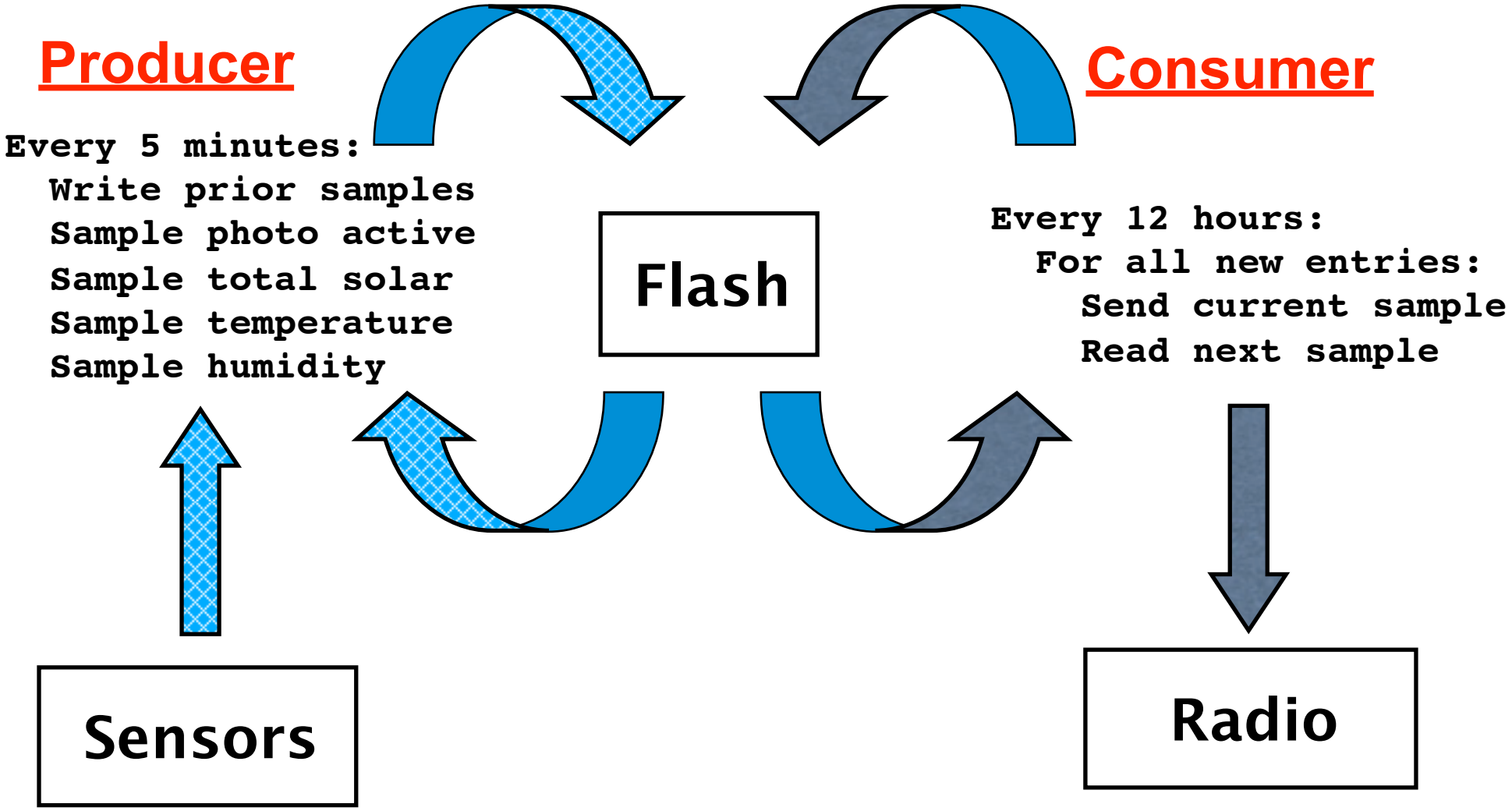

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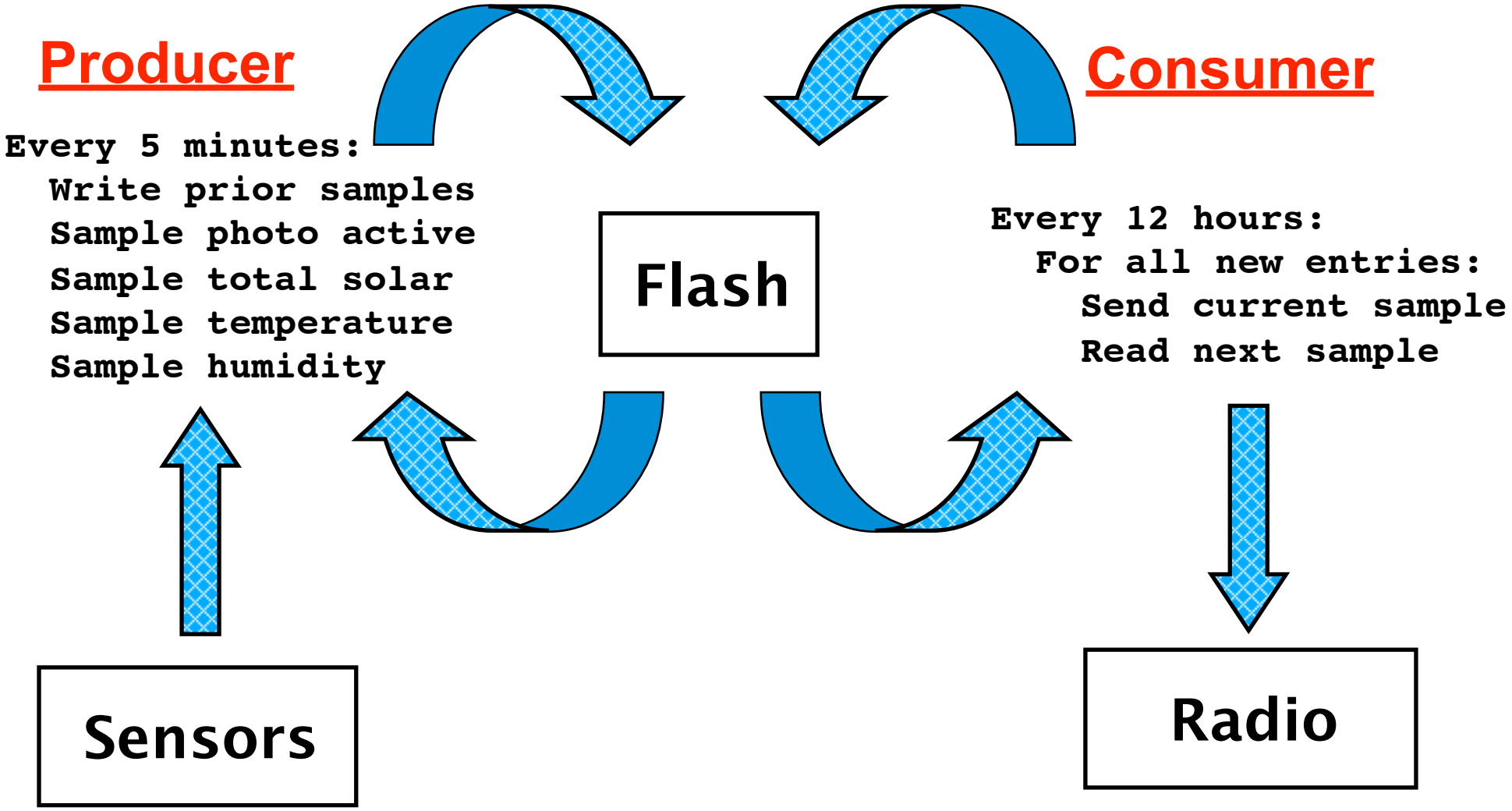

Code Complexity

Hand-Tuned Application

```
Every 5 minutes:
  Turn on SPI bus
  Turn on flash chip
  Turn on voltage reference
  Turn on I²C bus
  Log prior readings
  Start humidity sample
  Wait 5ms for log
  Turn off flash chip
  Turn off SPI bus
  Wait 12ms for vref
  Turn on ADC
  Start total solar sample
  Wait 2ms for total solar
  Start photo active sample
  Wait 2ms for photo active
  Turn off ADC
  Turn off voltage reference
  Wait 34ms for humidity
  Start temperature sample
  Wait 220ms for temperature
  Turn off I²C bus
```

ICEM Application

```
Every 5 minutes:
  Log prior readings
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  sample total solar
  sample photo active
  sample temperature
```

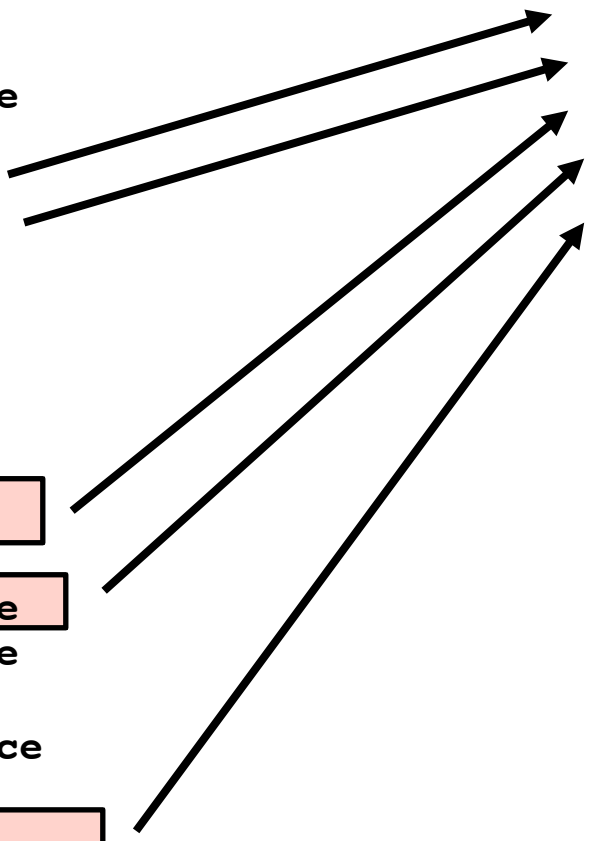

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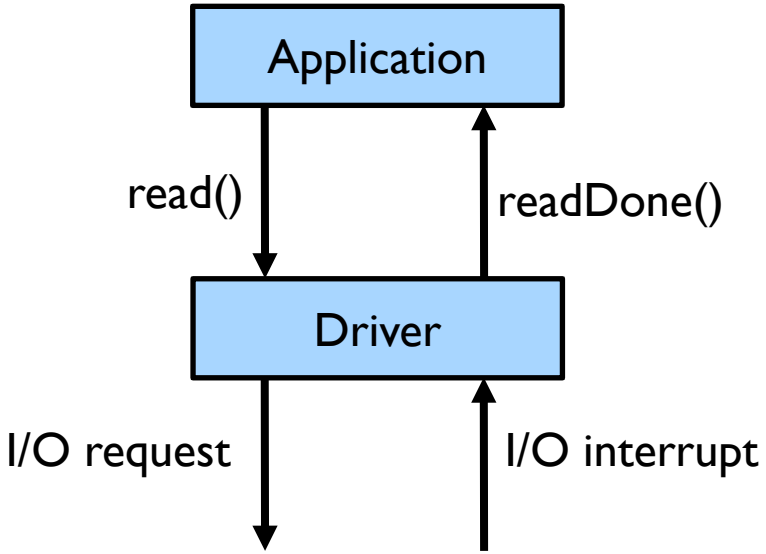
Split-Phase I/O Operations

- **Split-phase I/O operations**
  - Implemented within a single thread of control
  - Application notified of I/O completion through direct upcall
  - Driver given workload information before returning control
  - Example: read() readDone()



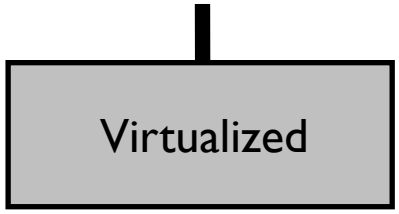

```
void readDone(uint16_t val) {
  next_val = val;
  read();
}
```

ICEM Architecture

- **Defines three classes of drivers**
  - Virtualized – provide only functional interface
  - Dedicated – provide functional and power interface
  - Shared – provide functional and lock interface

Virtualized Device Drivers

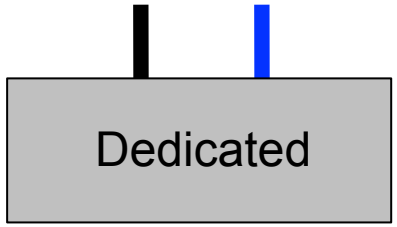
- **Provide only a Functional interface**
  - Assume multiple users
- **Implicit concurrency control through buffering requests**
- **Implicit energy management based on pending requests**
- **Implemented for higher-level services that can tolerate longer latencies**



Energy: Implicit
Concurrency: Implicit

Dedicated Device Drivers

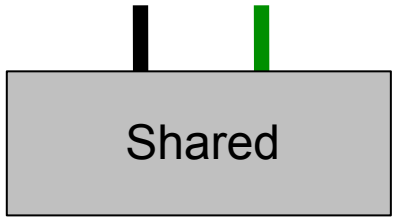
- **Provide Functional and Power Control interfaces**
  - Assume a single user
  - No concurrency control
- **Explicit energy management**
- **Low-level hardware and bottom-level abstractions have a dedicated driver**



Energy: Implicit
Concurrency: None

Shared Device Drivers

- **Provide Functional and Lock interfaces**
  - Assume multiple users
  - Explicit concurrency control through Lock request
  - Implicit energy management based on pending requests
  - Used by users with stringent timing requirements



Energy: Implicit
Concurrency: Explicit

ICEM Architecture

- **Defines three classes of drivers**
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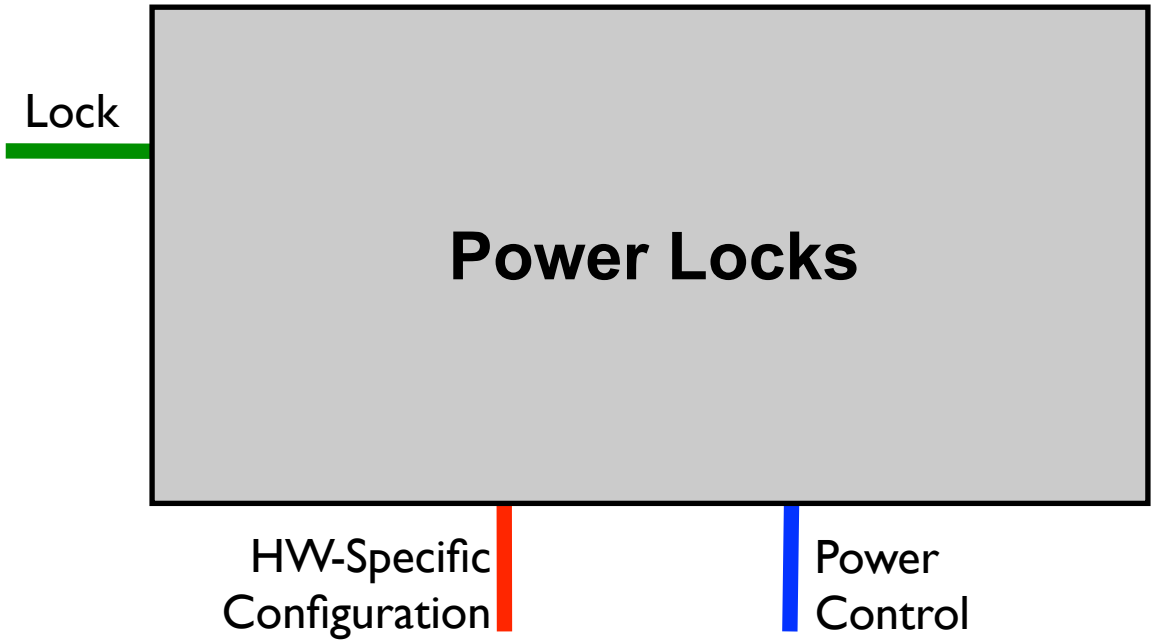
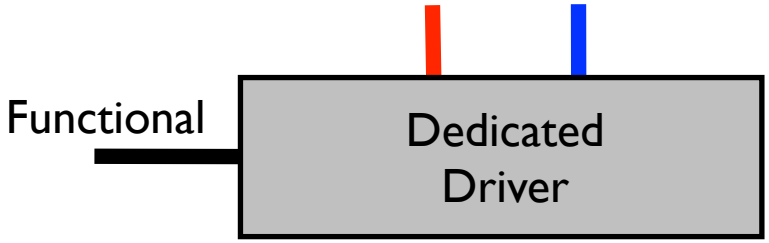
- **Power Locks** split-phase locks with integrated energy and configuration management

Power Locks


Lock
Power Locks
HW-Specific Configuration
Power Control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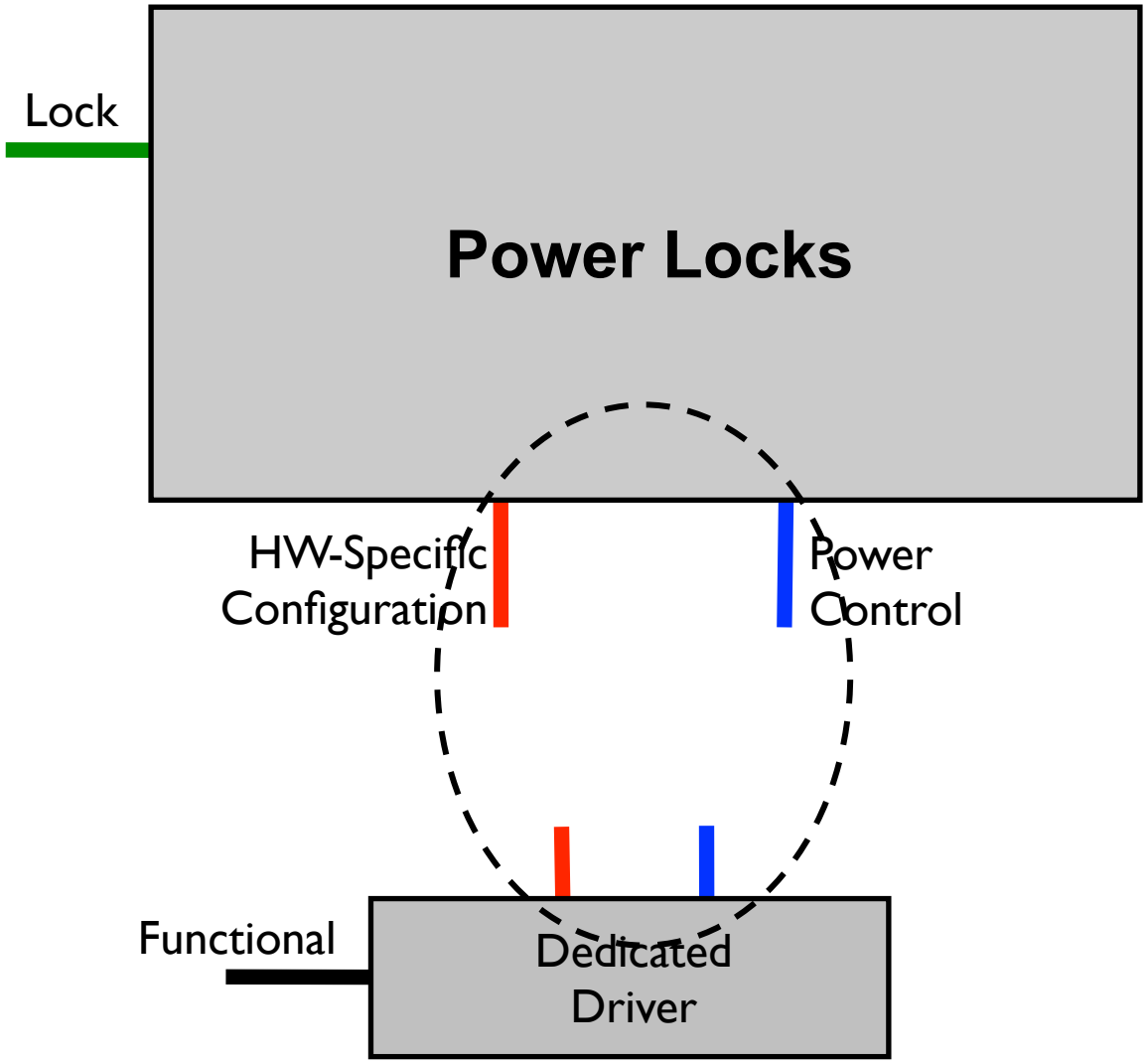
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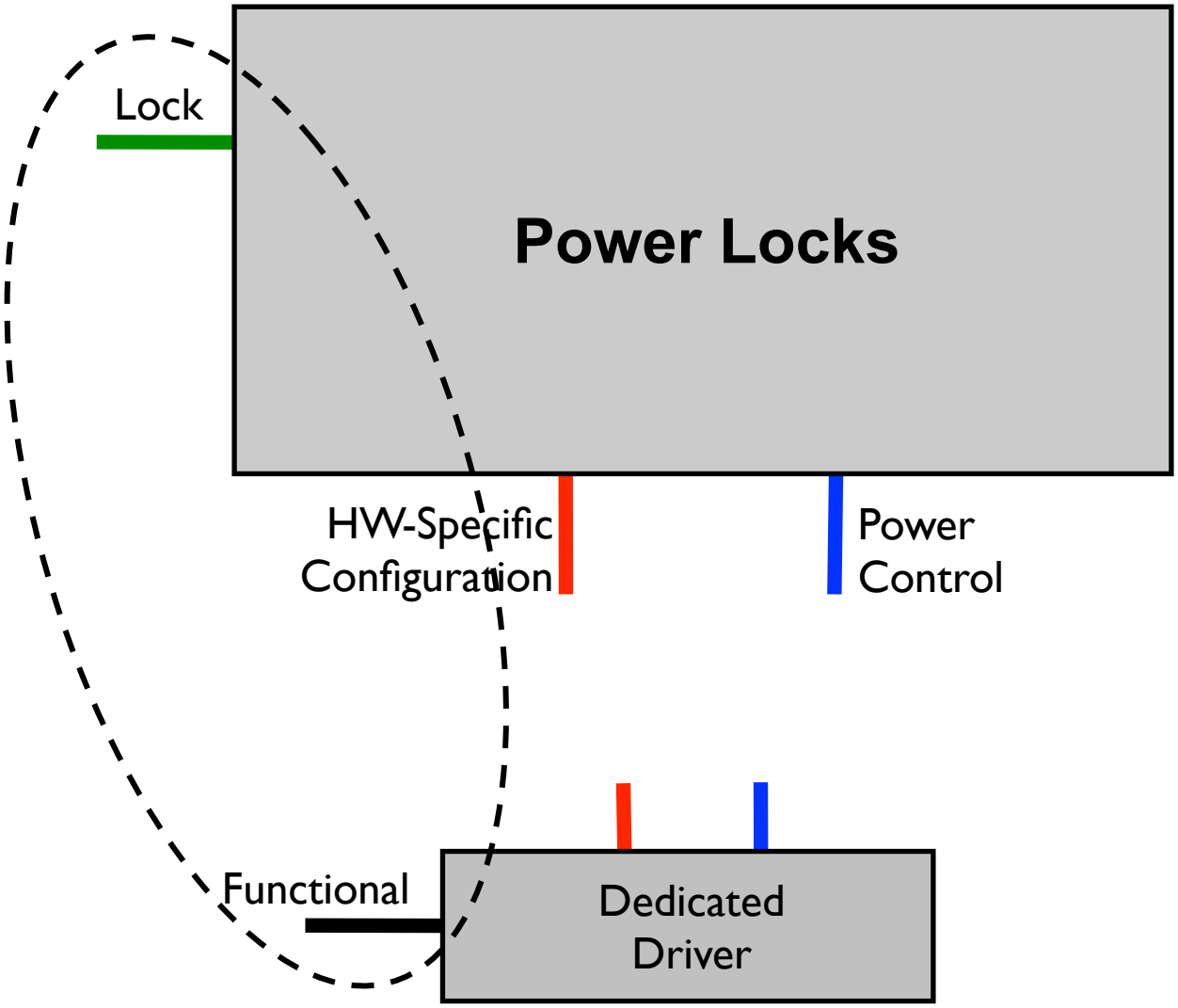
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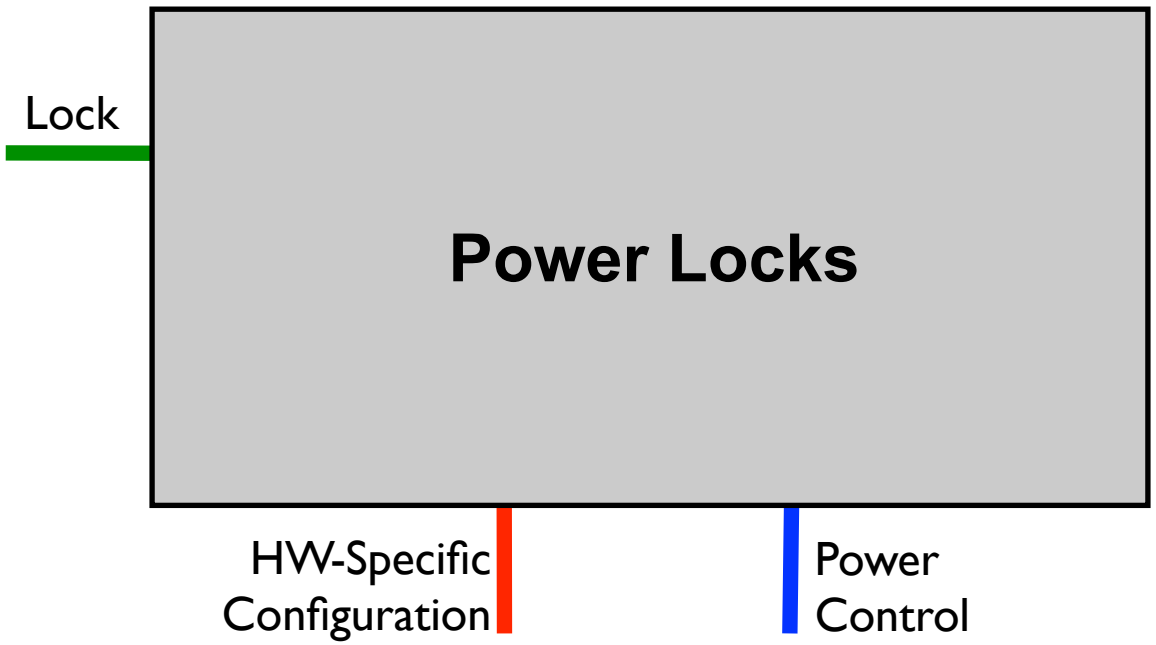
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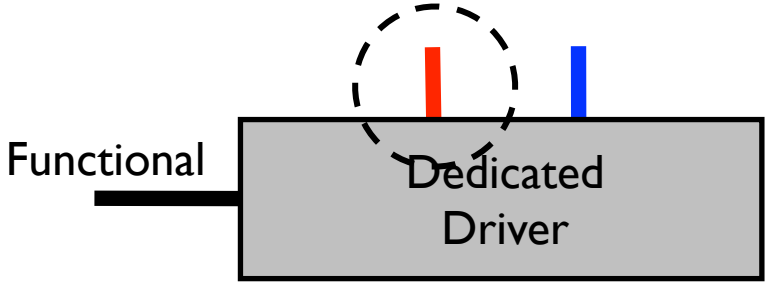
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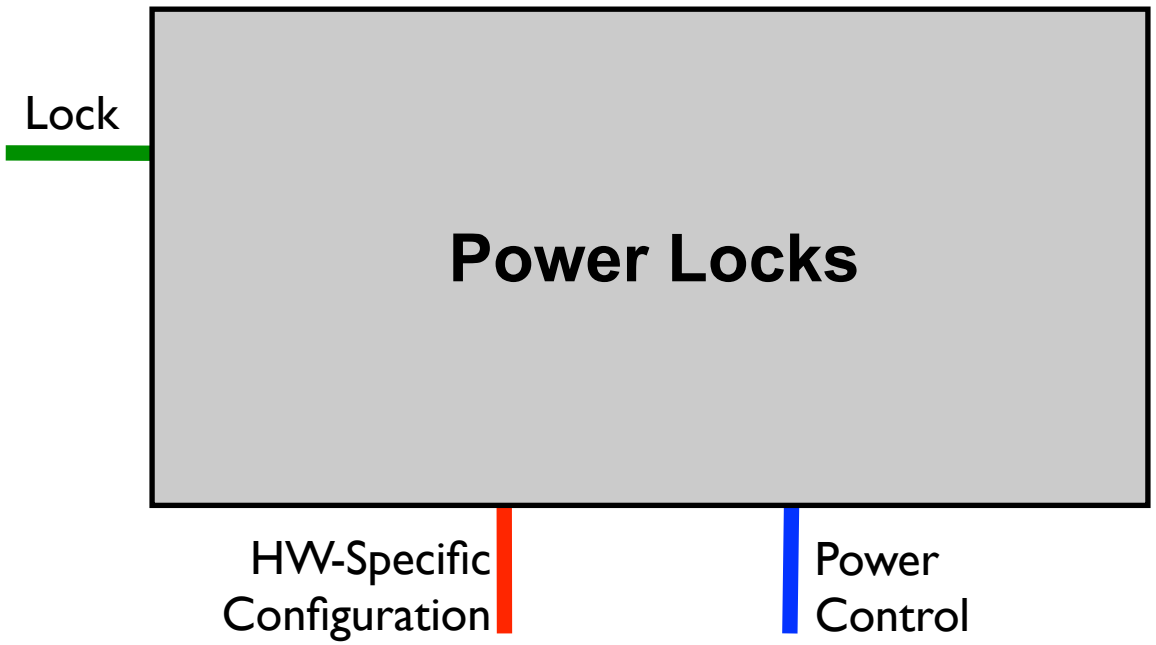
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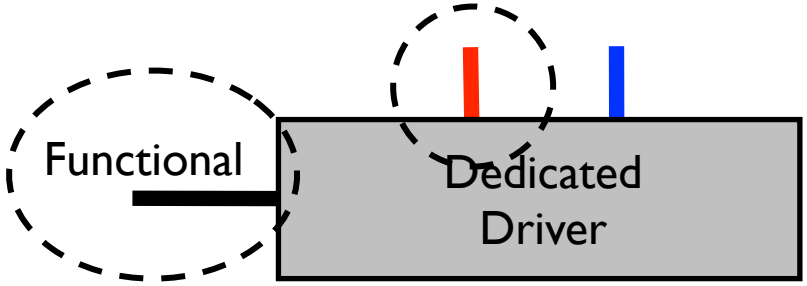
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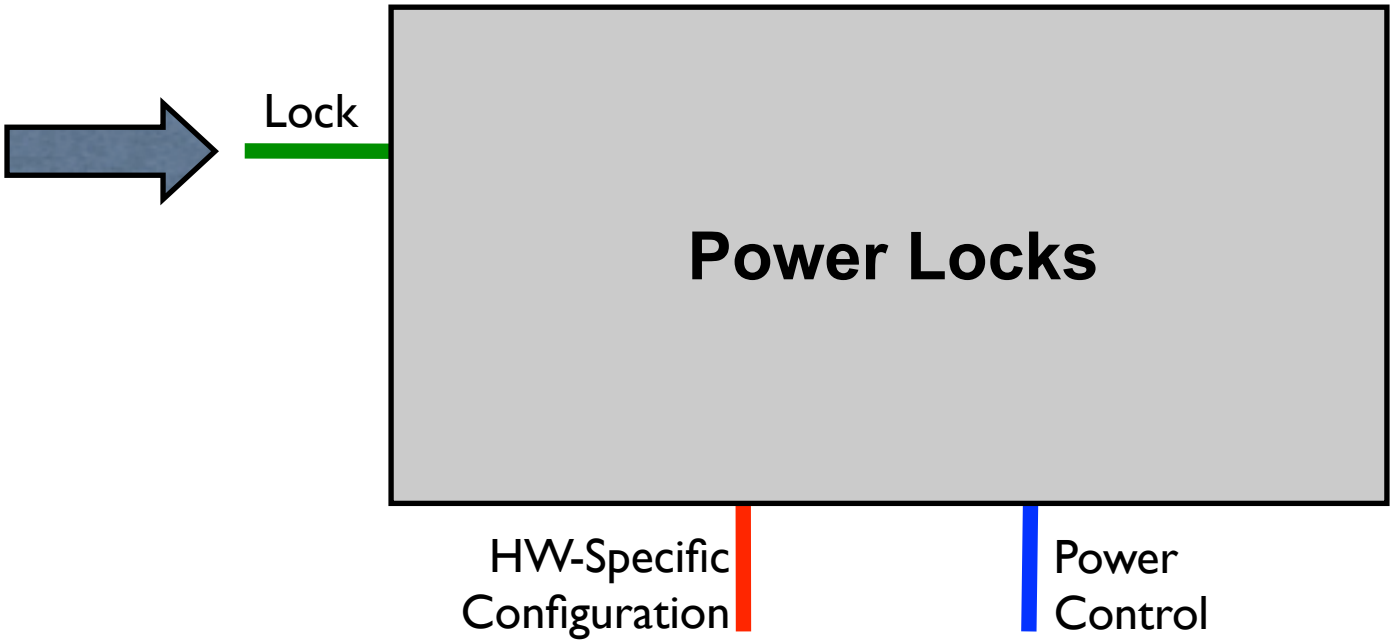
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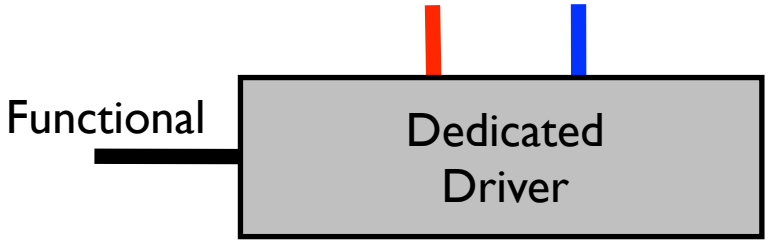
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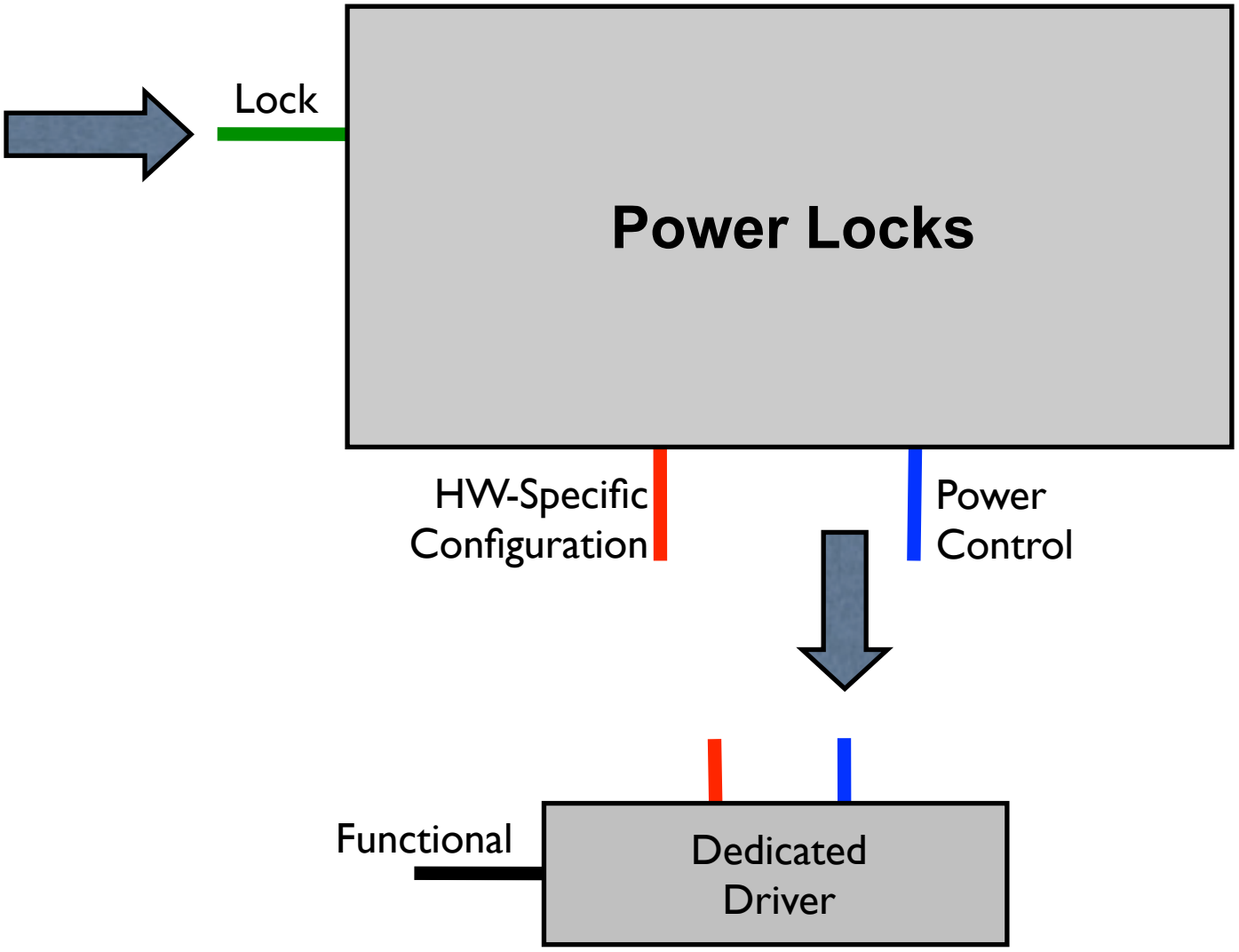
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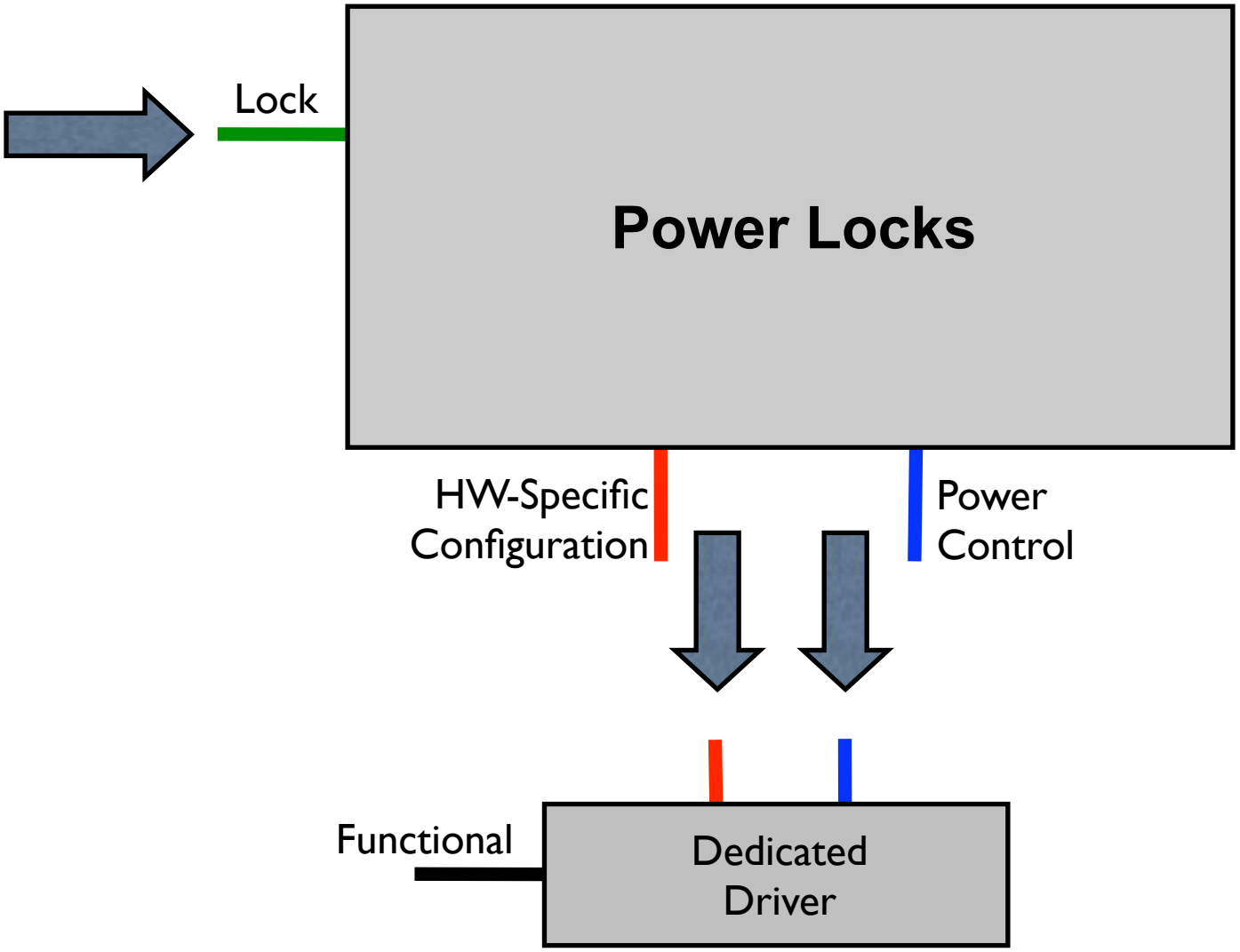
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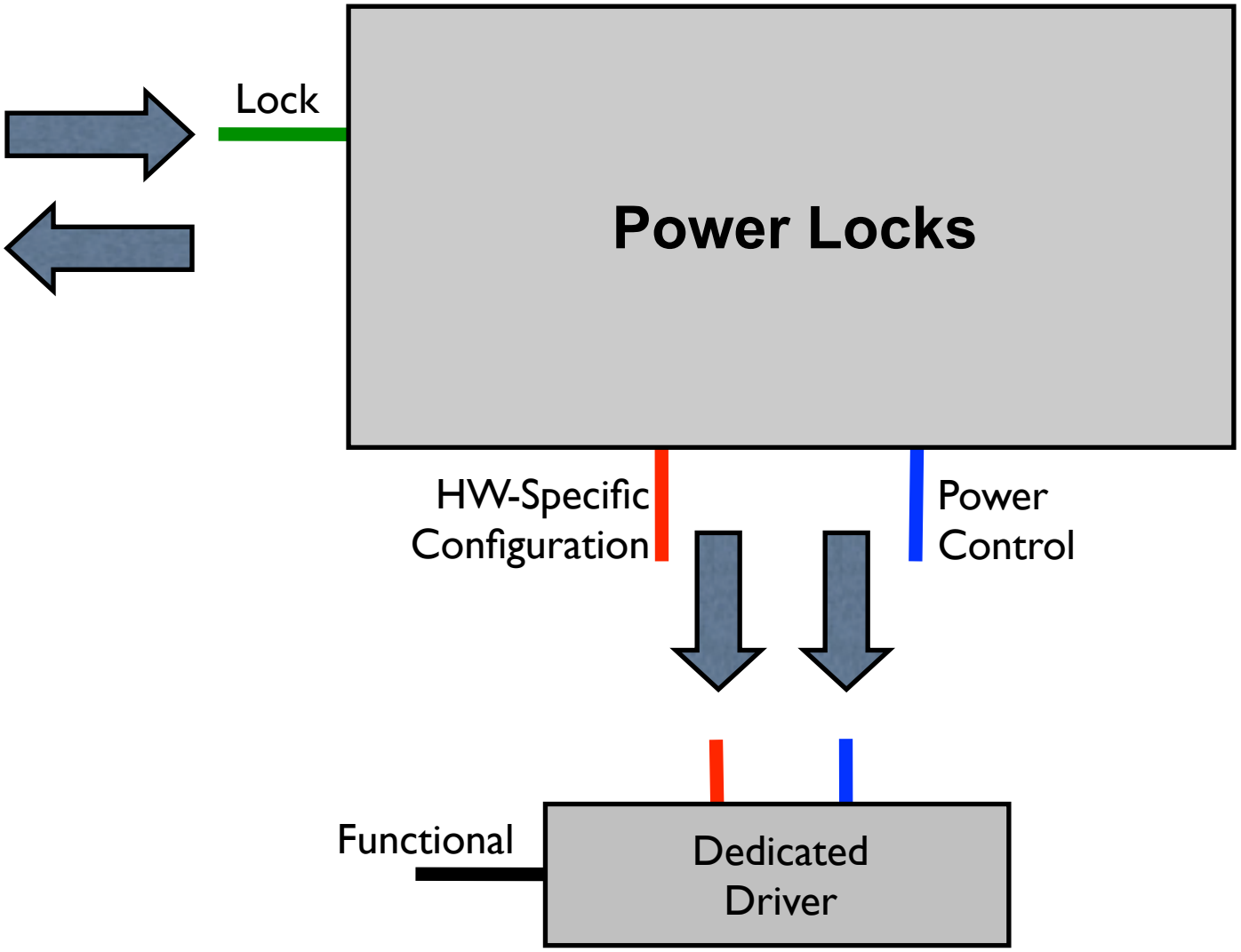
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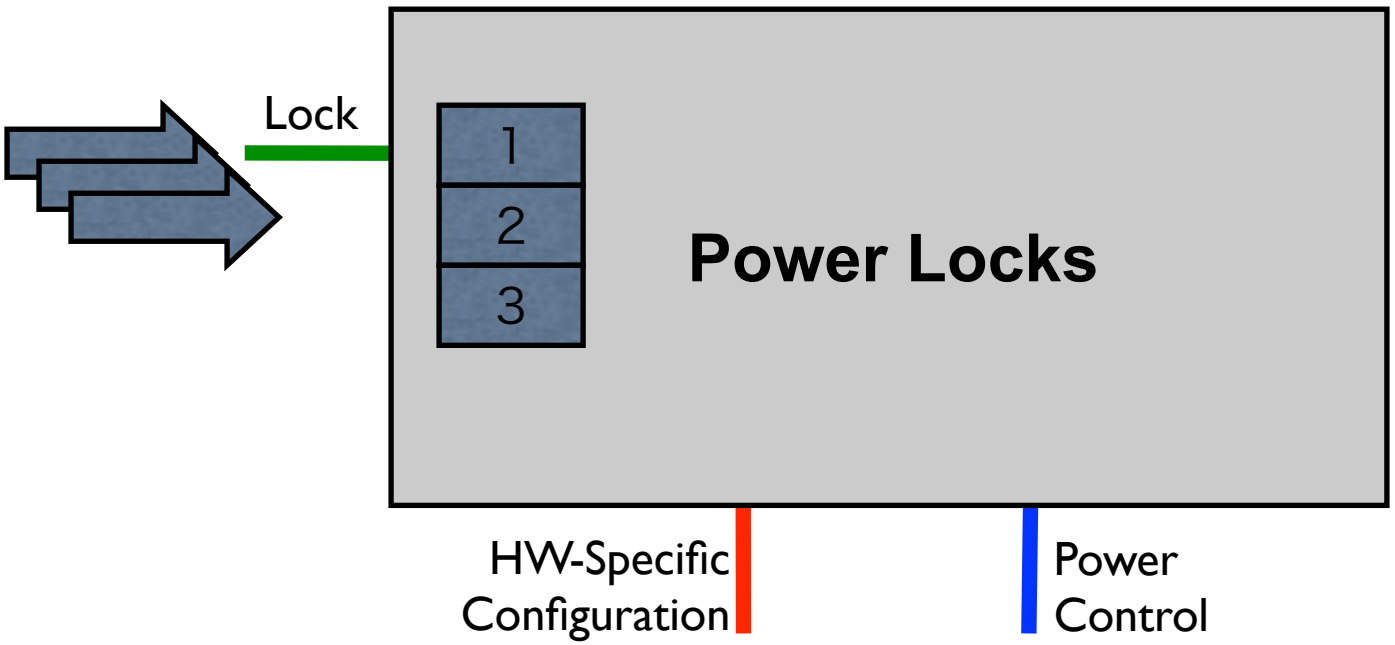
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2
3
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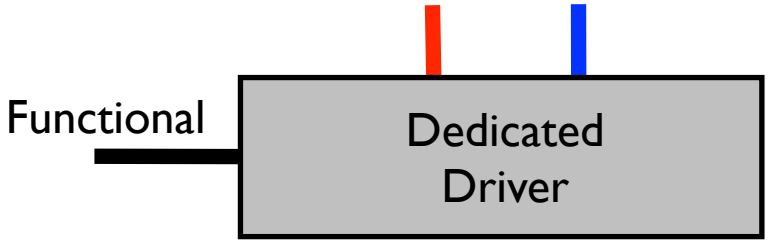
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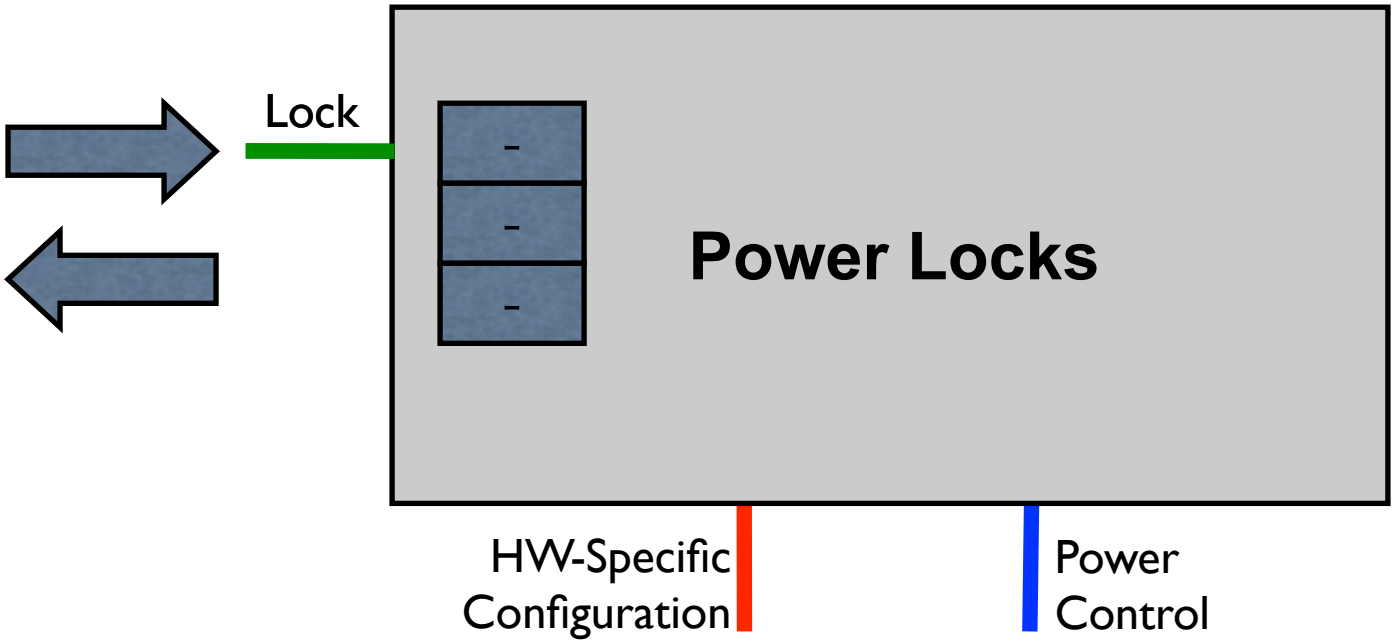
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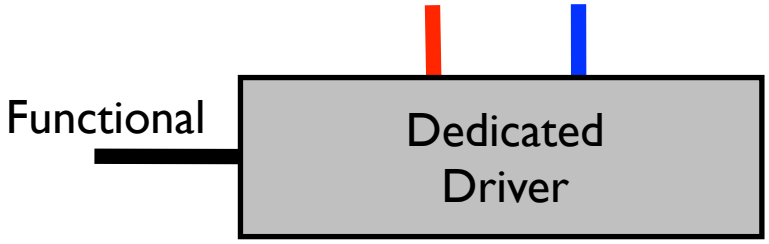
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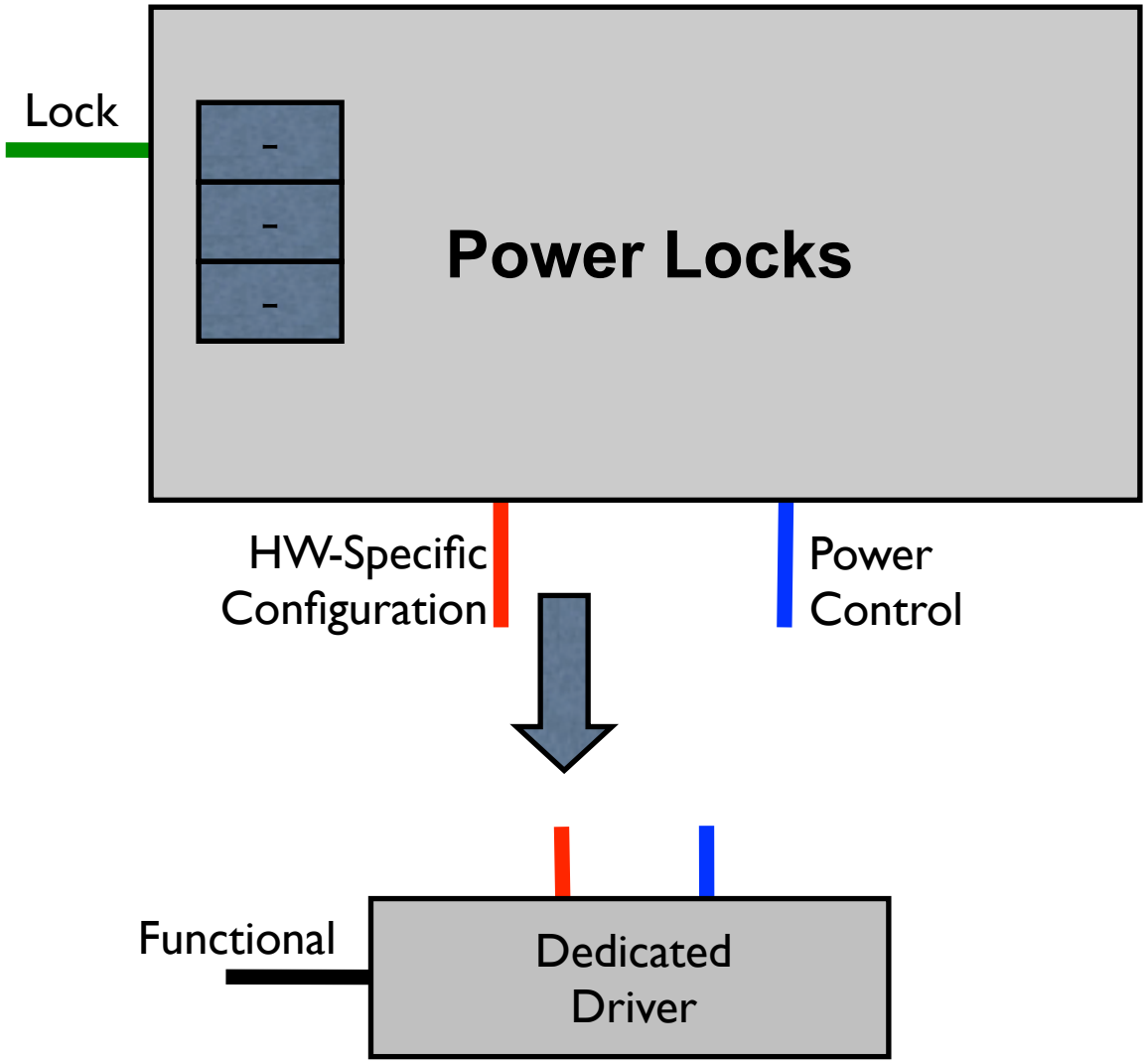
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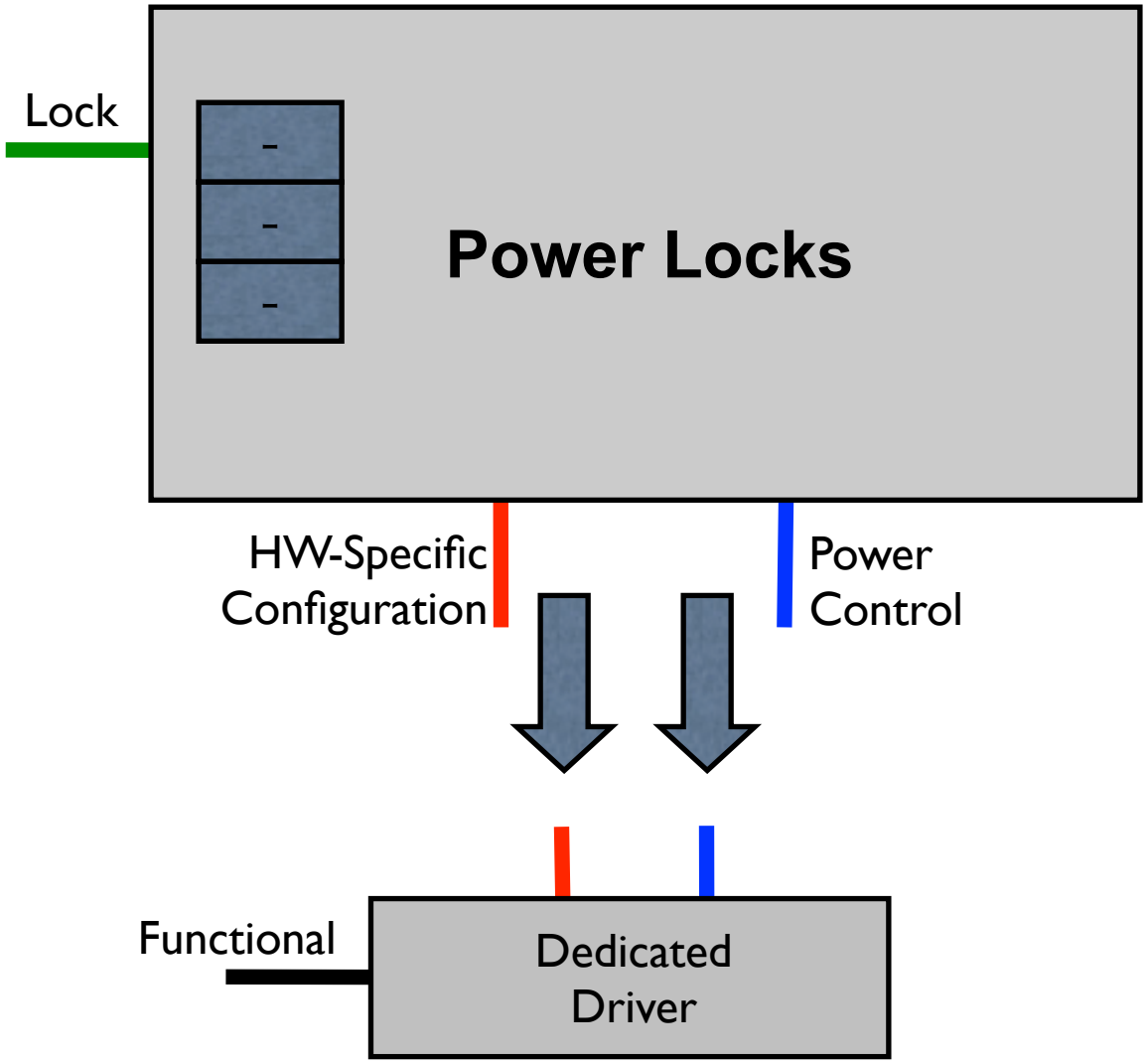
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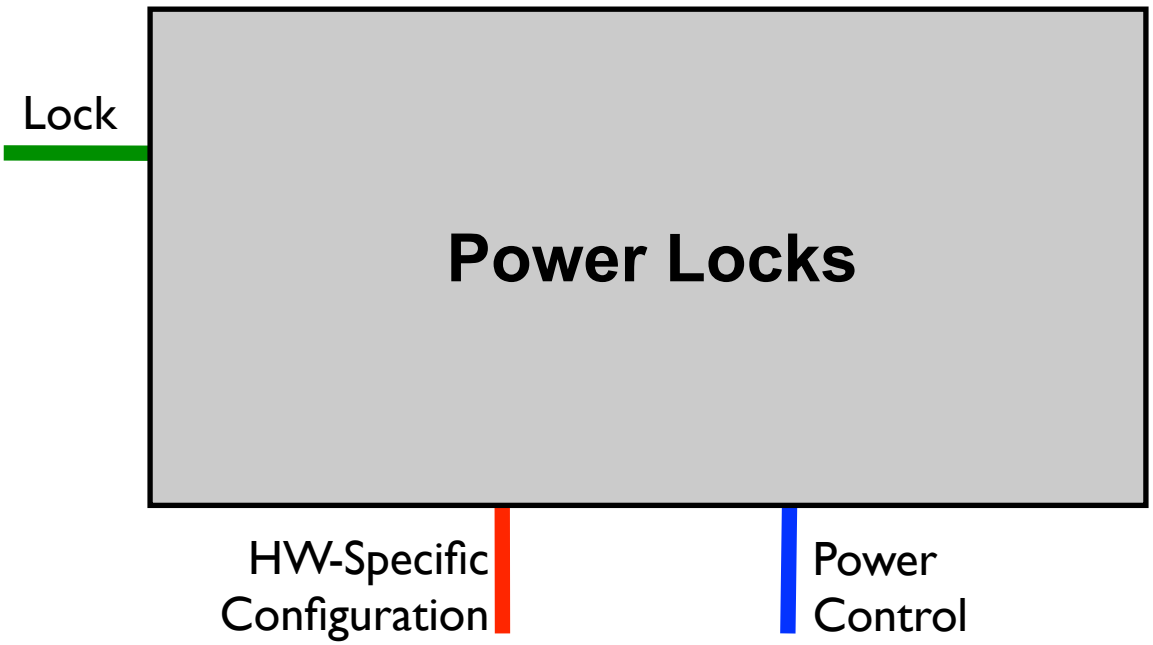
ICEM Architecture

- **Defines three classes of drivers**
  - Virtualized – provide only functional interface
  - Dedicated – provide functional and power interface
  - Shared – provide functional and lock interface
- **Power Locks:** split-phase locks with integrated energy and configuration management
- **Component library**
  - Arbiters – manage I/O concurrency
  - Configurators – setup device specific configurations
  - Power Managers – provide automatic power management

Component Library



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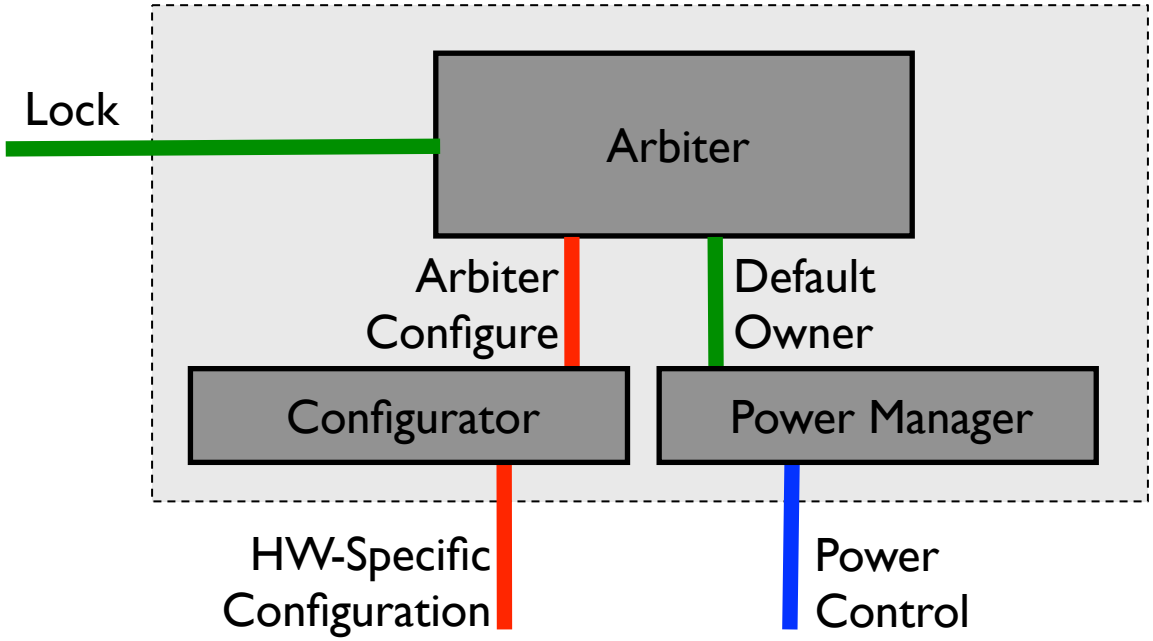

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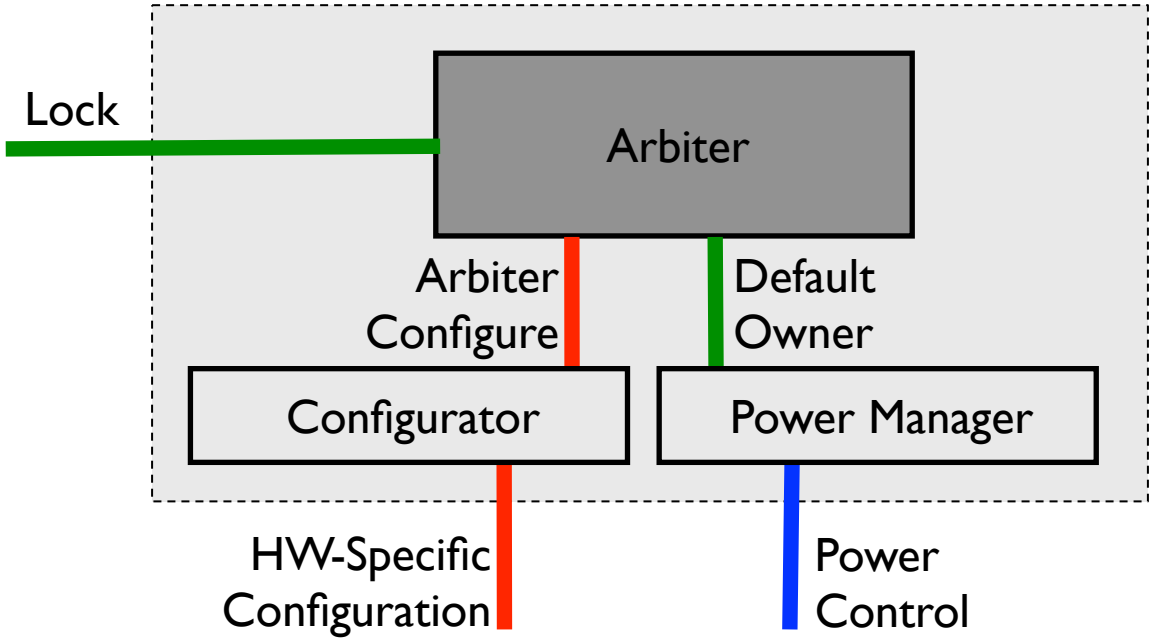
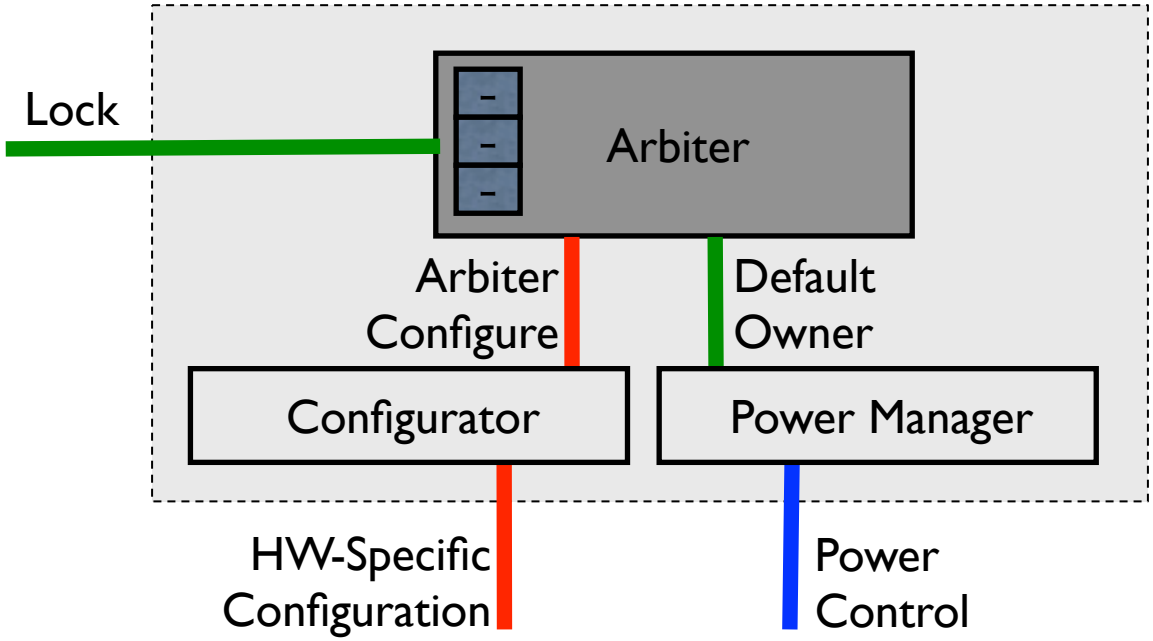


- **Lock** interface for concurrency control (FCFS, Round-Robin)
- **ArbiterConfigure** interface automatic hardware configuration
- **DefaultOwner** interface for automatic power management

Component Library



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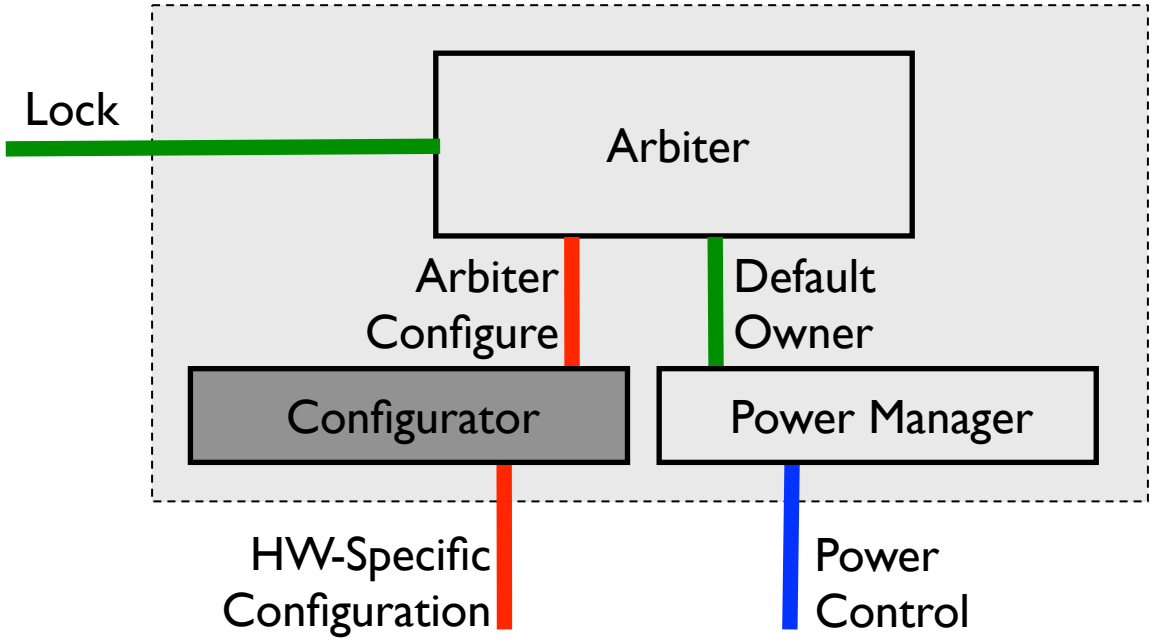

- Implement **ArbiterConfigure** interface
- Call hardware specific configuration from dedicated driver

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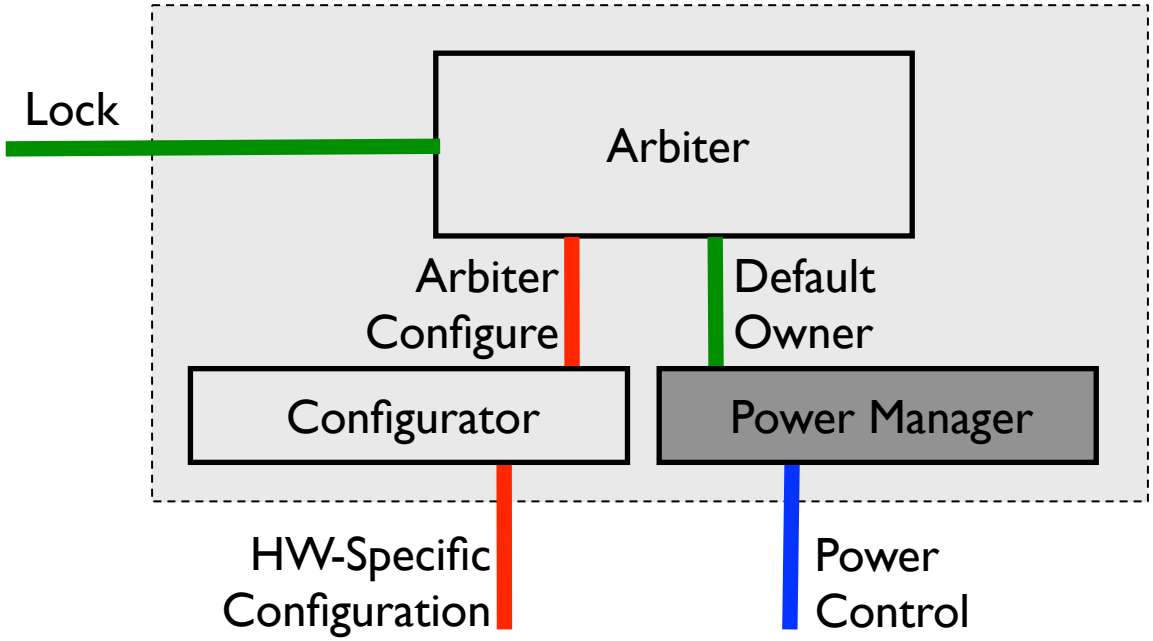
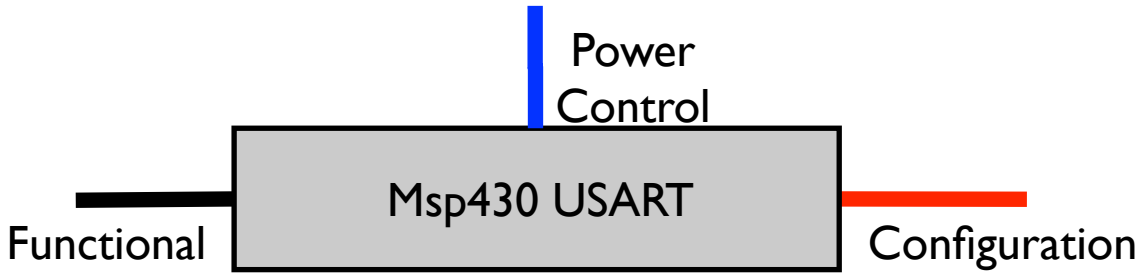


- Implement **DefaultOwner** interface
- Power down device when device falls idle
- Power up device when new lock request comes in
- Currently provide *Immediate* and *Deferred* policies

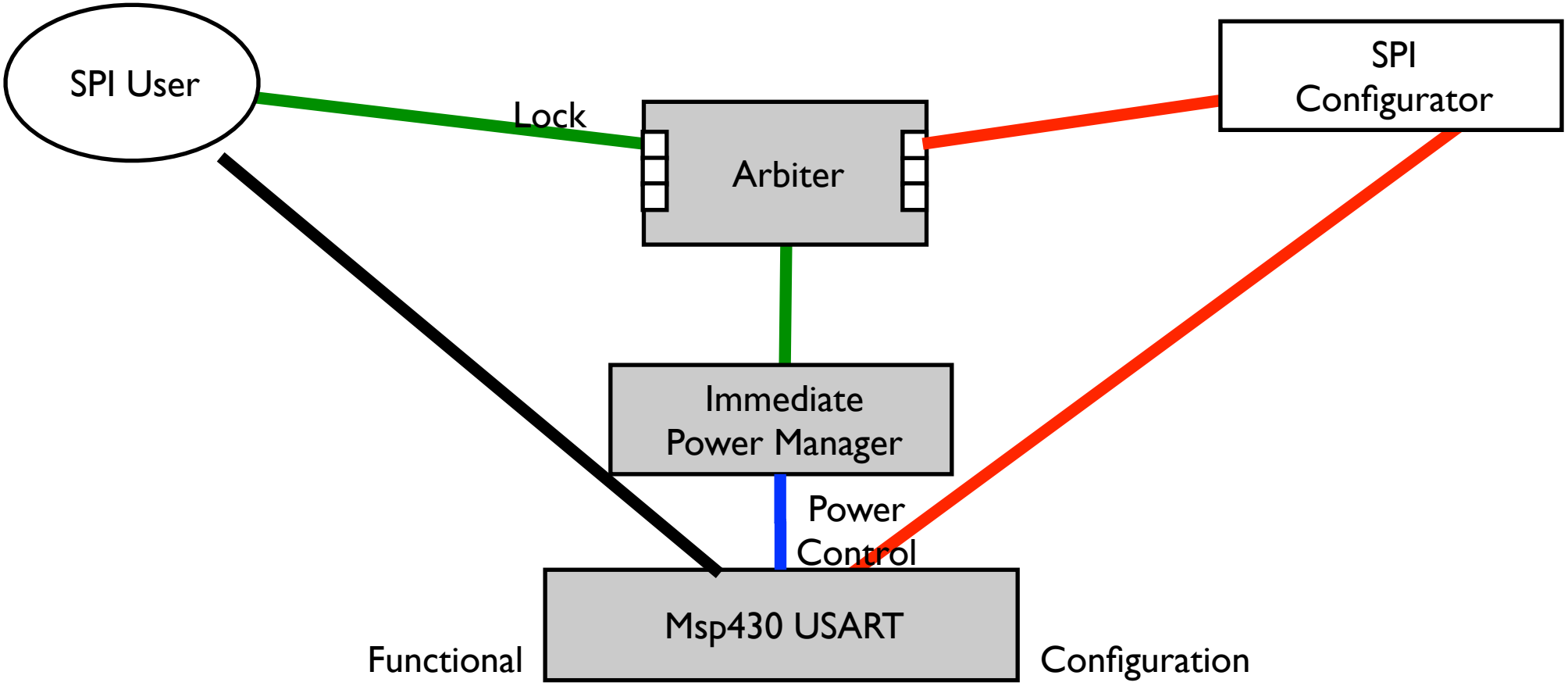
Shared Driver Example

- **Msp430 USART (Serial Controller)**
  - Three modes of operation – SPI, I2C, UART

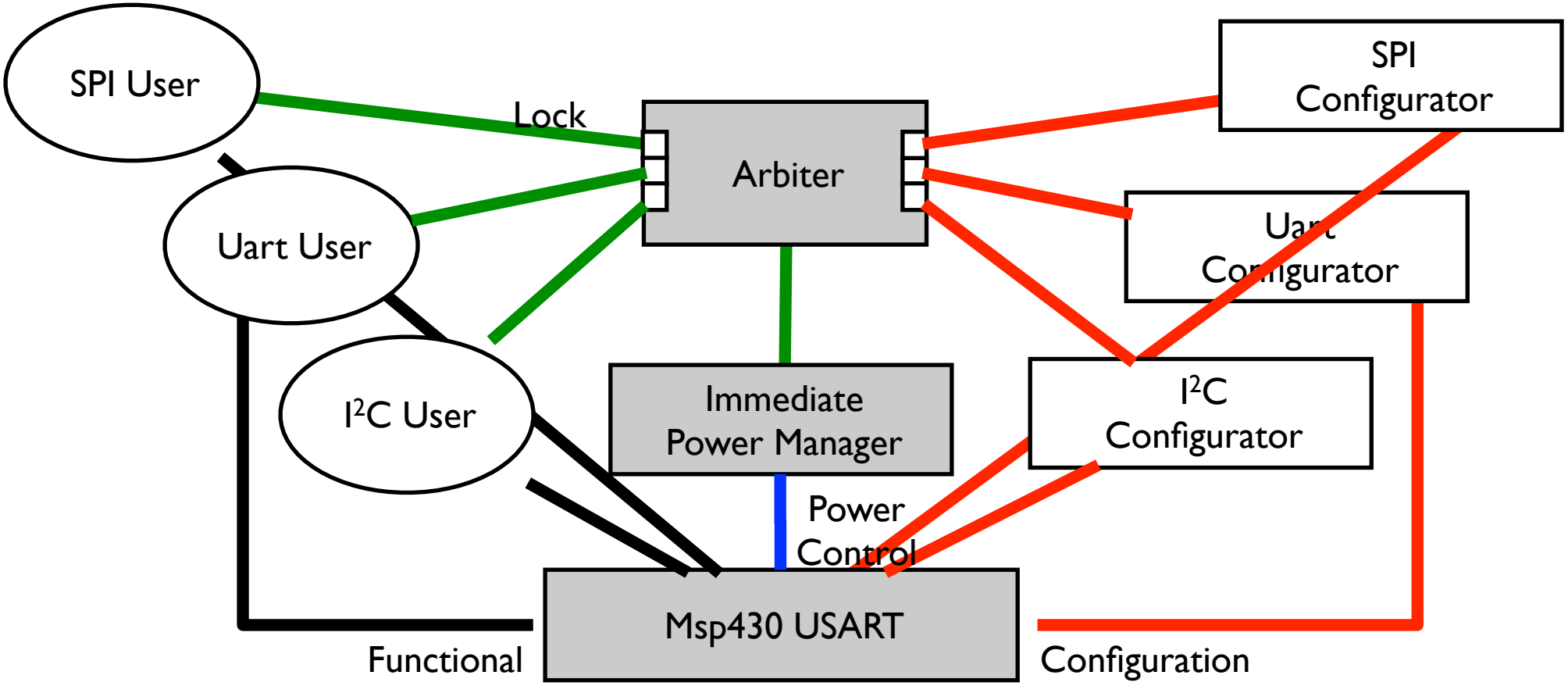
Shared Driver Example



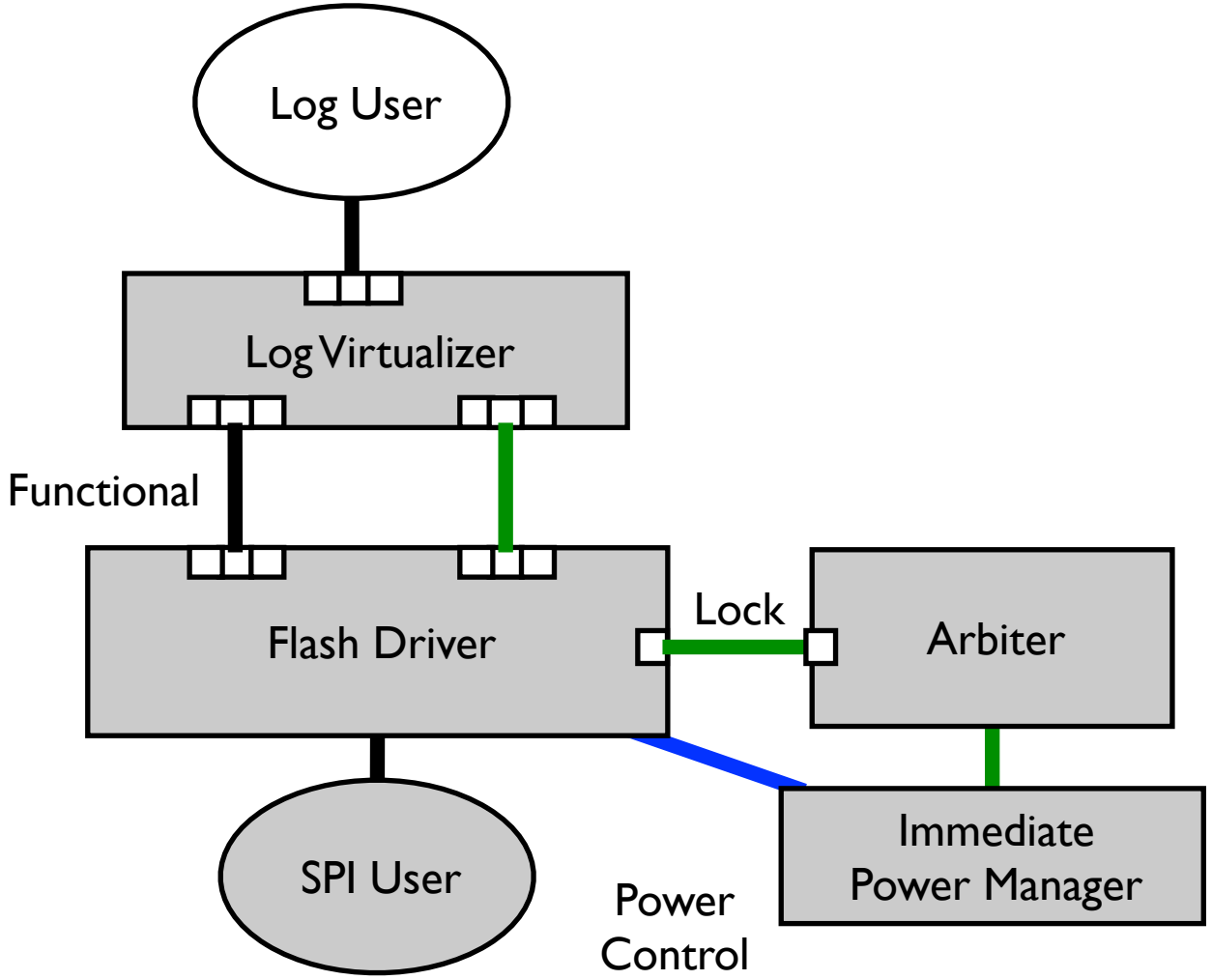
Shared Driver Example



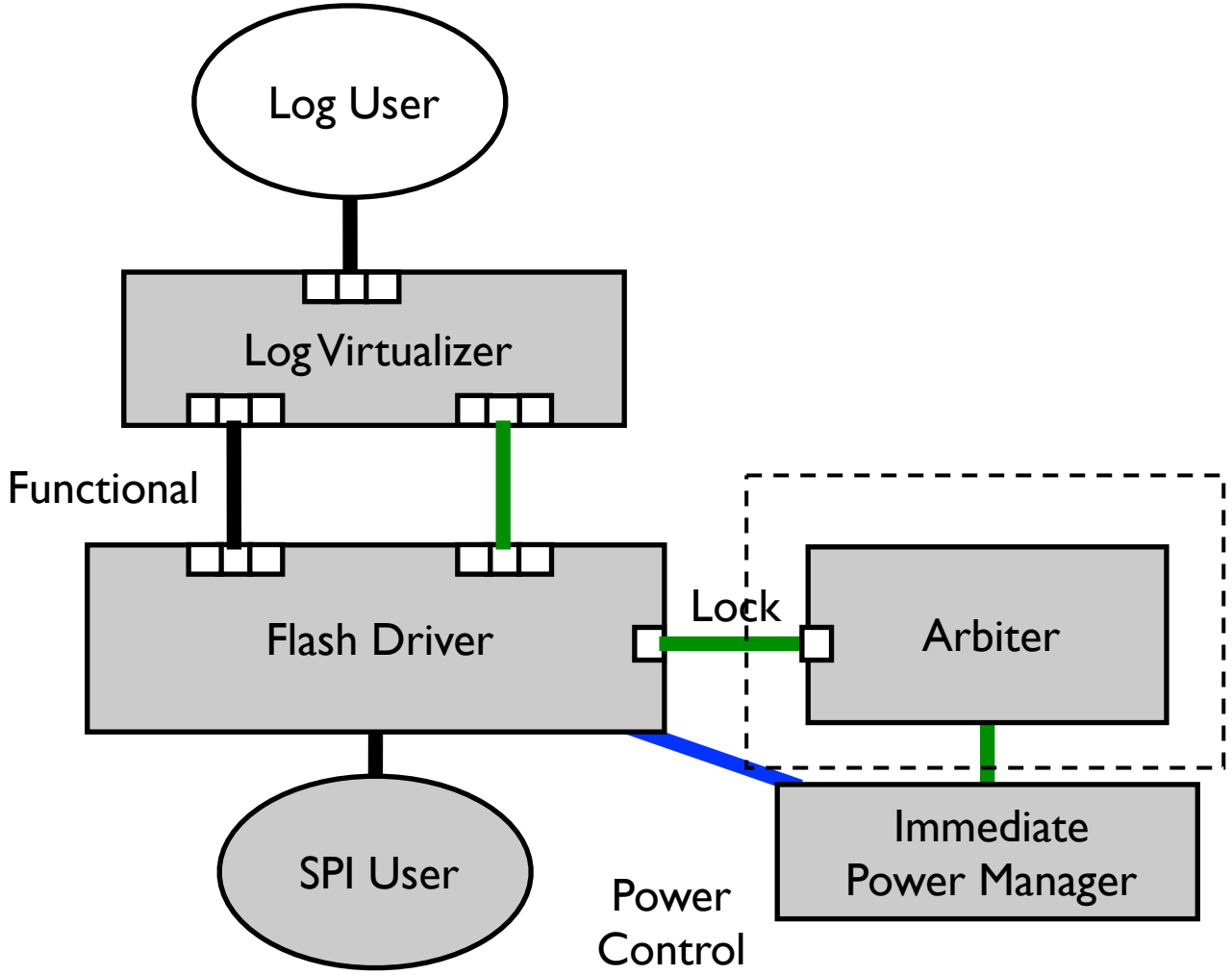
Shared Driver Example



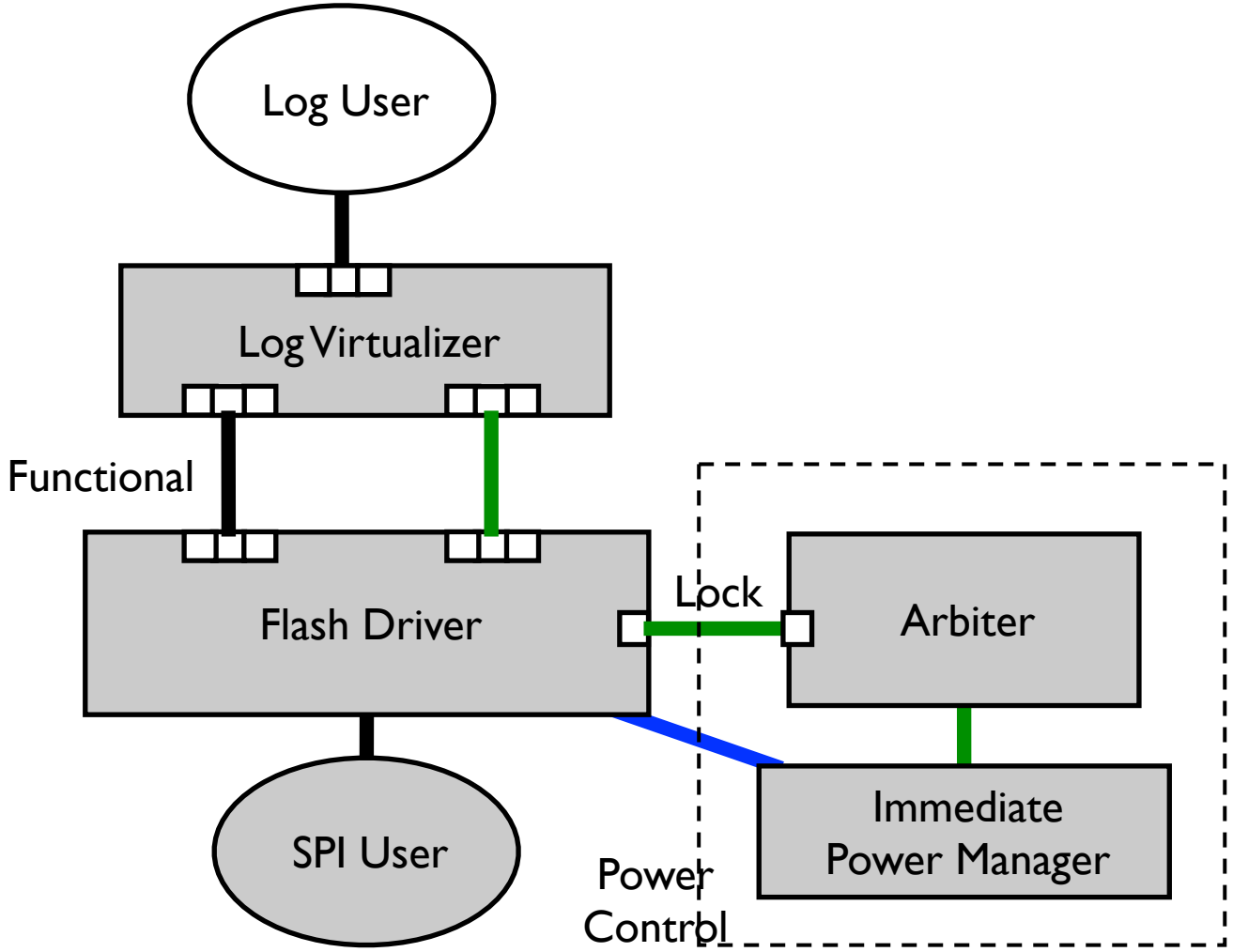
Virtualized Driver Example



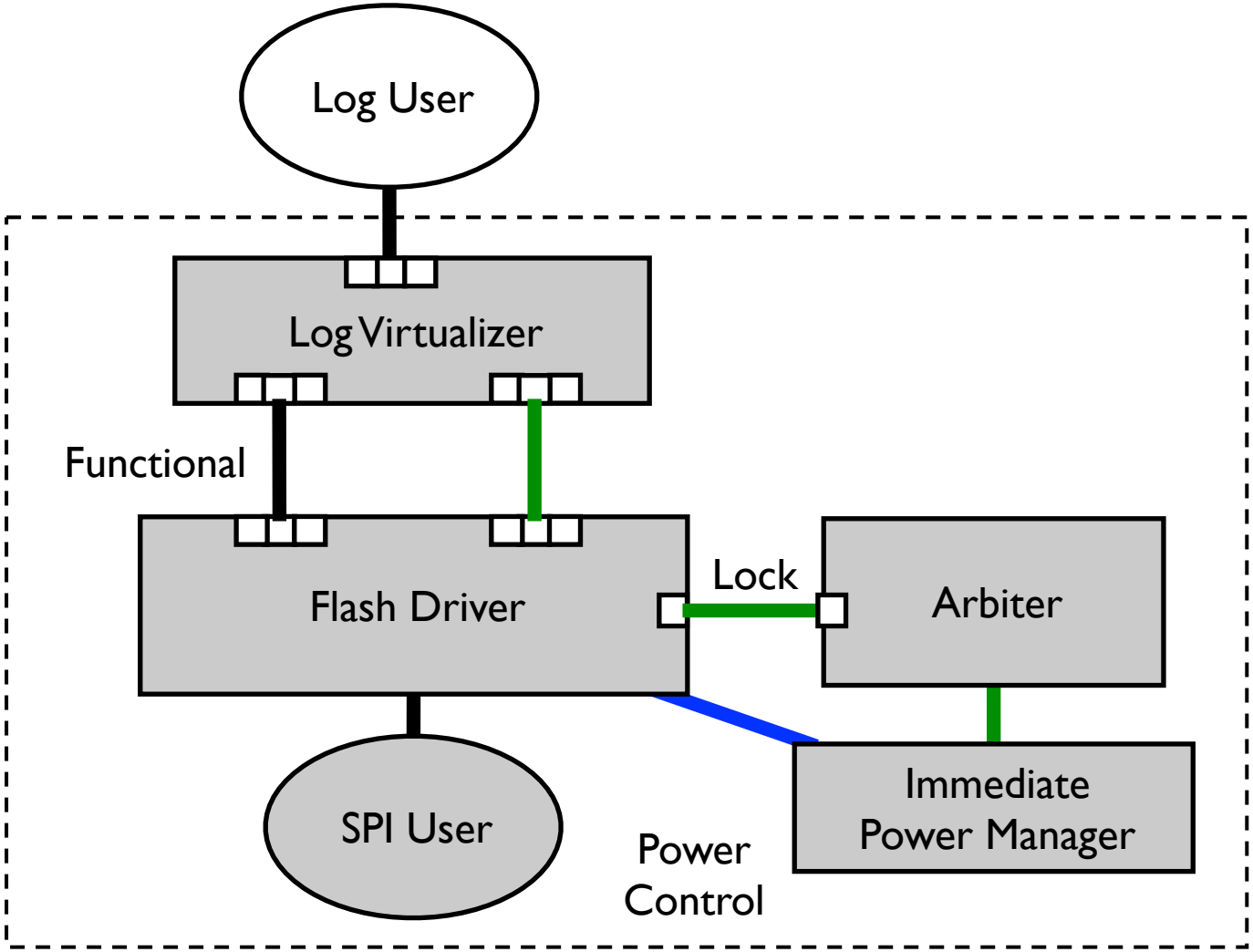
Virtualized Driver Example



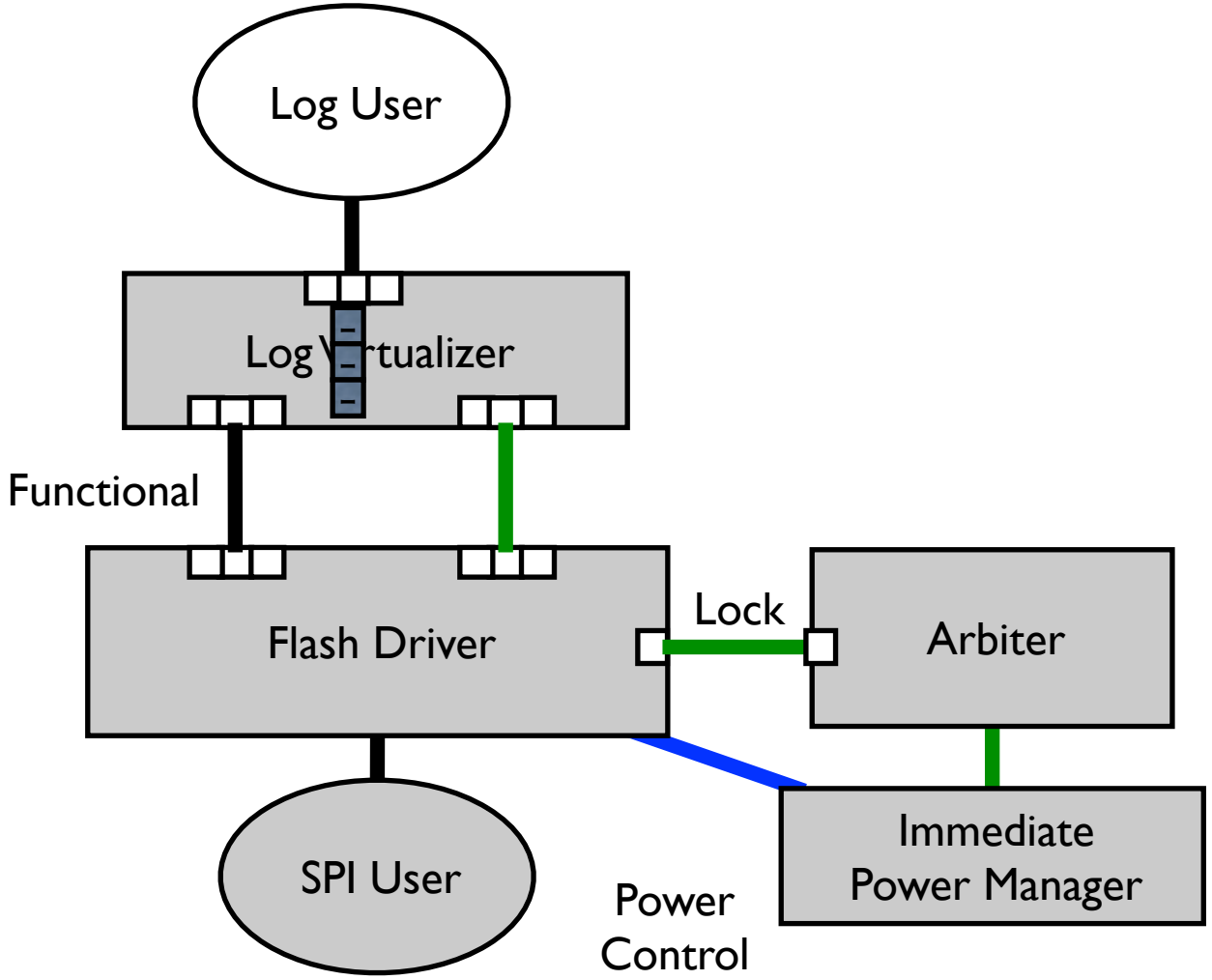
Virtualized Driver Example



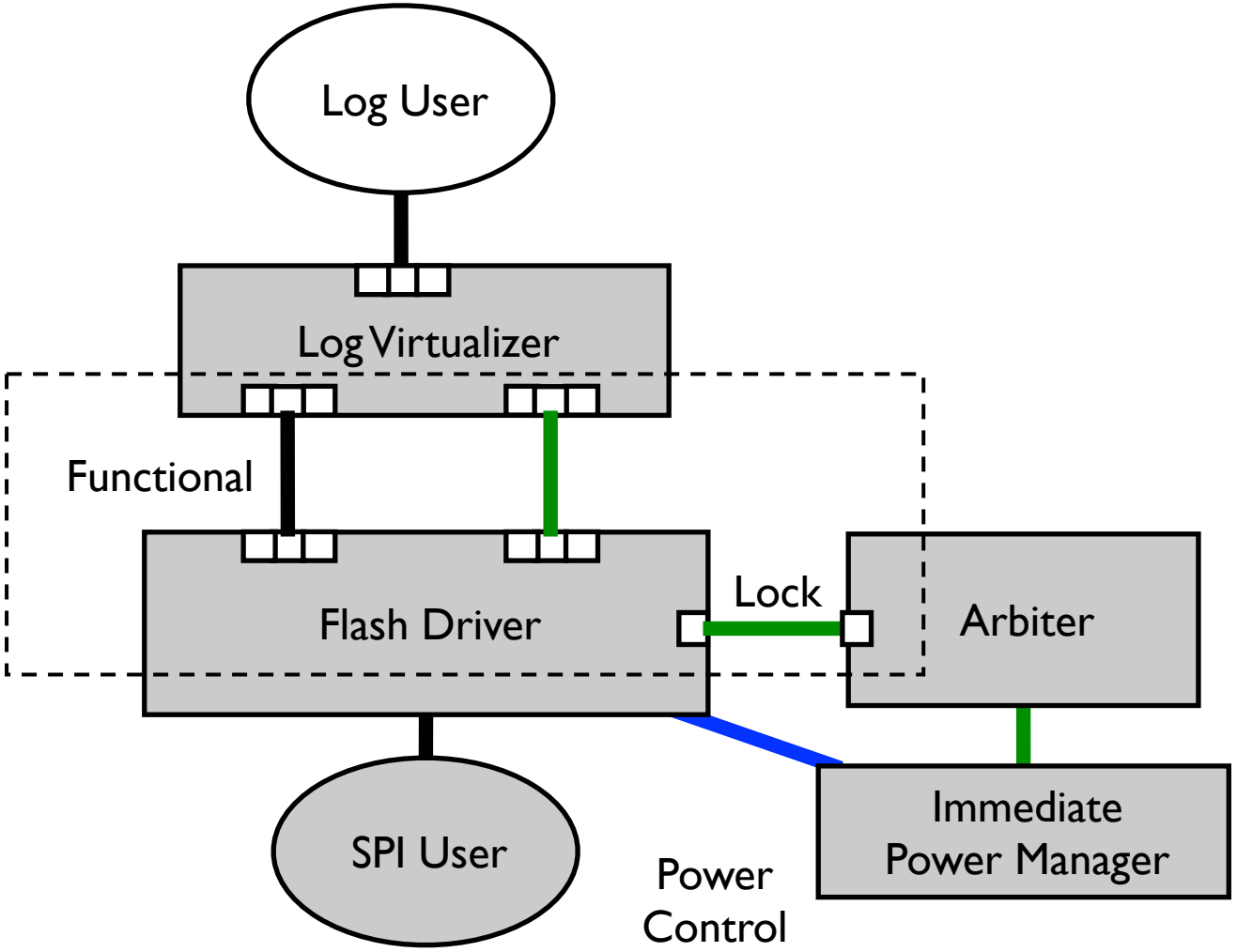
Virtualized Driver Example



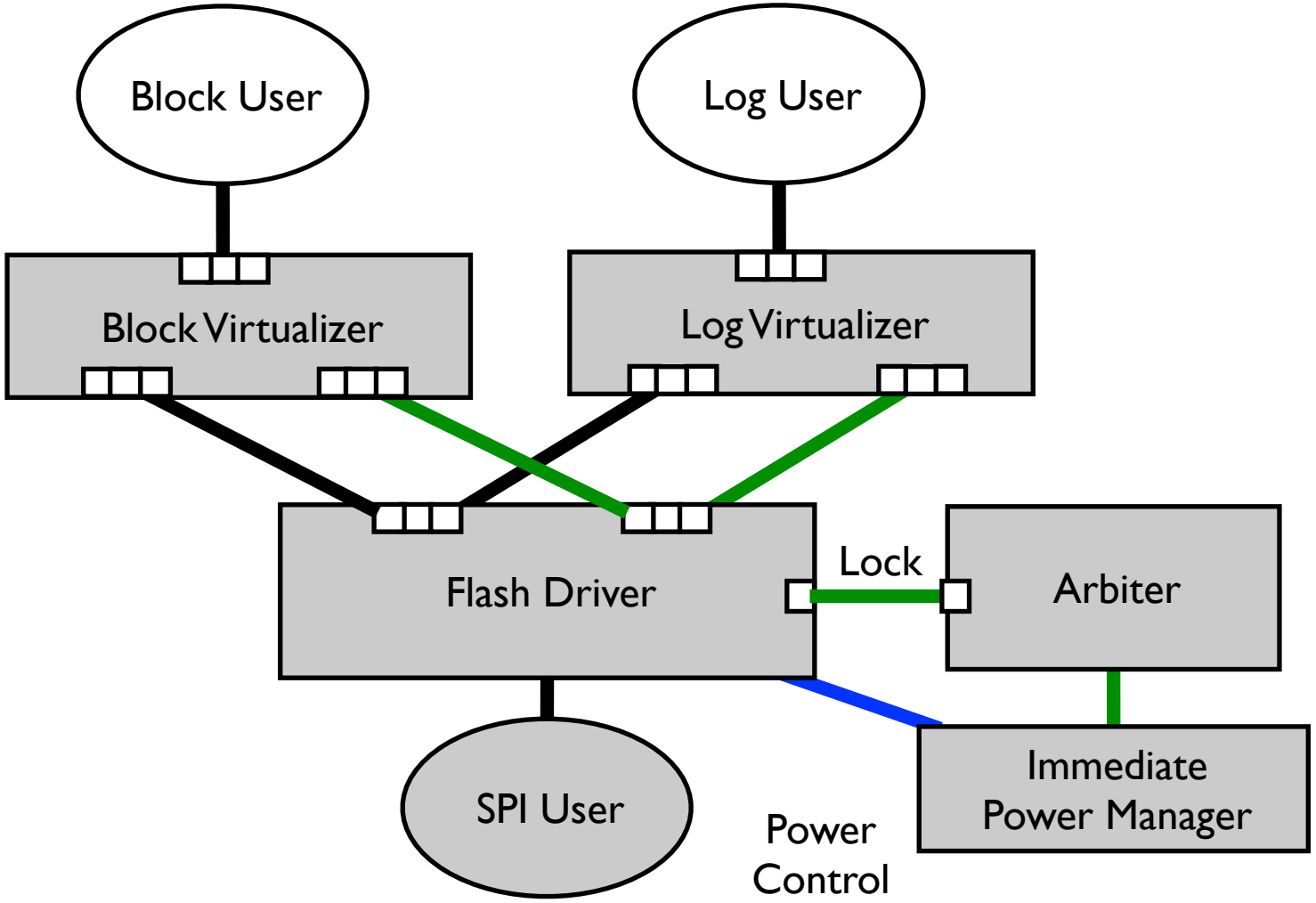
Virtualized Driver Example



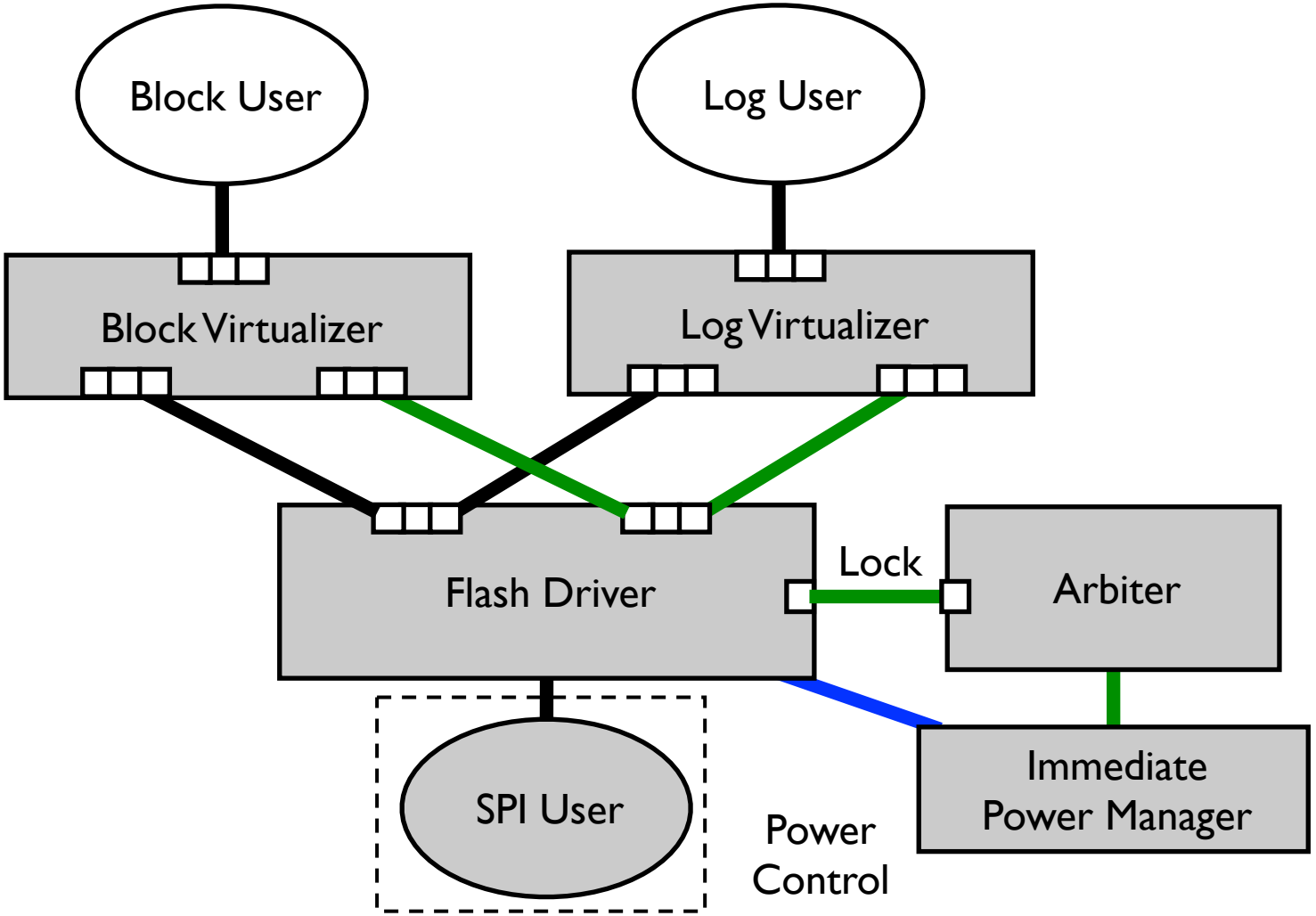
Virtualized Driver Example



Virtualized Driver Example



Virtualized Driver Example

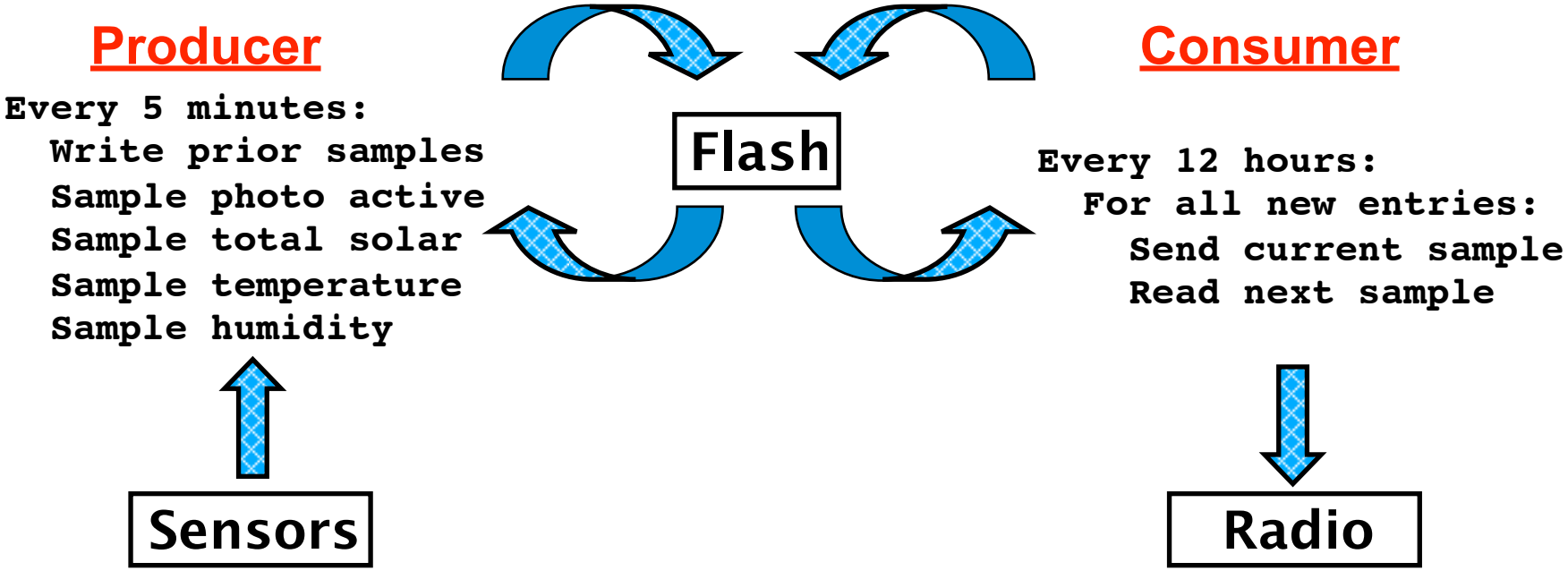


Outline

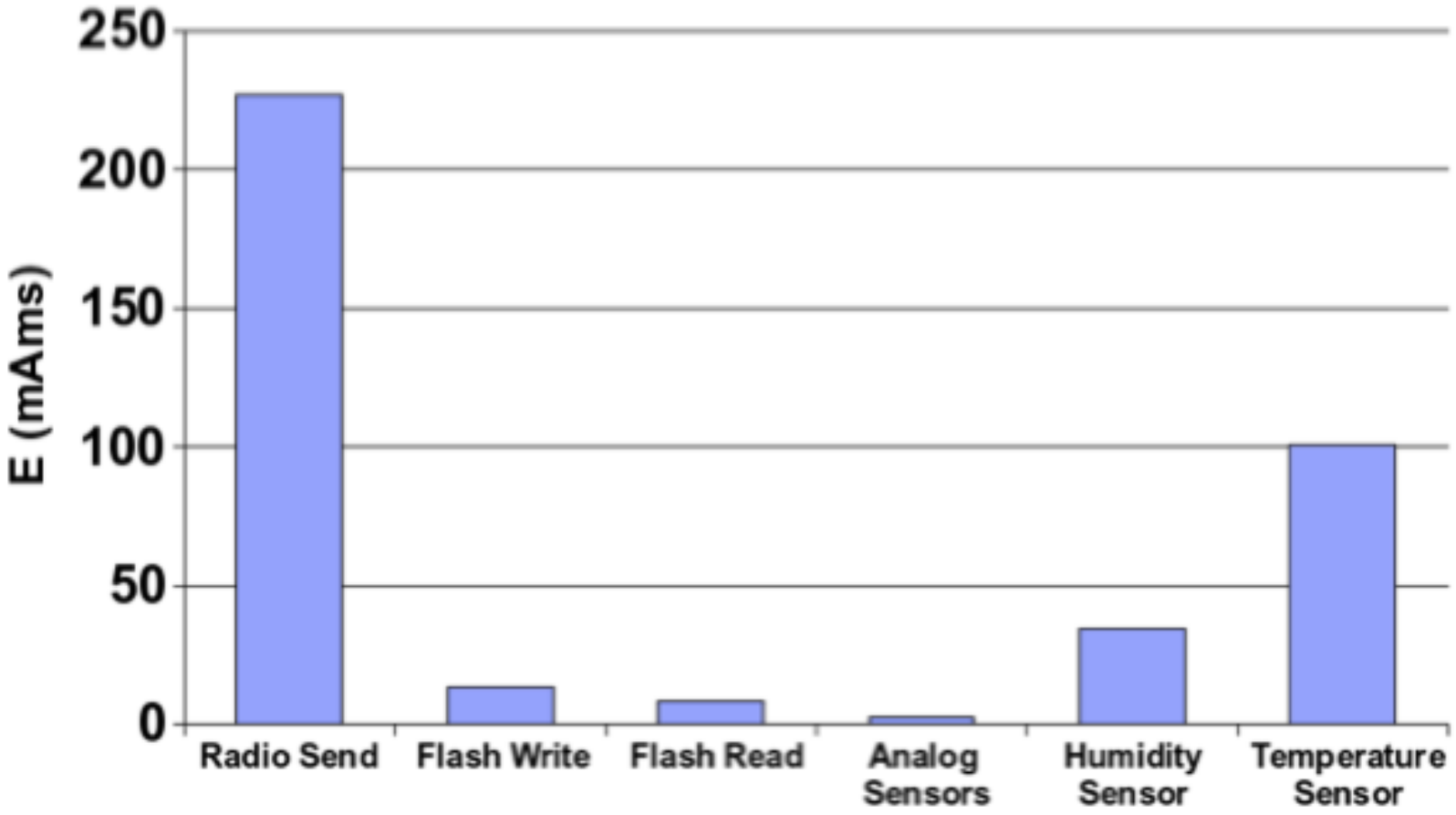
- Introduction and Motivation
- Platform and Application
- ICEM architecture
- Evaluation
- Conclusion

Applications

- **Hand Tuned – Most energy efficient**
- **ICEM – All concurrent operations**
- **Serial + – Optimal serial ordering**
- **Serial - – Worst case serial ordering**

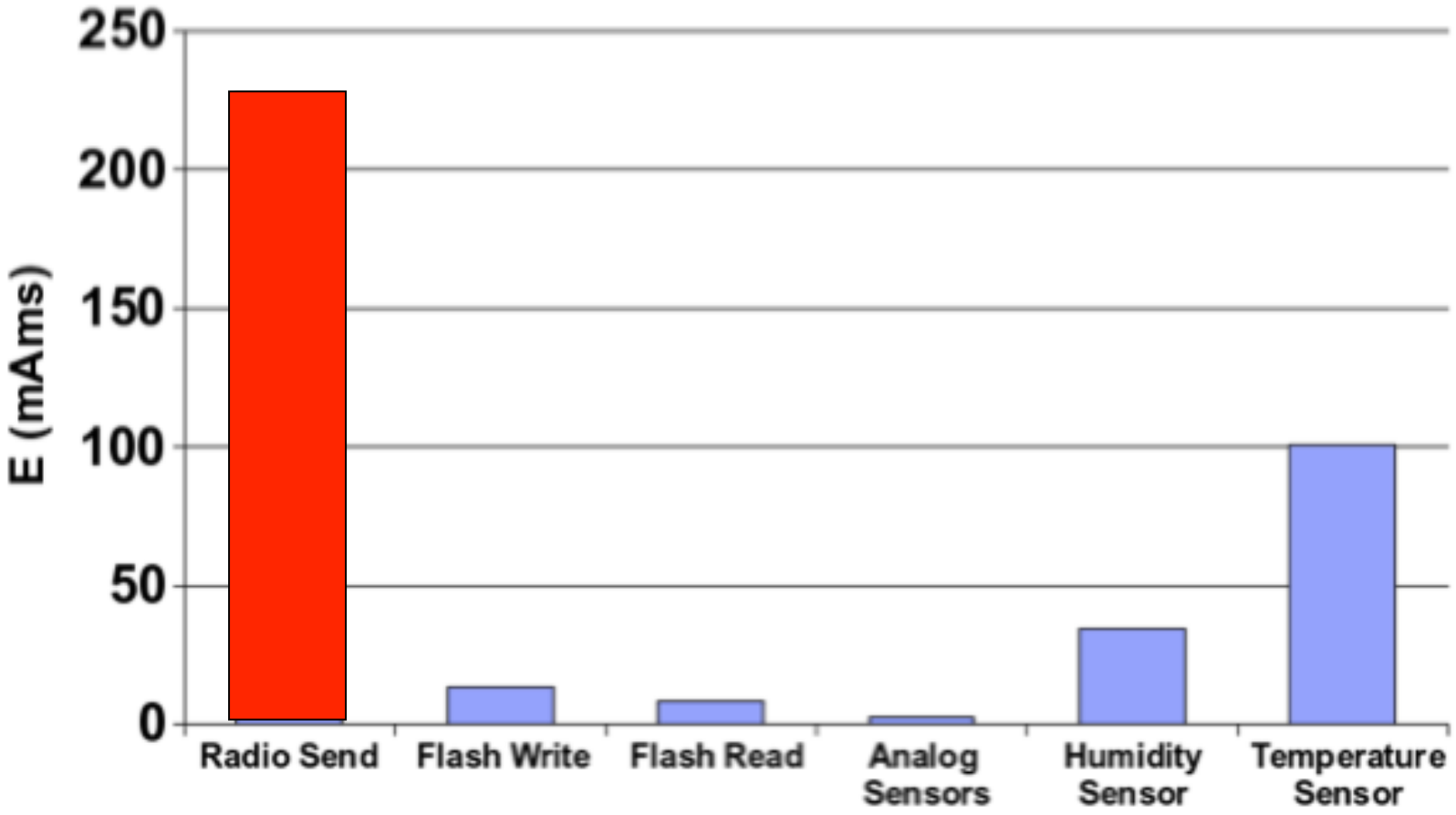


Tmote Energy Consumption



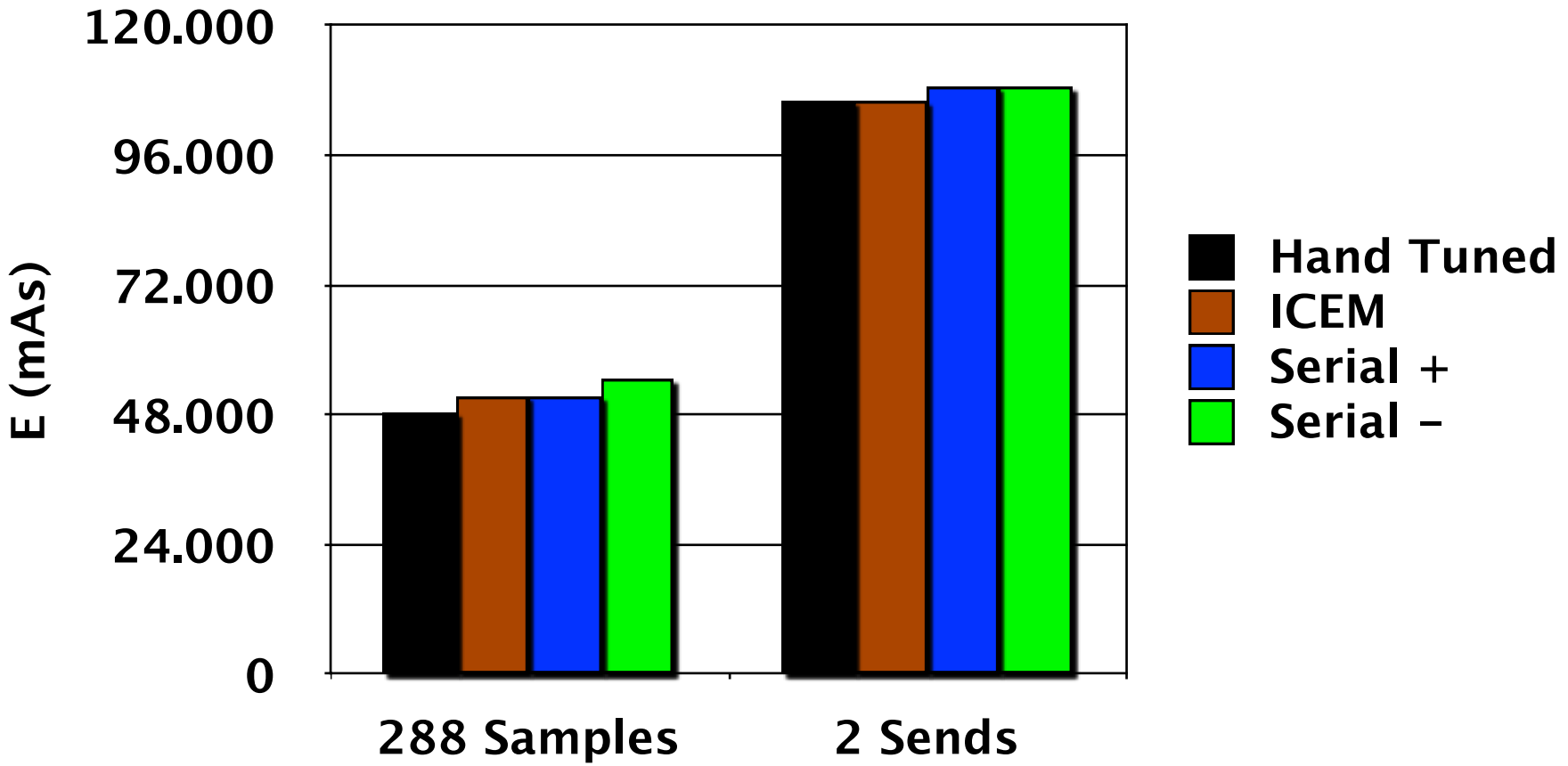
Average energy consumption for application operations

Tmote Energy Consumption



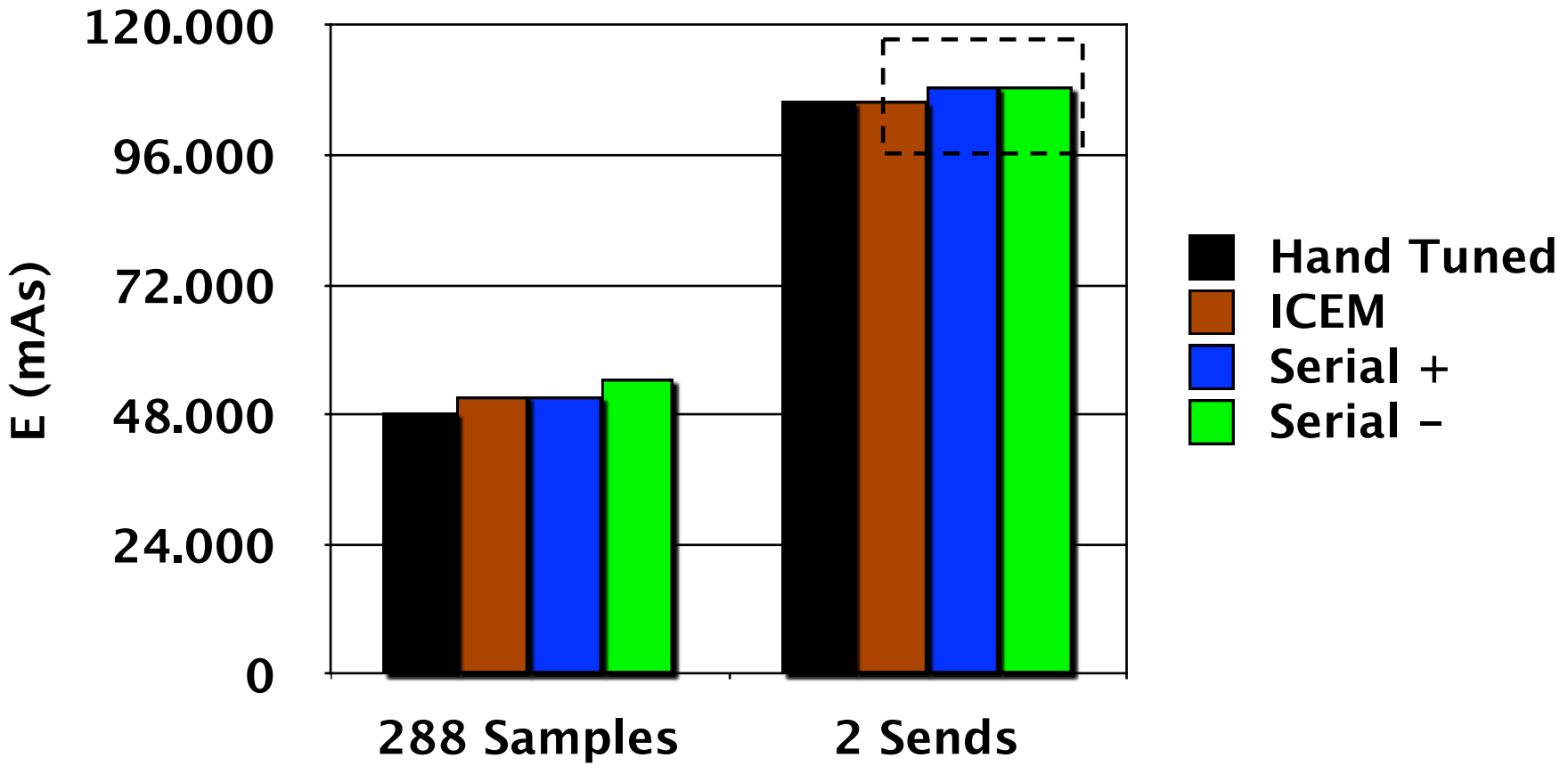
Average energy consumption for application operations

Application Energy Consumption



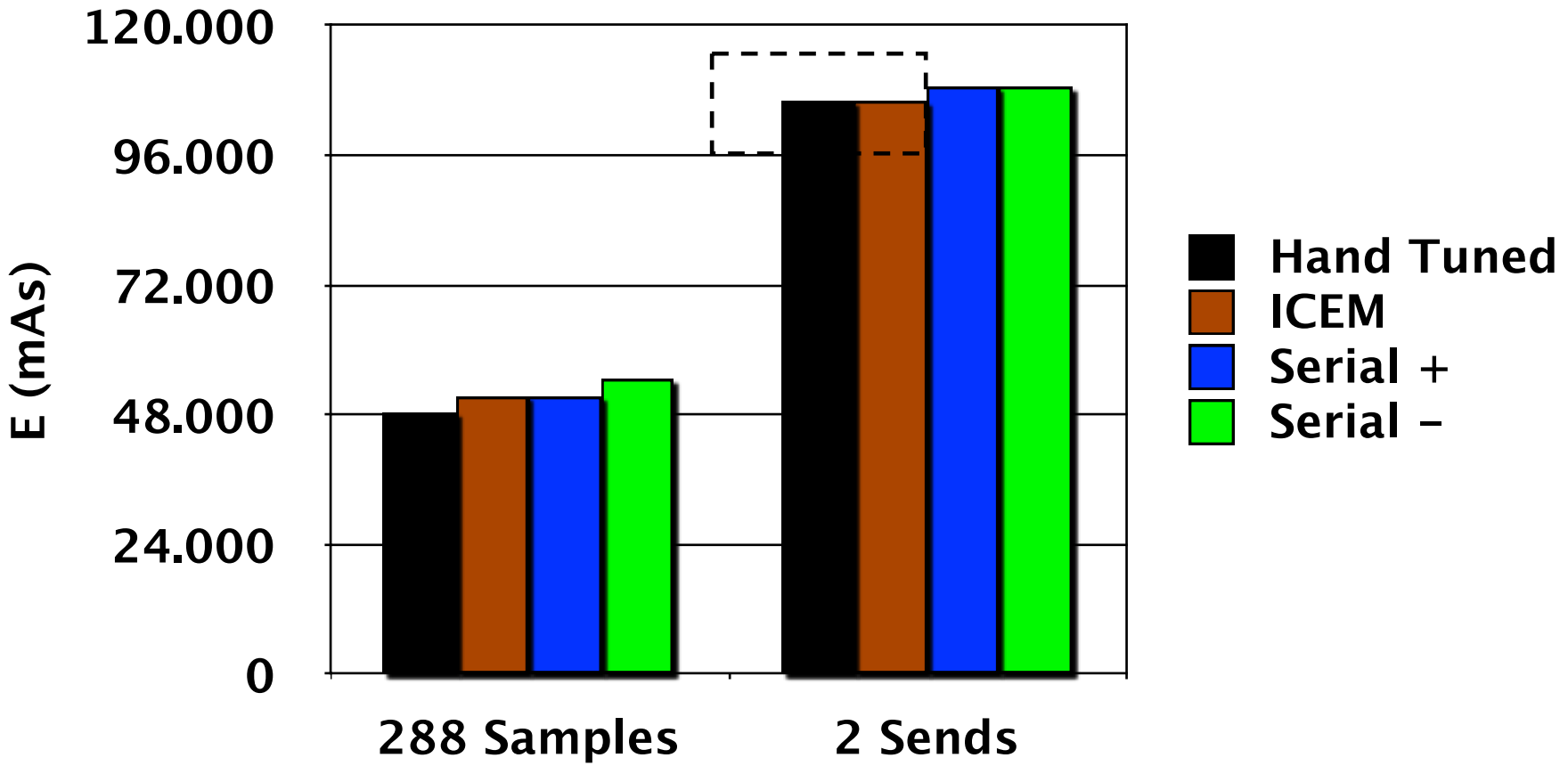
Application energy with 5 minute sampling interval and one send batch every 12 hours

Application Energy Consumption



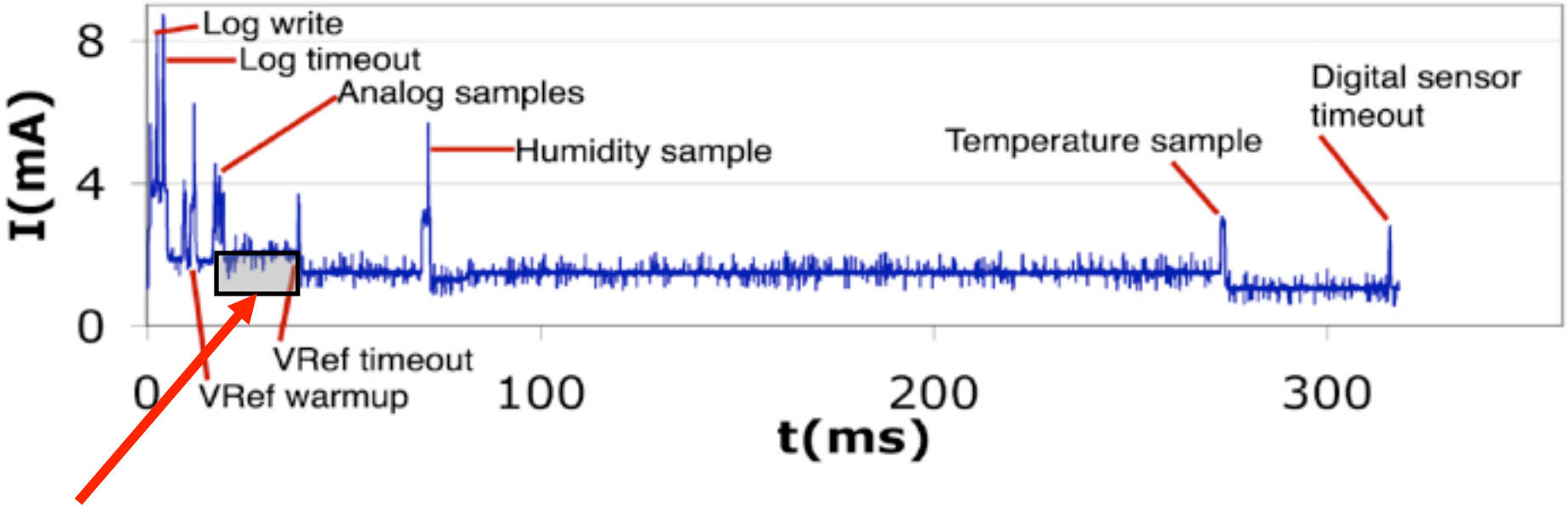
Application energy with 5 minute sampling interval and one send batch every 12 hours

Application Energy Consumption



Application energy with 5 minute sampling interval and one send batch every 12 hours

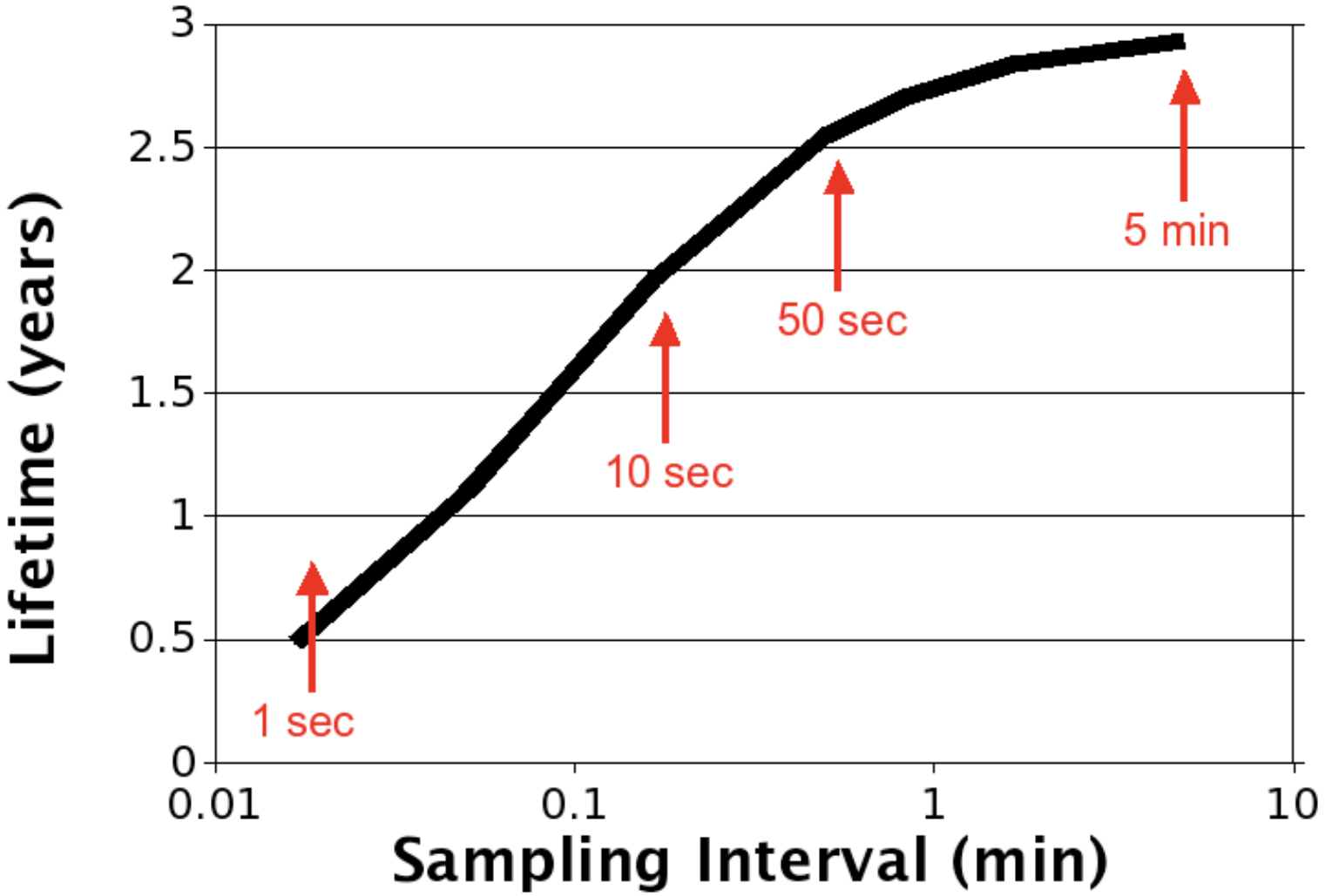
Sampling Power Trace



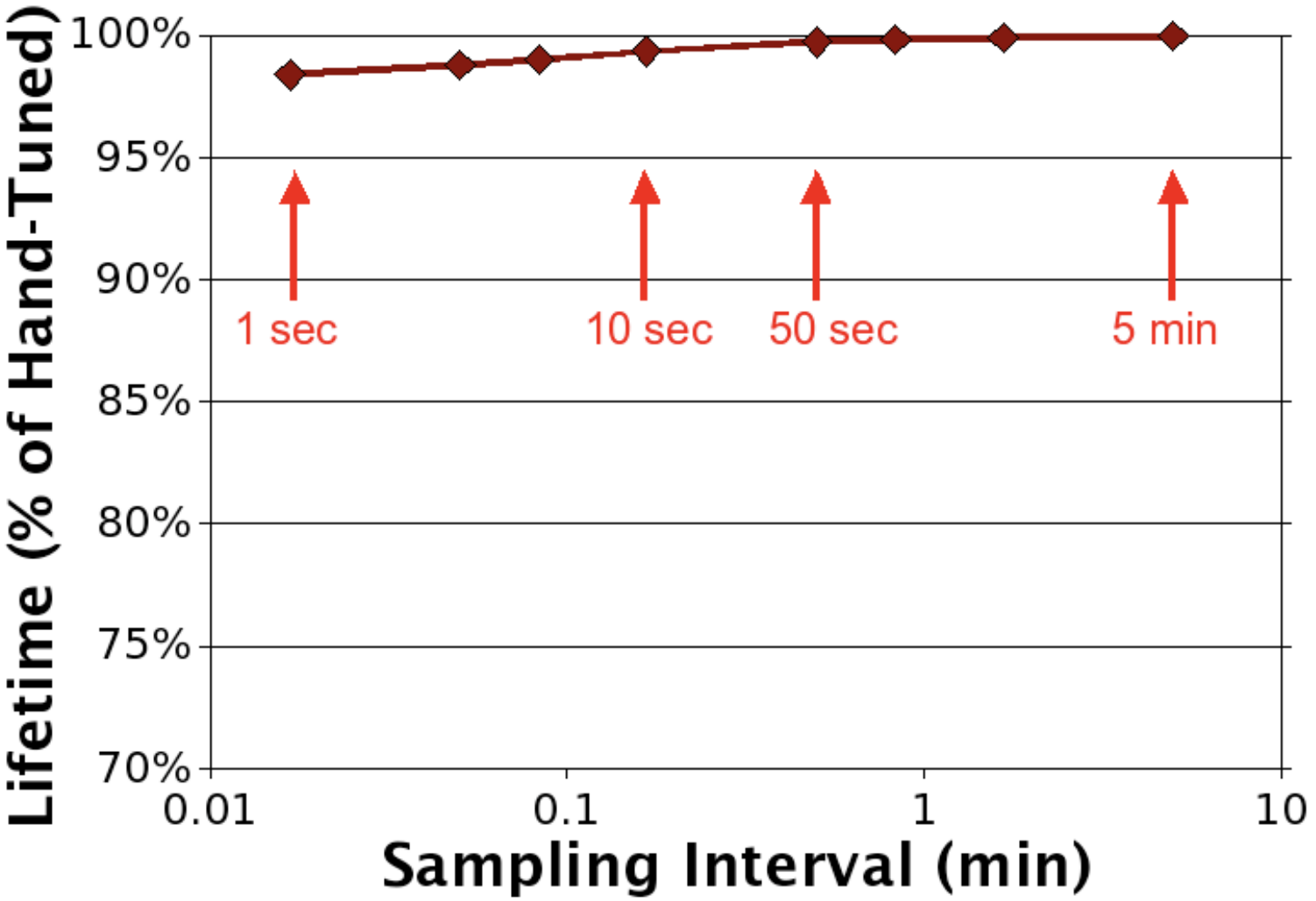
Overhead of ICEM to Hand-Tuned Implementation
= ADC Timeout + Power Lock Overheads
With 288 samples per day
≈ 2.9 mAs/day
≈ 1049 mAs/year

Insignificant compared to total
5.60% of total sampling energy
0.03% of total application energy

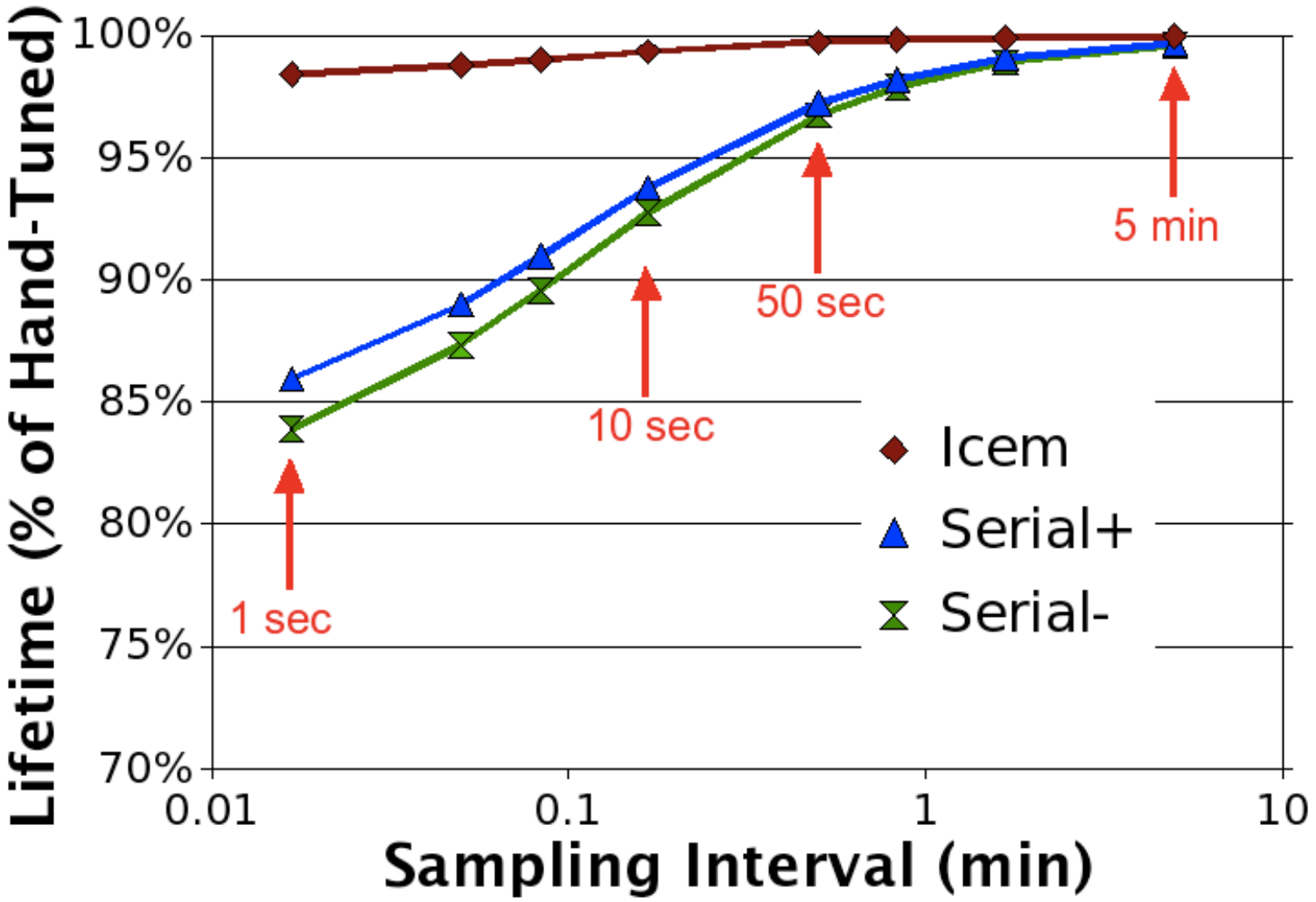
Expected Node Lifetimes



Expected Node Lifetimes



Expected Node Lifetimes



Evaluation Conclusions

- **Conclusions about the OS**
  - Small RAM/ROM overhead
  - Small computational overhead
  - Efficiently manages energy when given enough information
- **Conclusions for the developer**
  - Build drivers short power down timeouts
  - Submit I/O requests in parallel

Conclusion

- **ICEM: Integrated Concurrency and Energy Management**
  - Device driver architecture for low power devices
  - At least 98.4% as energy efficient as hand-tuned implementation of representative application
- **Simplifies application and driver development**
- **Questions the assumption that applications must be responsible for all energy management and cannot have a standardized OS with a simple API**

Questions?

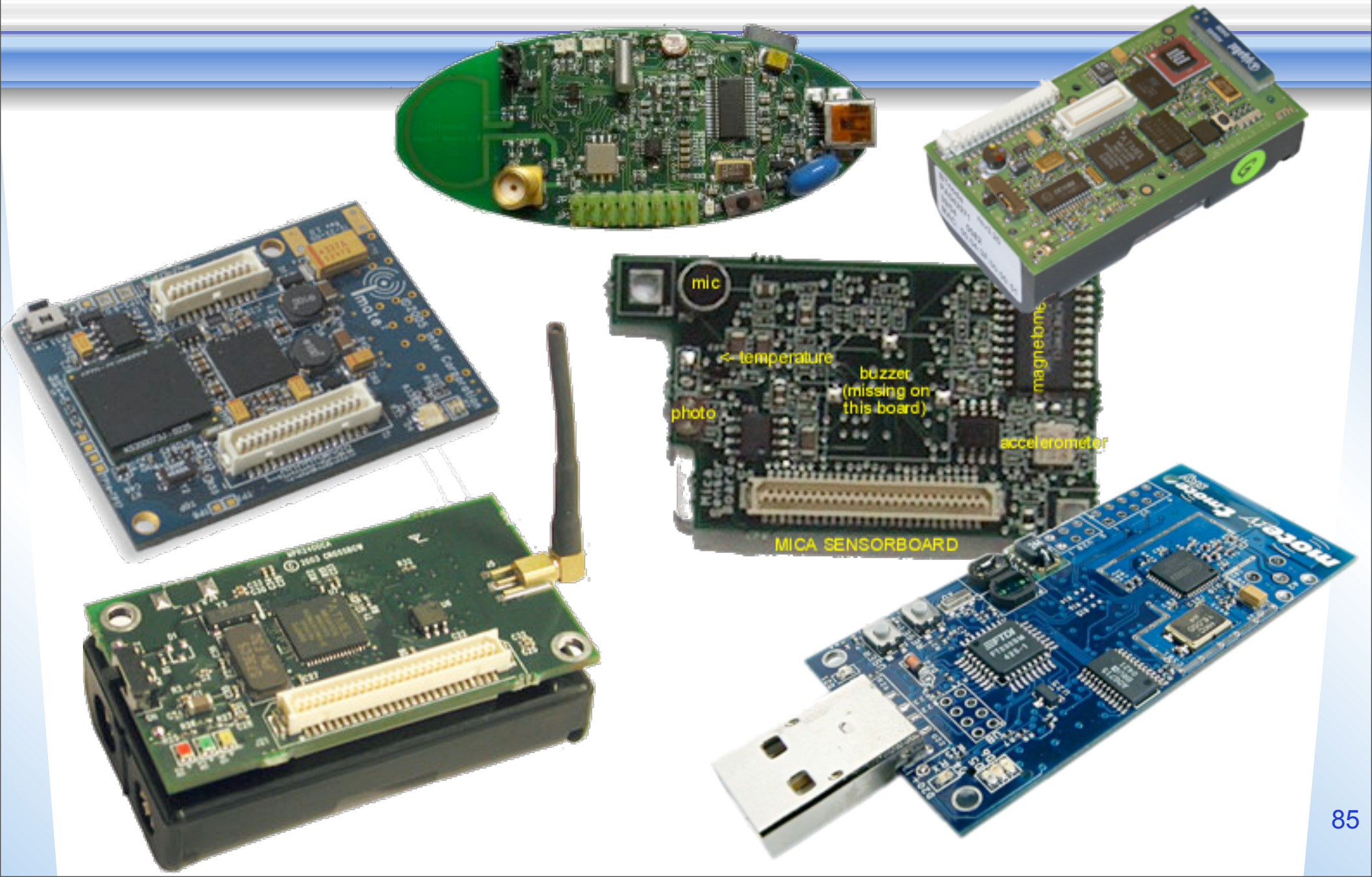
TKN Telecommunication Networks Group

ARCHROCK

Questions?

- SourceForge TinyOS CVS repository:
  - http://sourceforge.net/cvs/?group_id=28656
- Library components and interfaces
  - tinyos-2.x/tos/interfaces
  - tinyos-2.x/tos/lib/power
  - tinyos-2.x/tos/system
- Example Drivers
  - Atmega128 ADC: tos/chips/atm128/adc
  - MTS300 Photo: tos/sensorboards/mts300
  - MSP430 USART0: tos/chips/msp430/usart
  - Storage: tos/chips/stm25p
  - CC2420: tos/chips/cc2420

Hardware


mic
temperature
buzzer
(missing on
this board)
photo
magnetometer
accelerometer
MICA SENSORBOARD

Future Work

- Compile-time deadlock detection
- Conditional I/O Operations

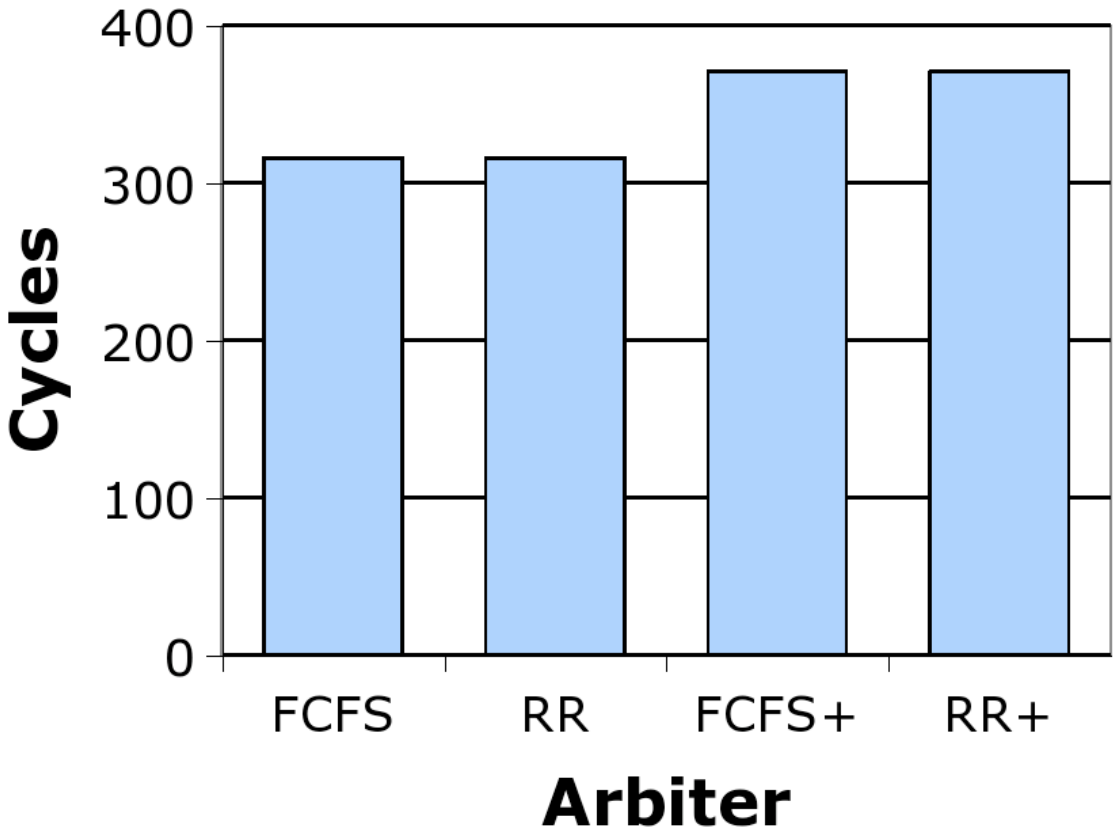
  if(Temp.read() > 30) Humidity.read()
- Improved OS scheduling

Disclaimers

- Omission of MCU power management discussion
- Run time checks on arbiter operations
- Implementing ICEM in threaded OS

Microbenchmarks: Overhead

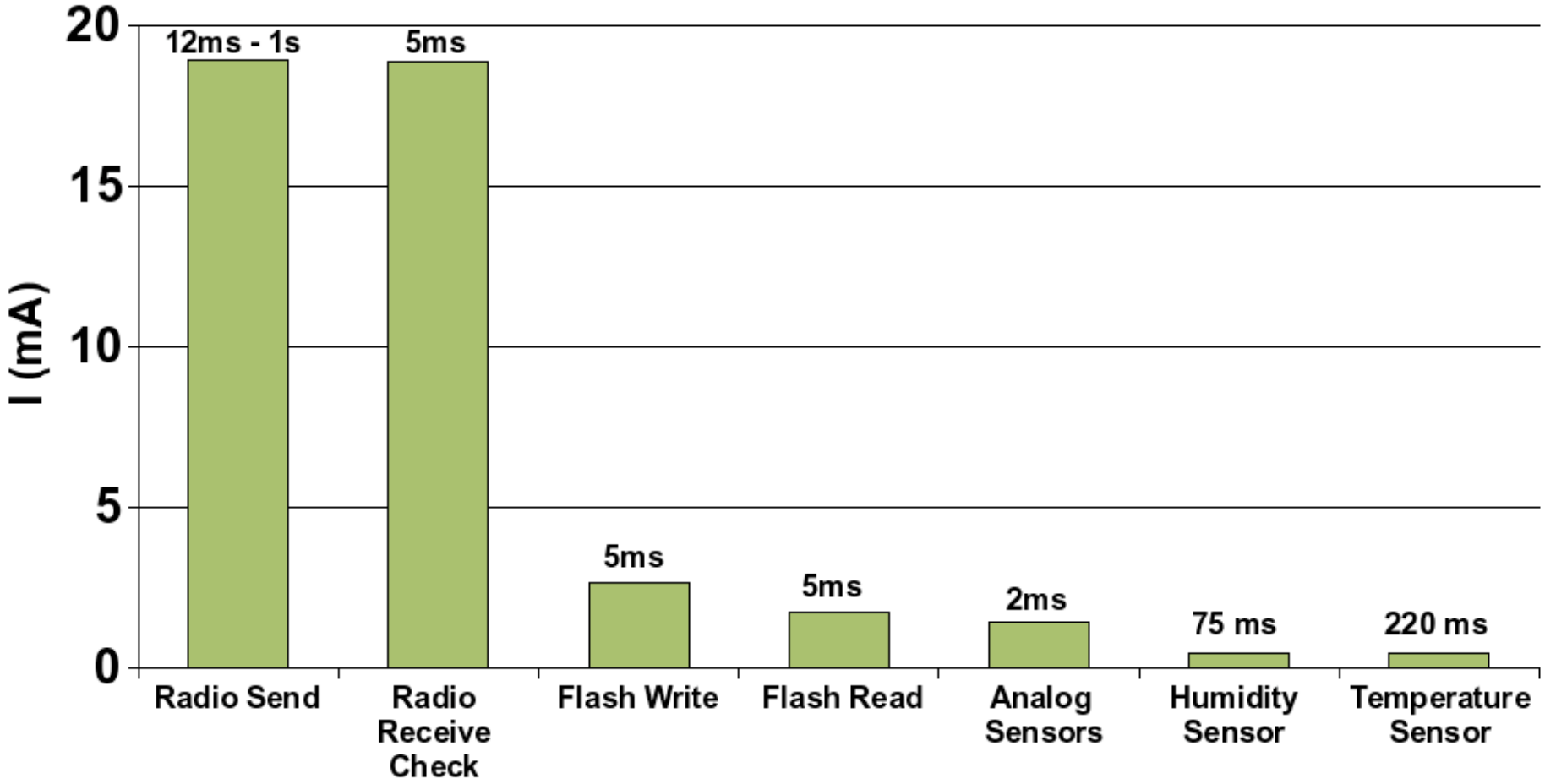
- Per request MCU cycle overhead (locking, unlocking)



Worst Case = 371 cycles
≈ 93 µs on Tmote
≈ 0.168 mAms

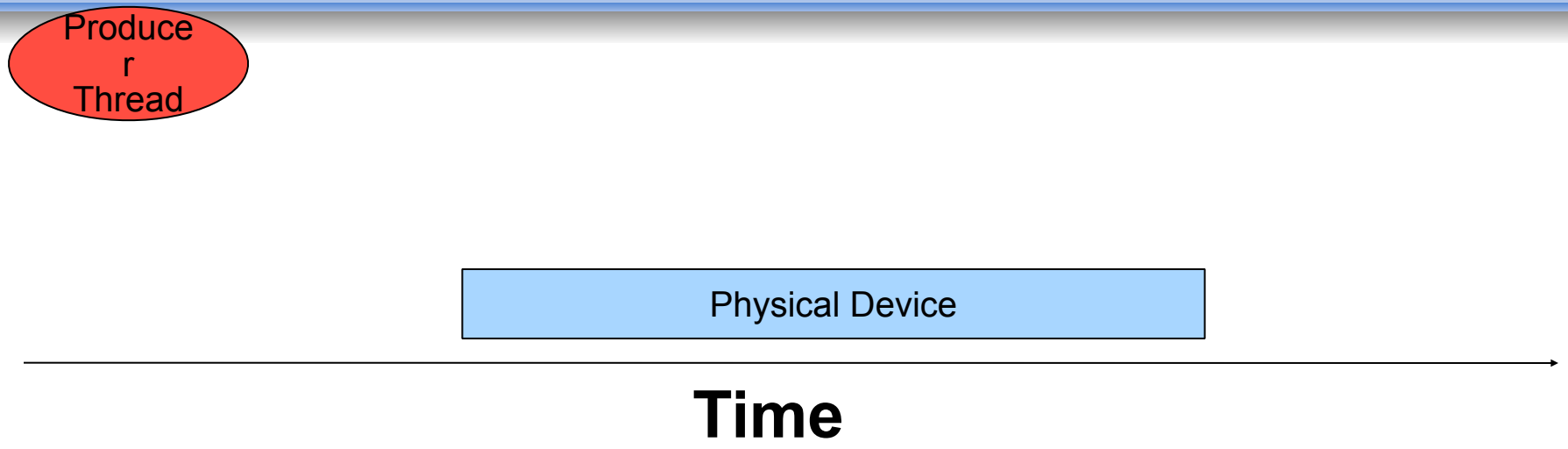
Very small

Tmote Current Consumption

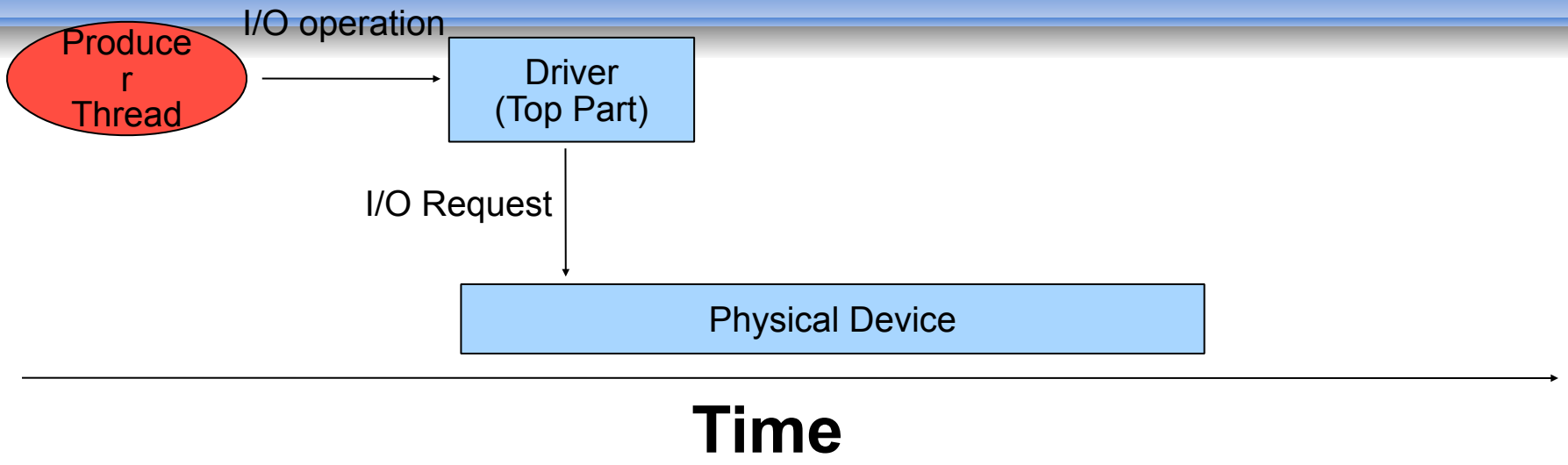


Average current consumption for application operations

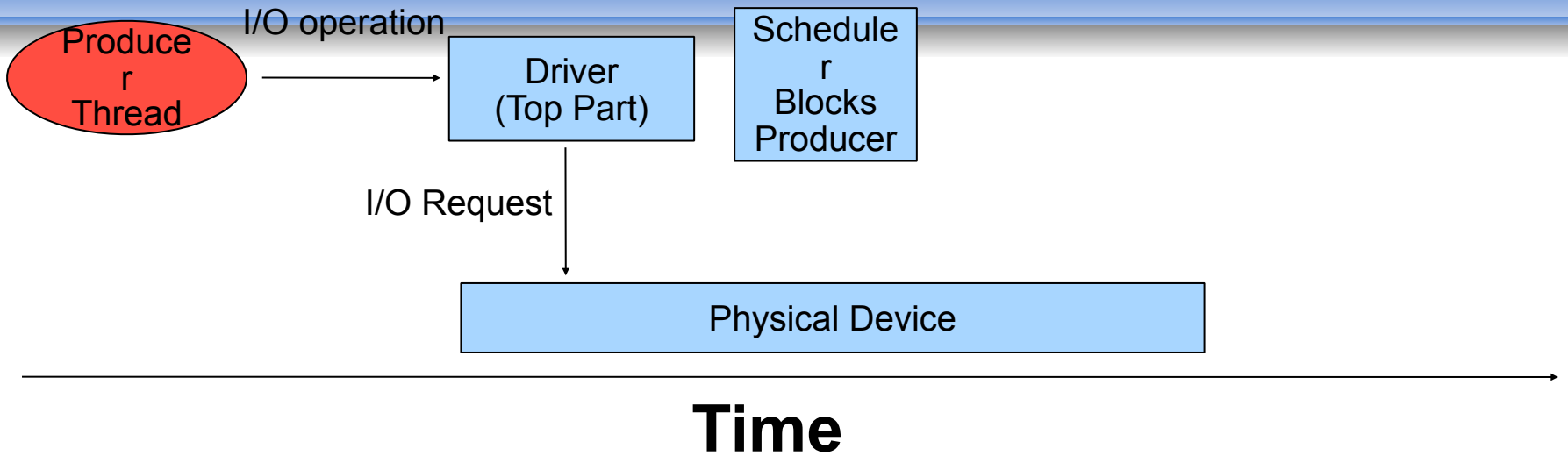
Traditional Concurrency Control



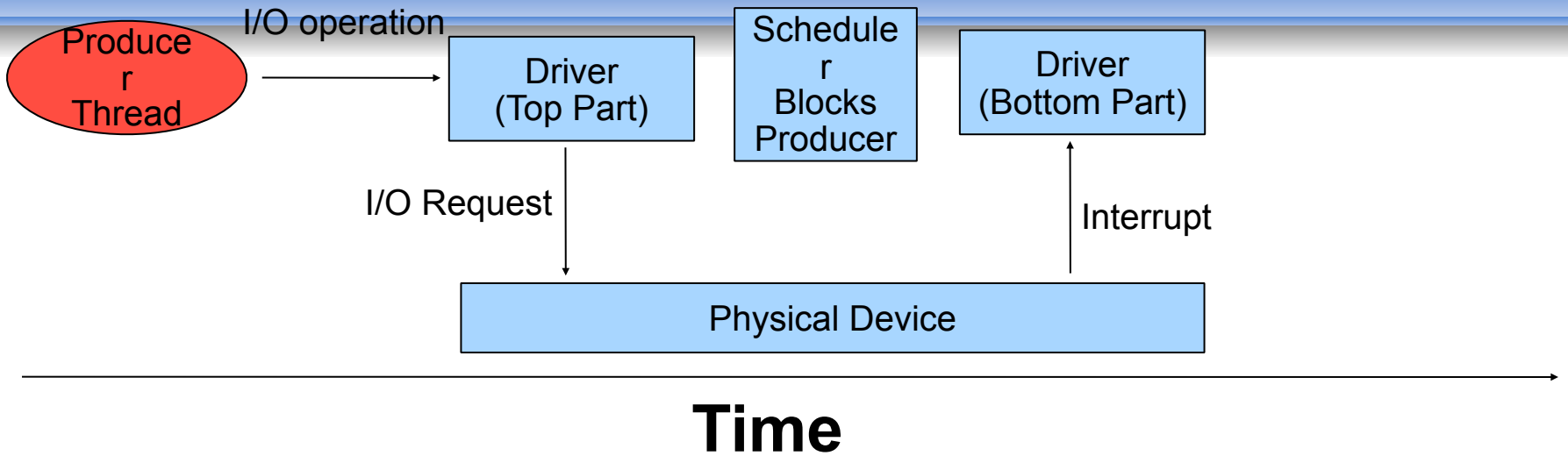
Traditional Concurrency Control



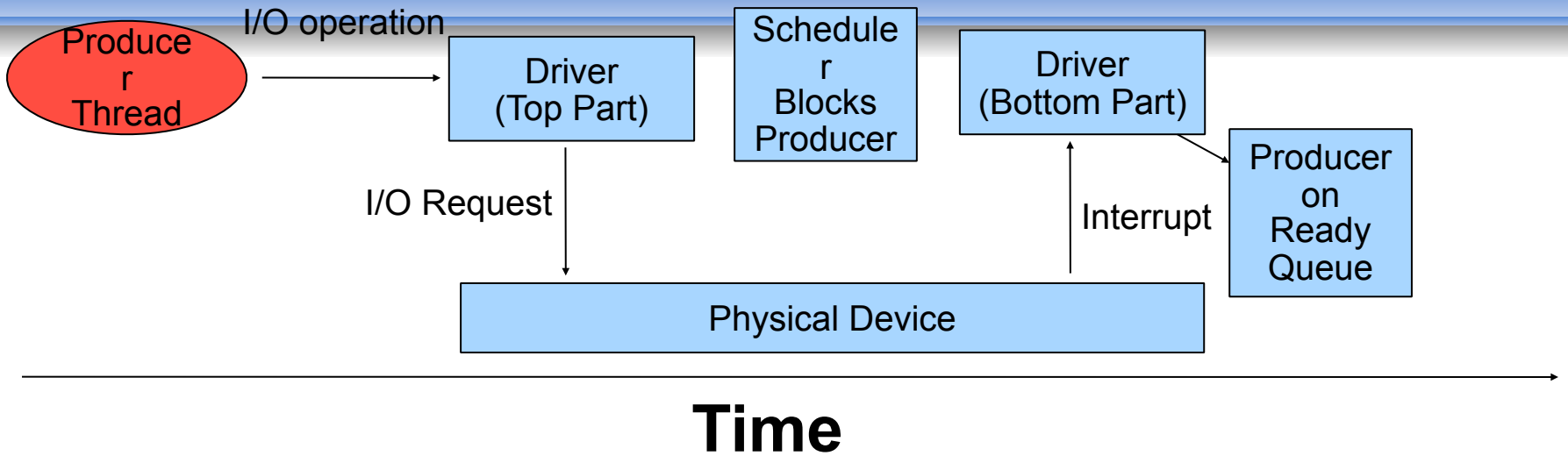
Traditional Concurrency Control



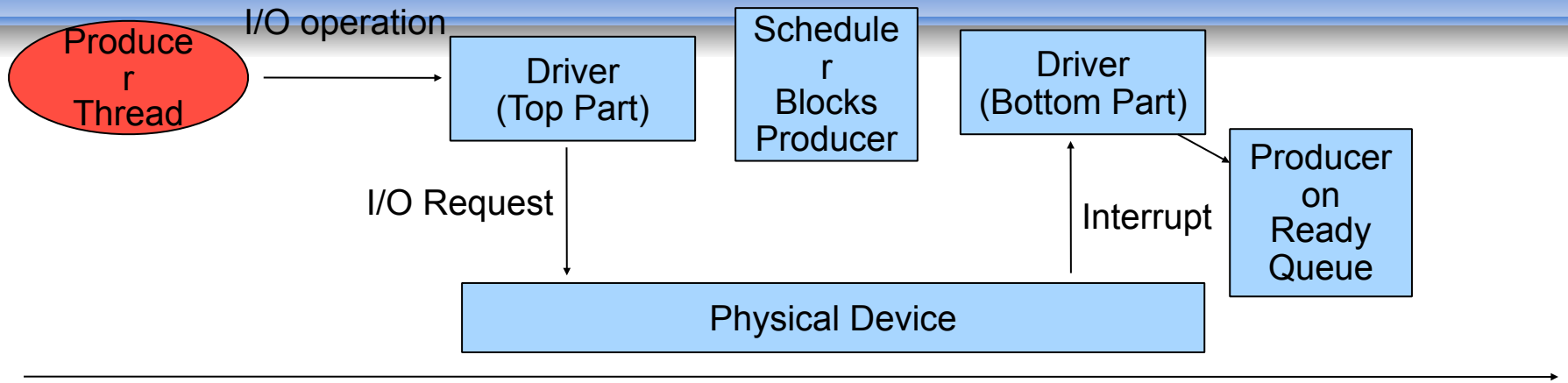
Traditional Concurrency Control



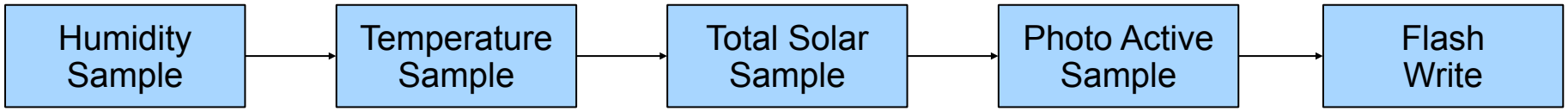
Traditional Concurrency Control



Traditional Concurrency Control

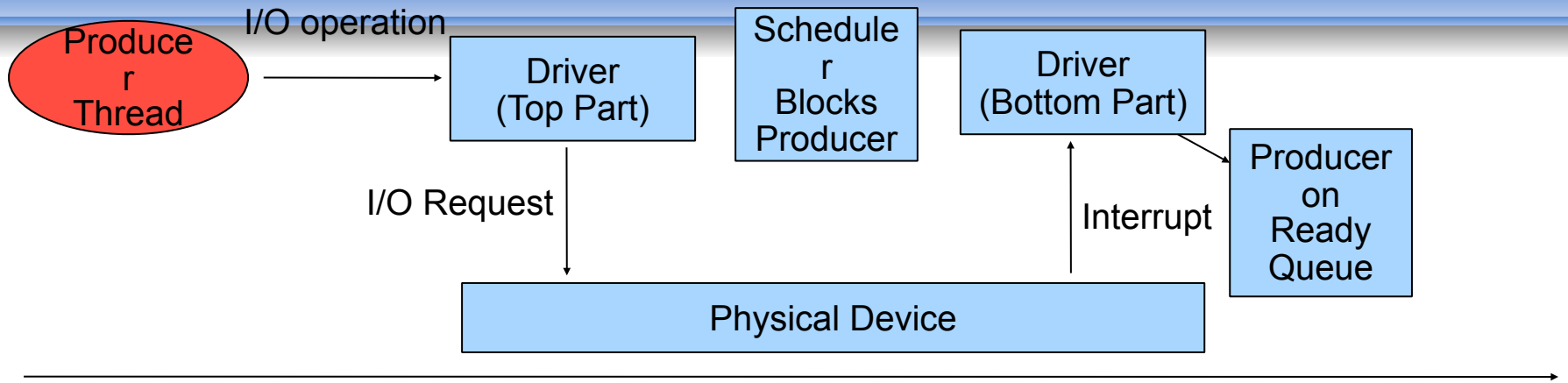


Single Thread:

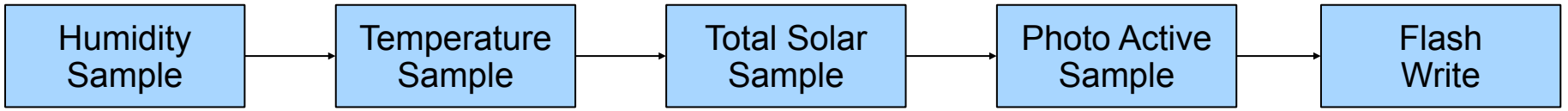


No potential for concurrency

Traditional Concurrency Control

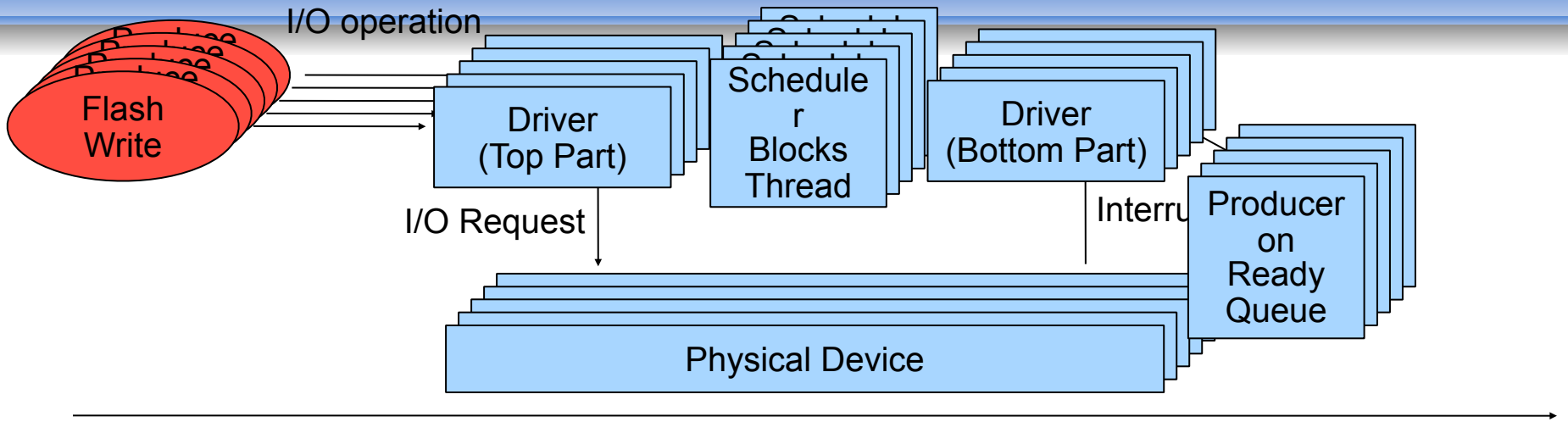


Single Thread:

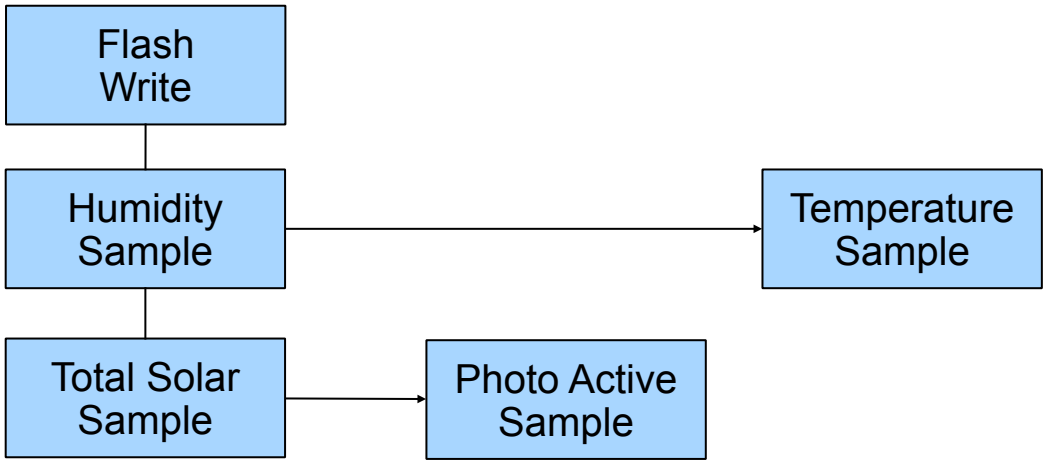


No potential for concurrency
Ordering Important

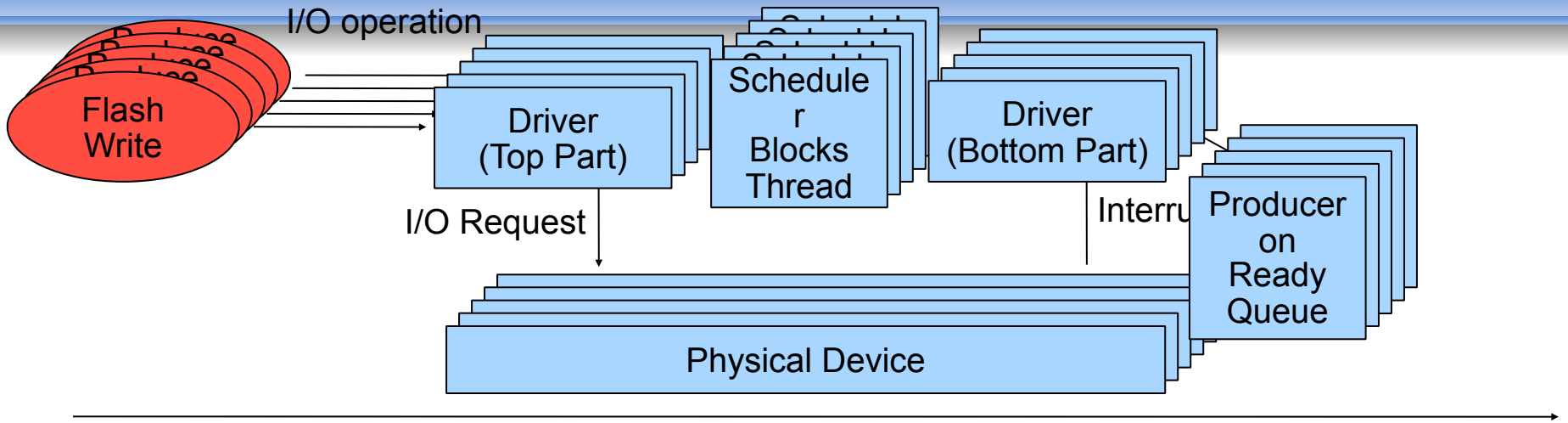
Traditional Concurrency Control



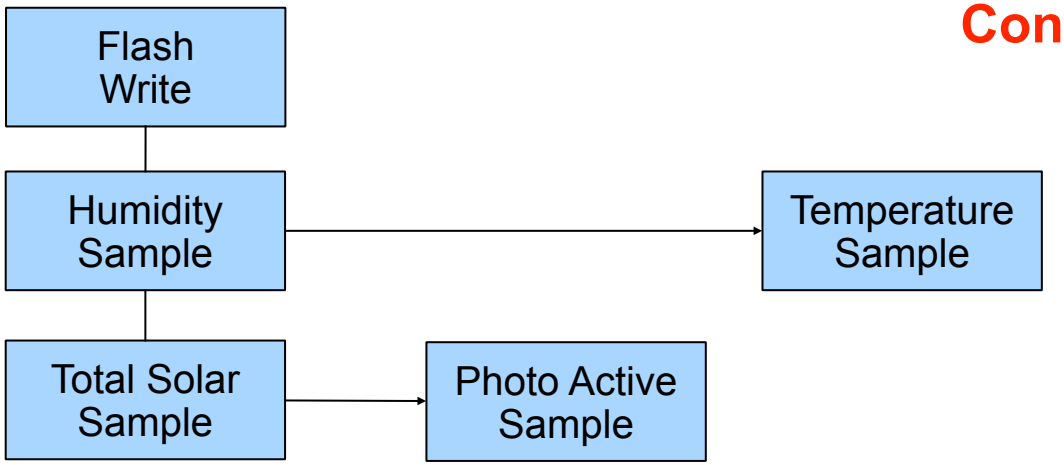
Multi-thread:



Traditional Concurrency Control

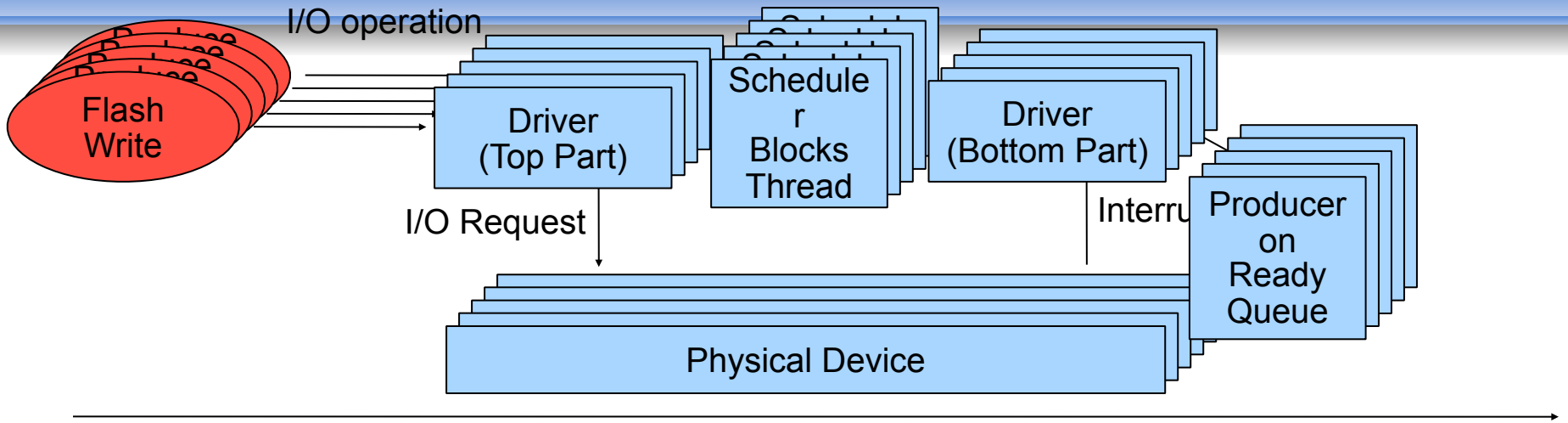


Multi-thread:

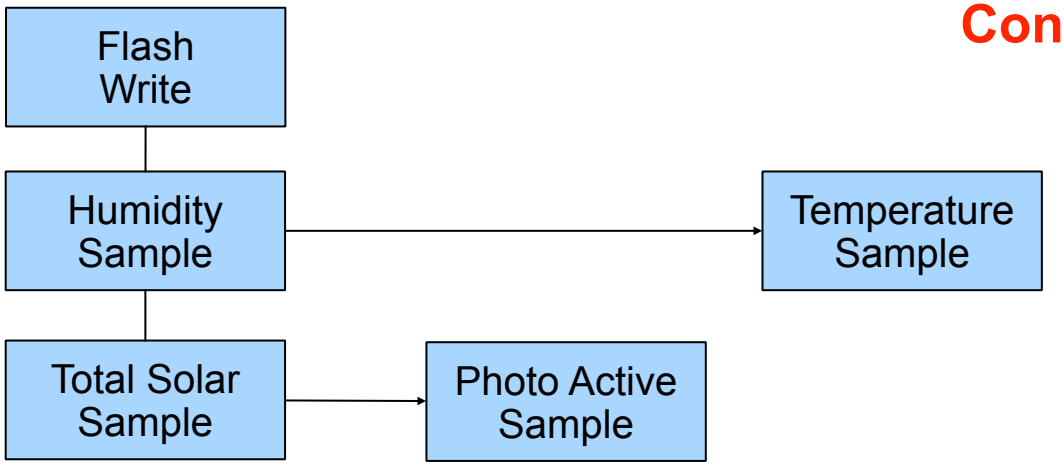


Concurrency can now be exploited

Traditional Concurrency Control

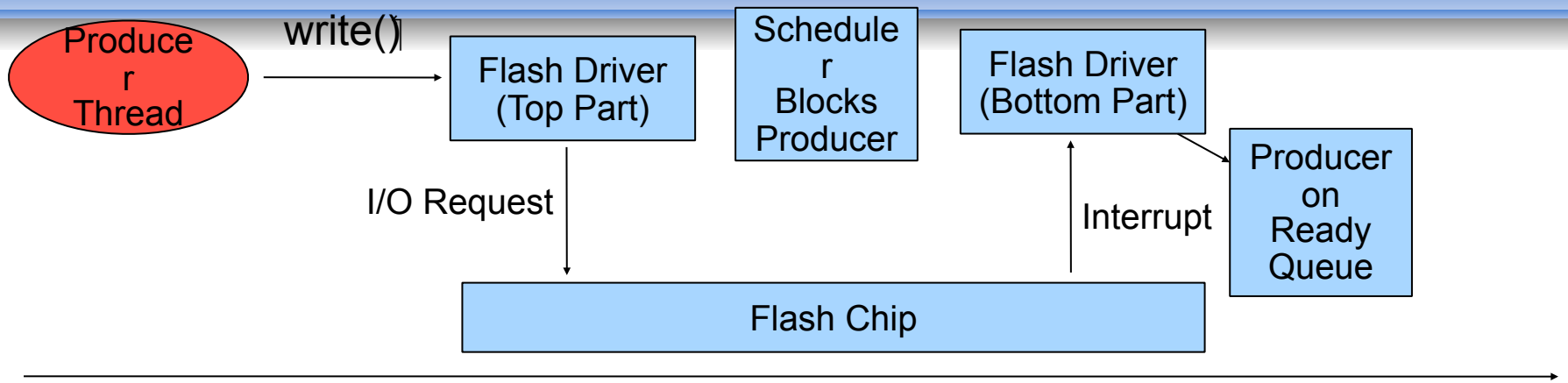


Multi-thread:

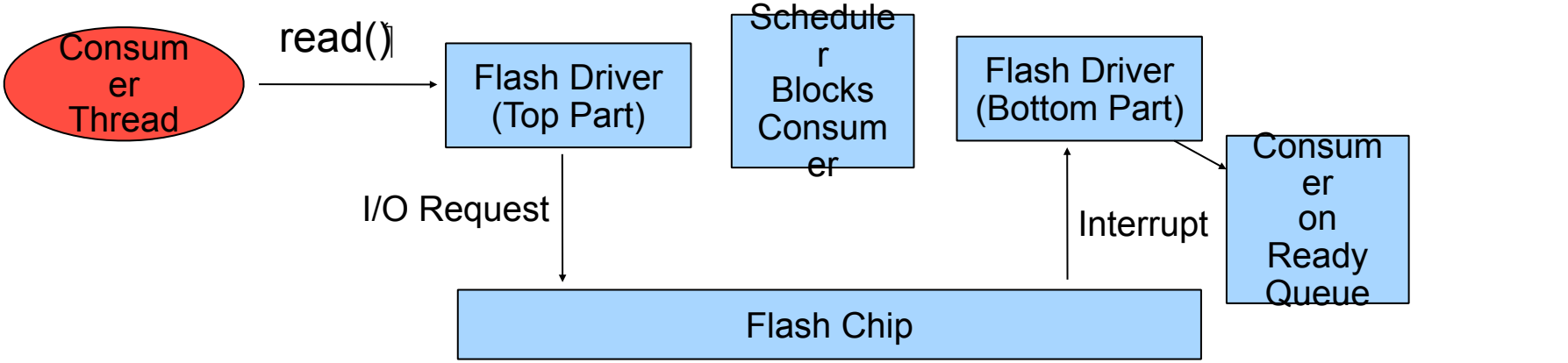


Concurrency can now be exploited
Potential innefficiencies

Traditional Concurrency Control

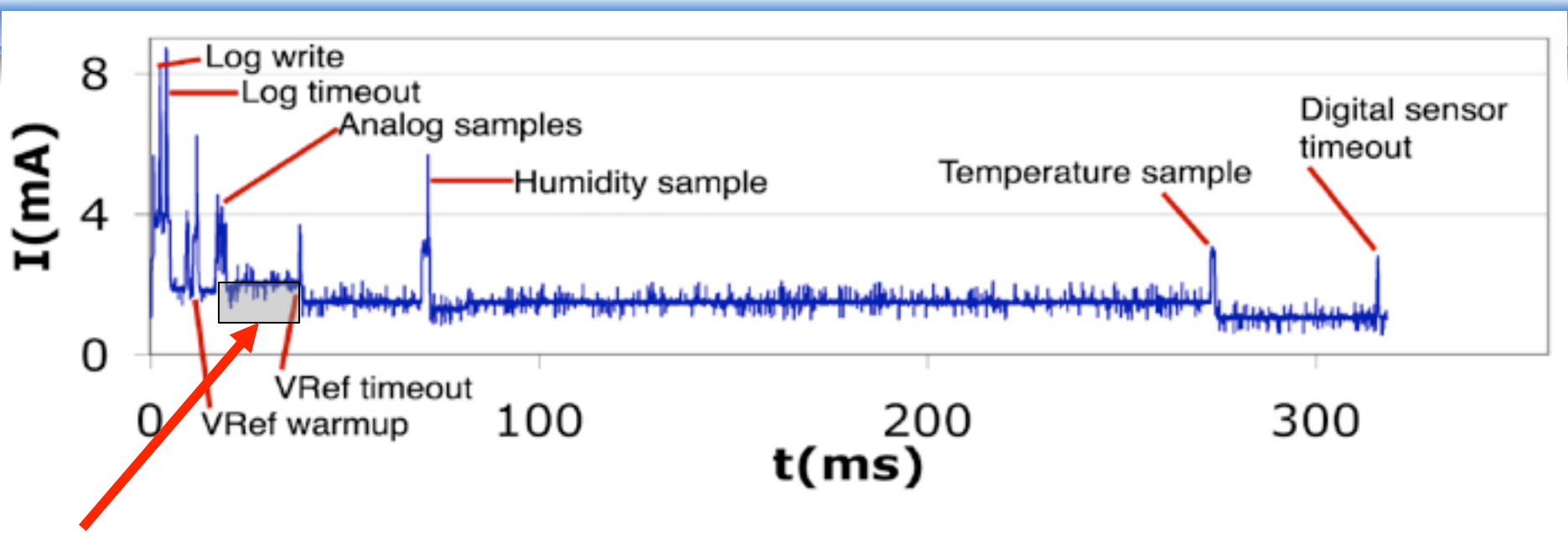


Time



Time

Sampling Power Trace



Overhead of ICEM over Hand-Tuned Implementation

= ADC Timeout + Arbiter Overheads

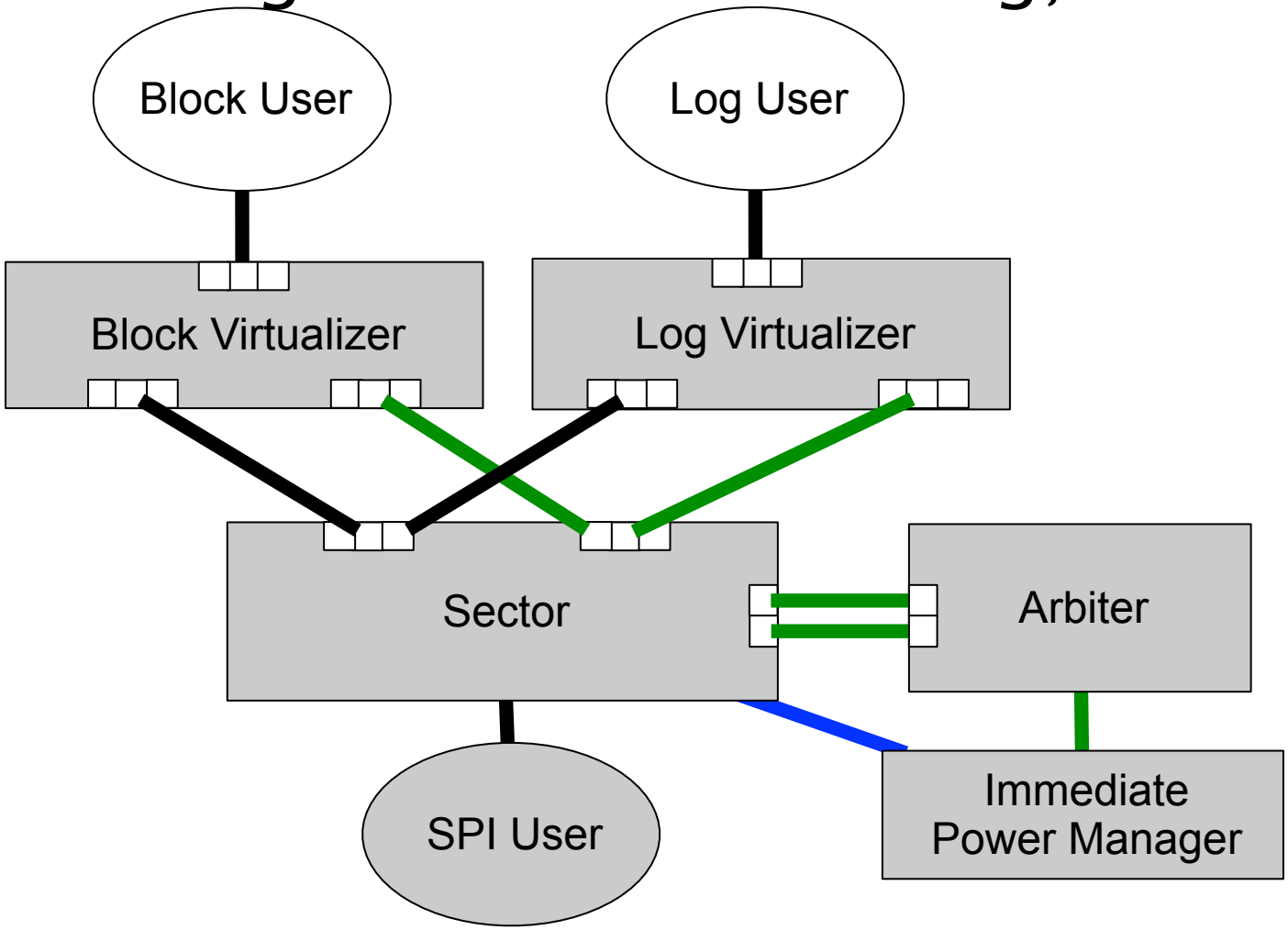
= (536uA * 17ms) + (1920uA * 0.45ms)

= 9976 uAms/sample

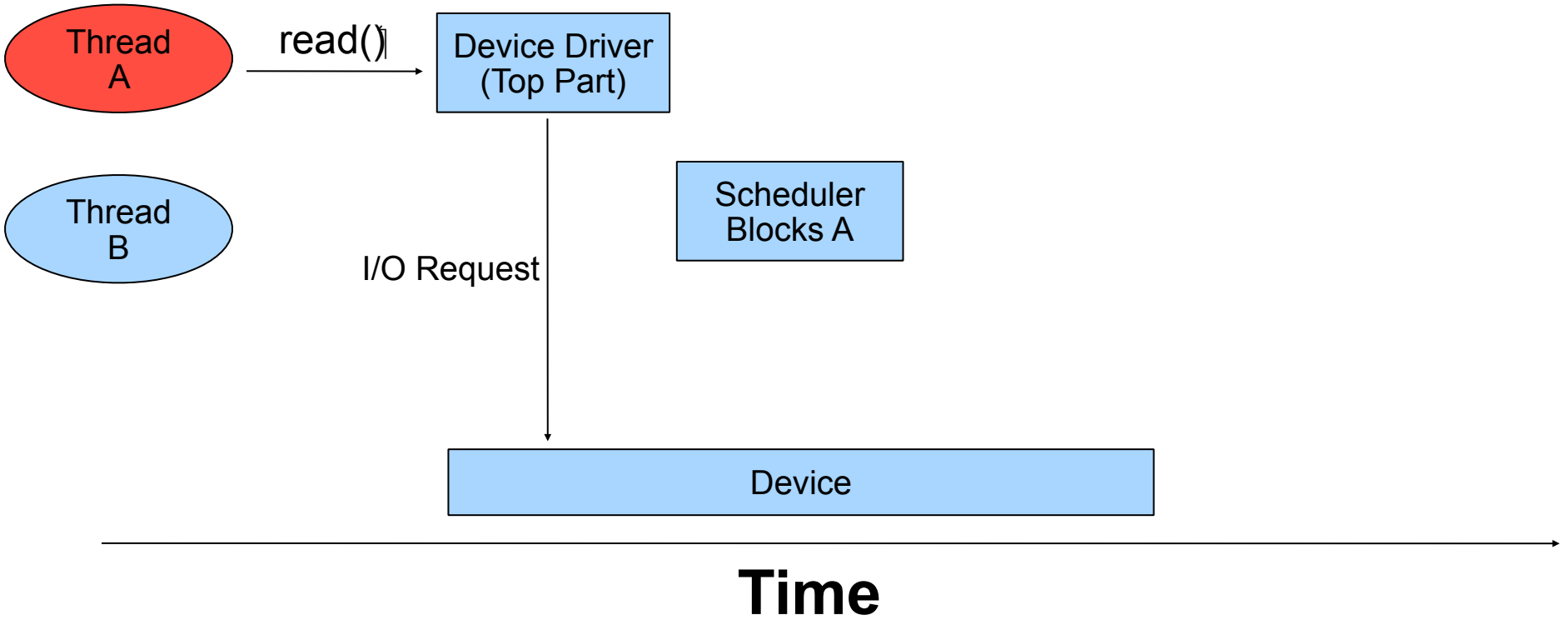
≈ 0.01mAs / sample

Virtualized Driver Example

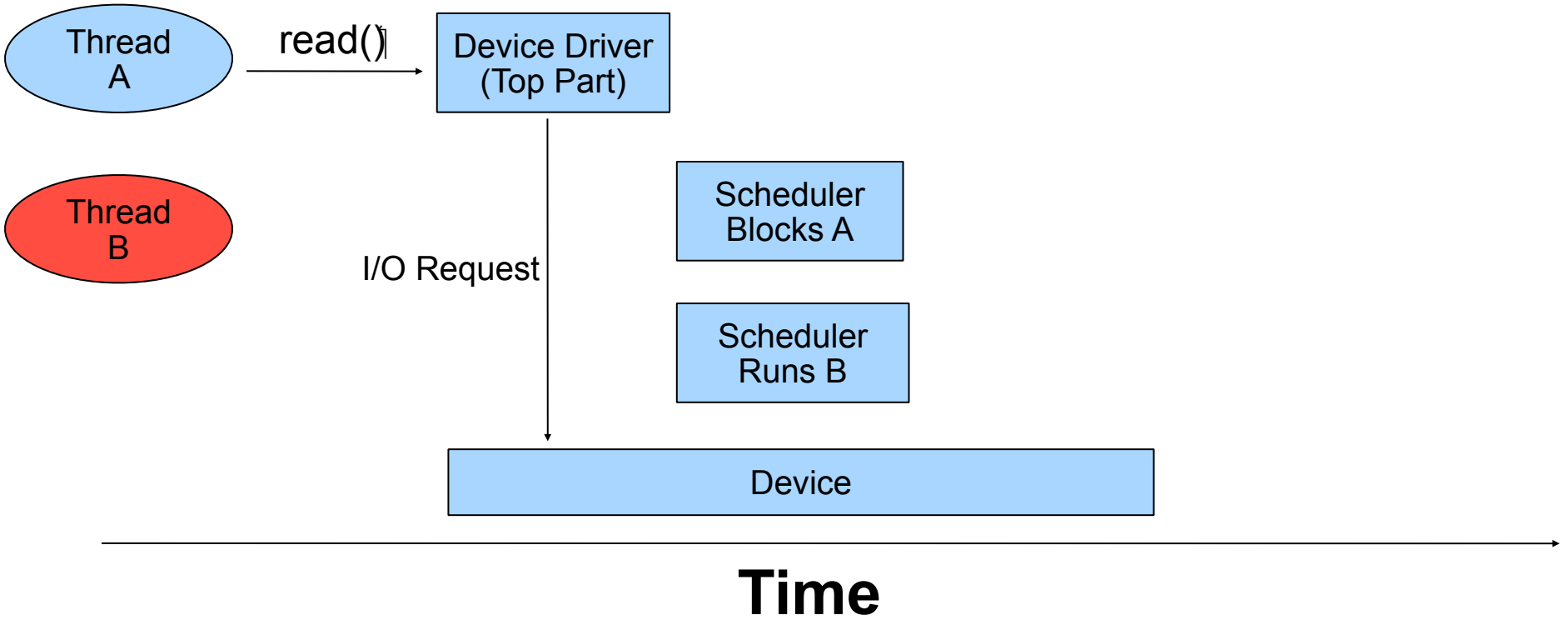
- Flash Storage
  - Two storage abstractions – Log, Block



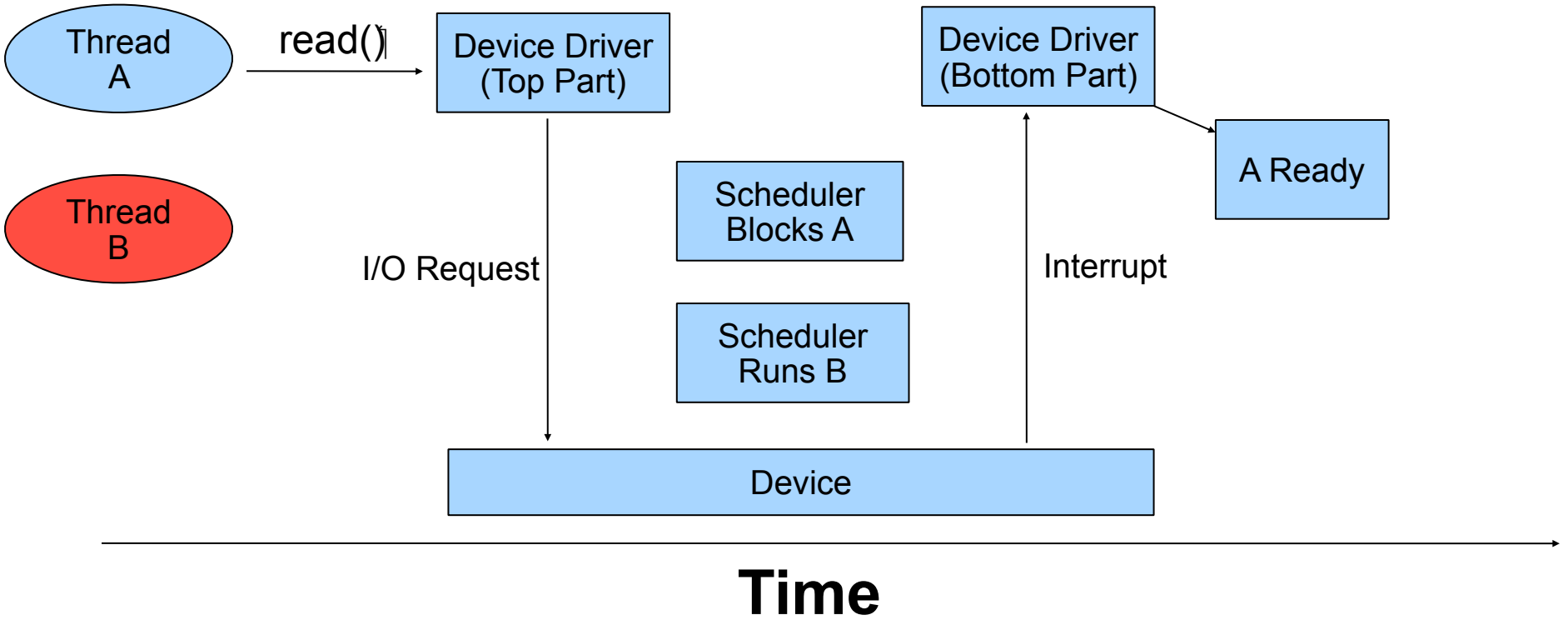
Traditional Concurrency Control



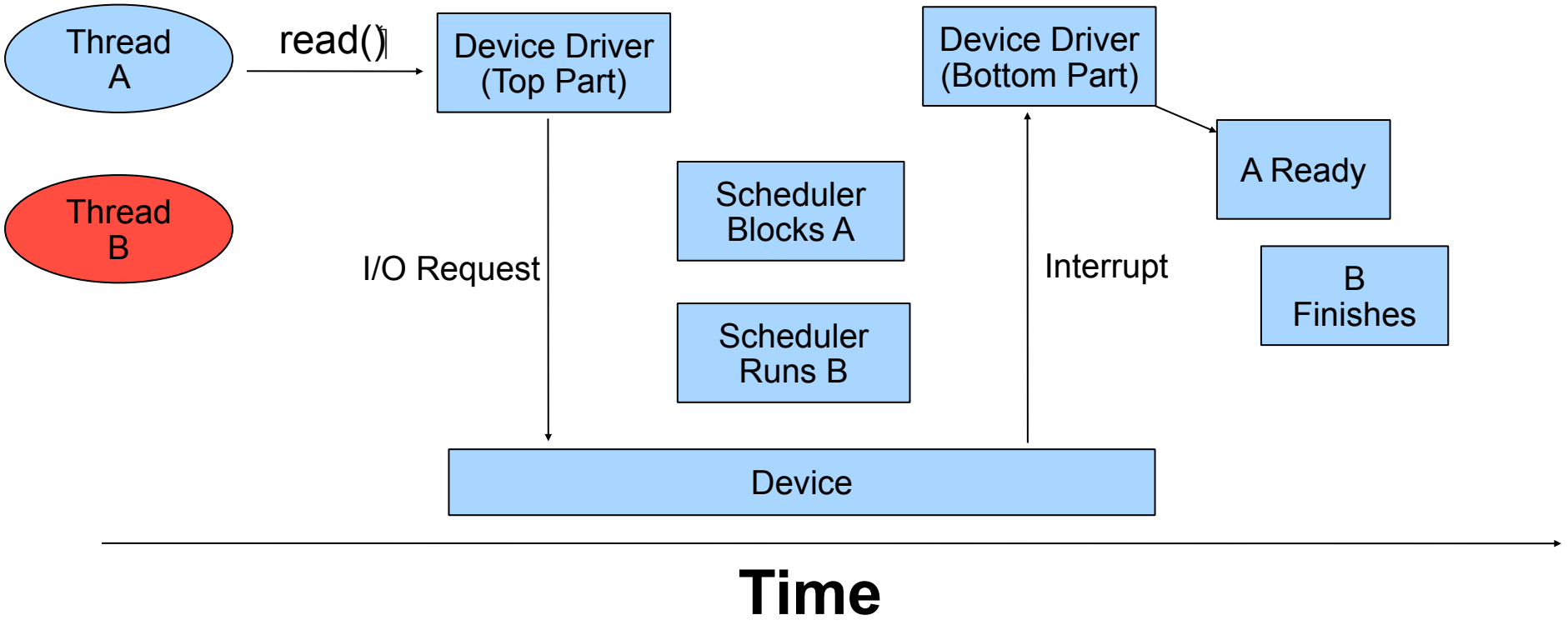
Traditional Concurrency Control



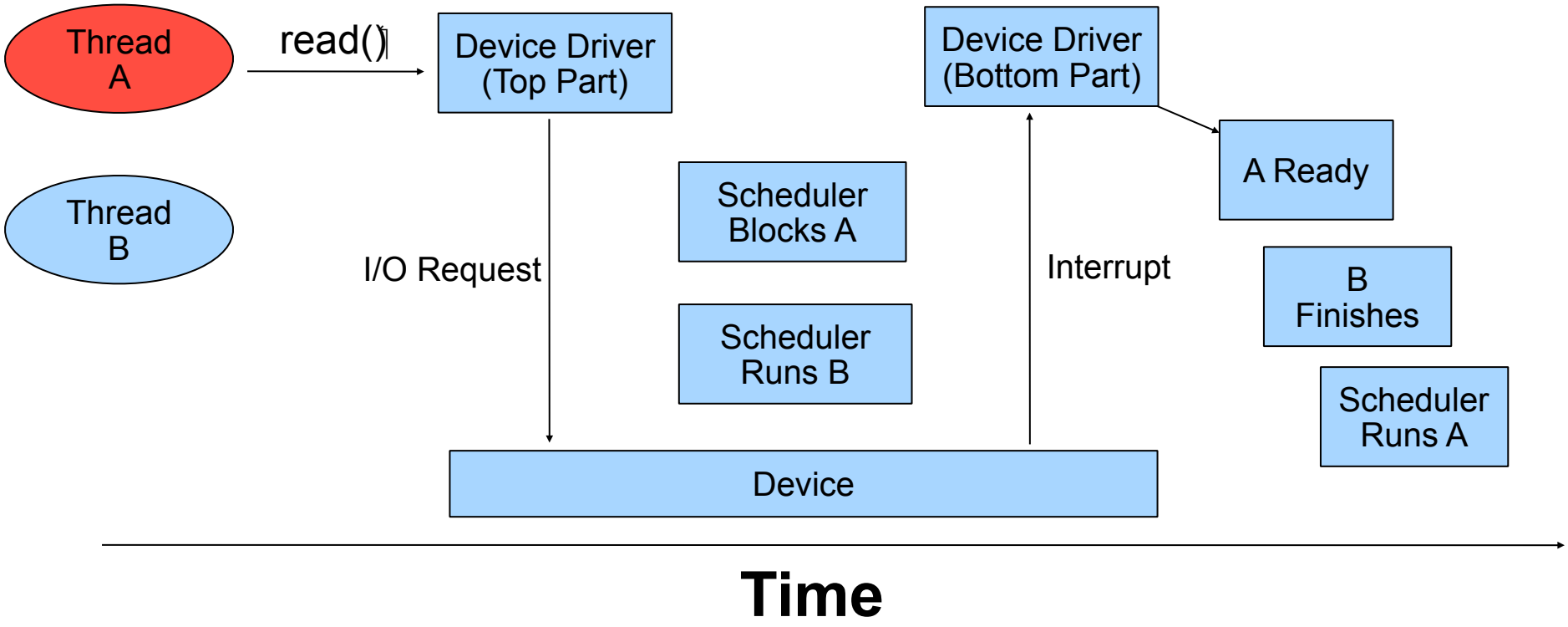
Traditional Concurrency Control



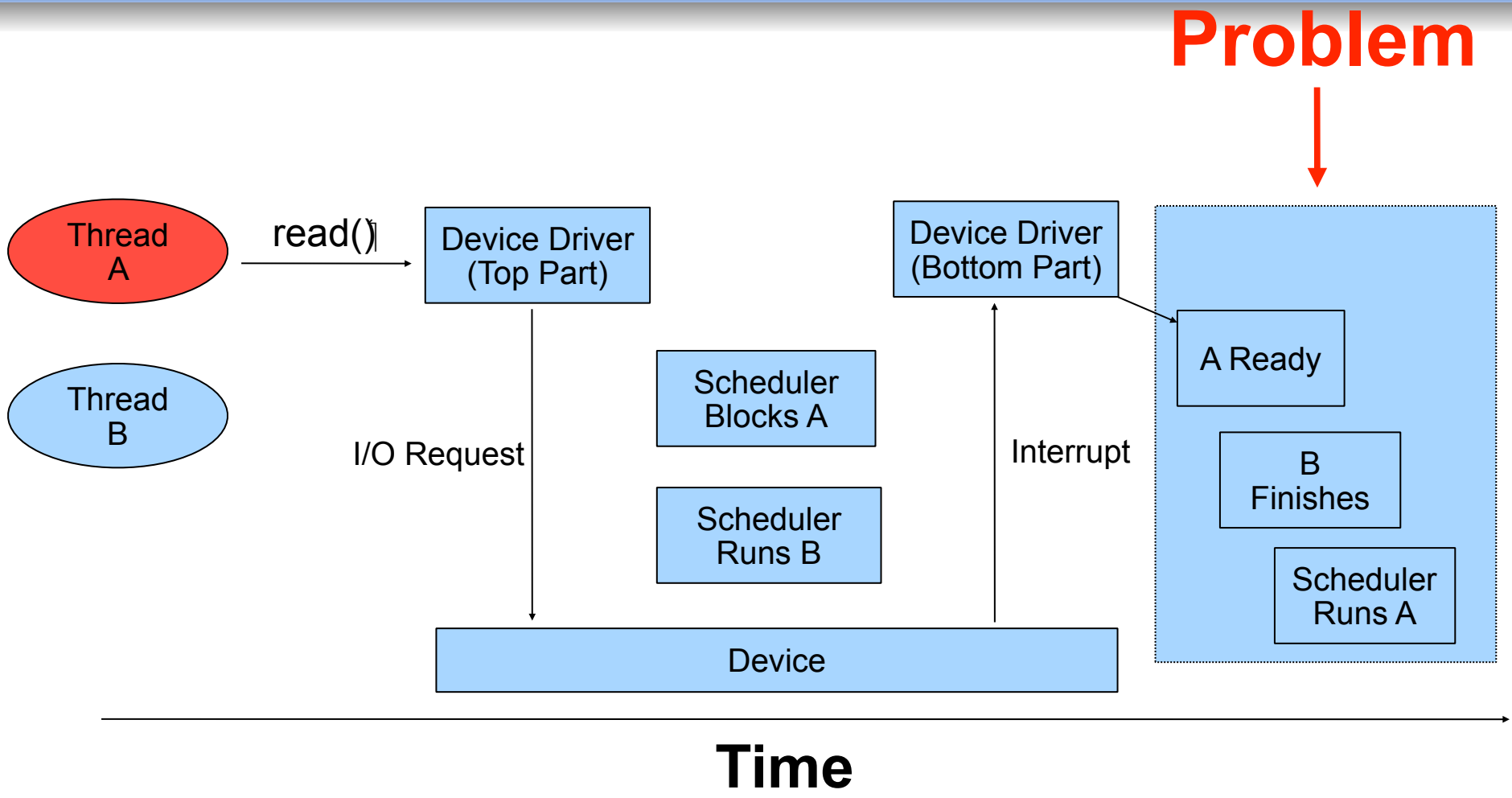
Traditional Concurrency Control



Traditional Concurrency Control

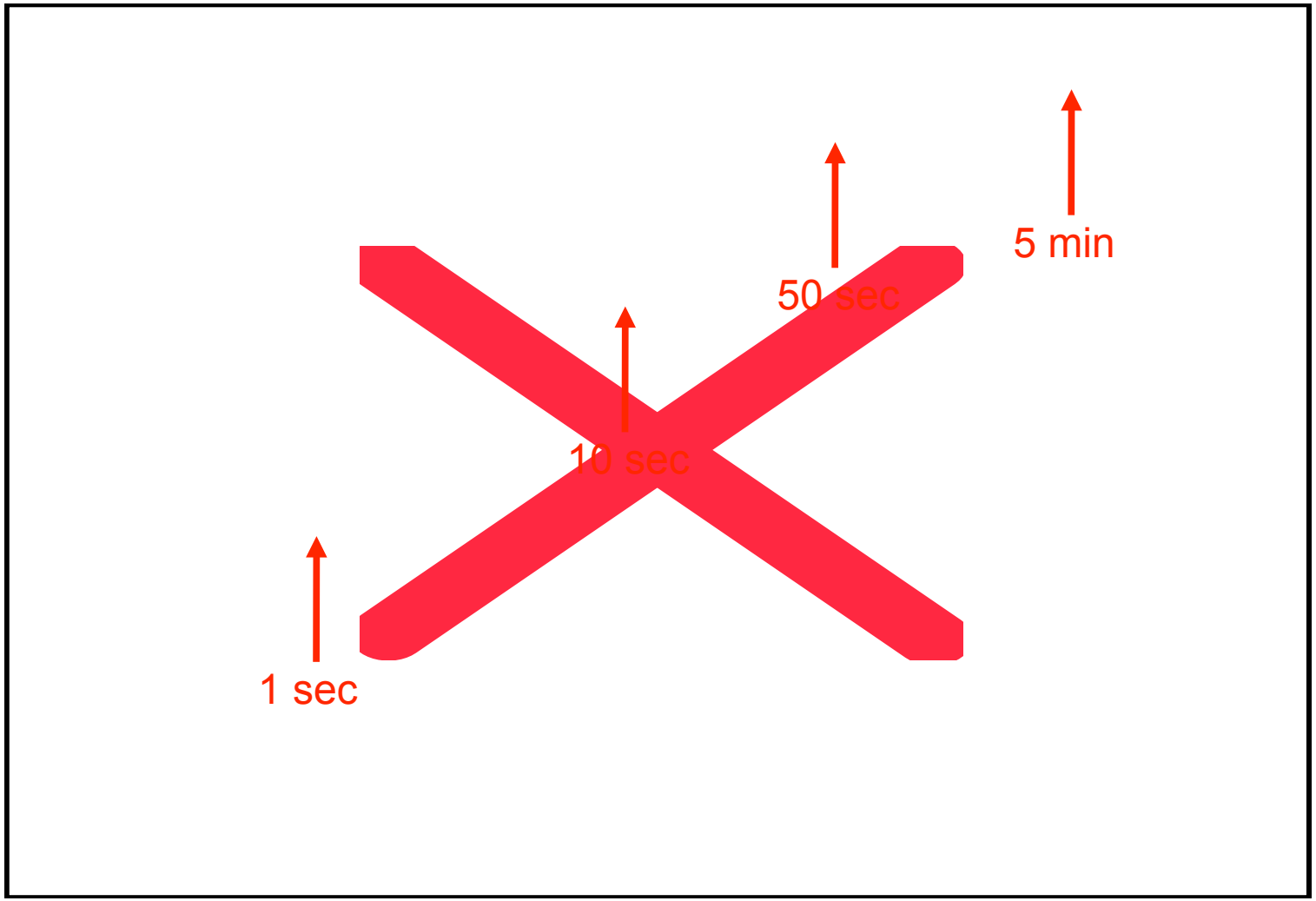


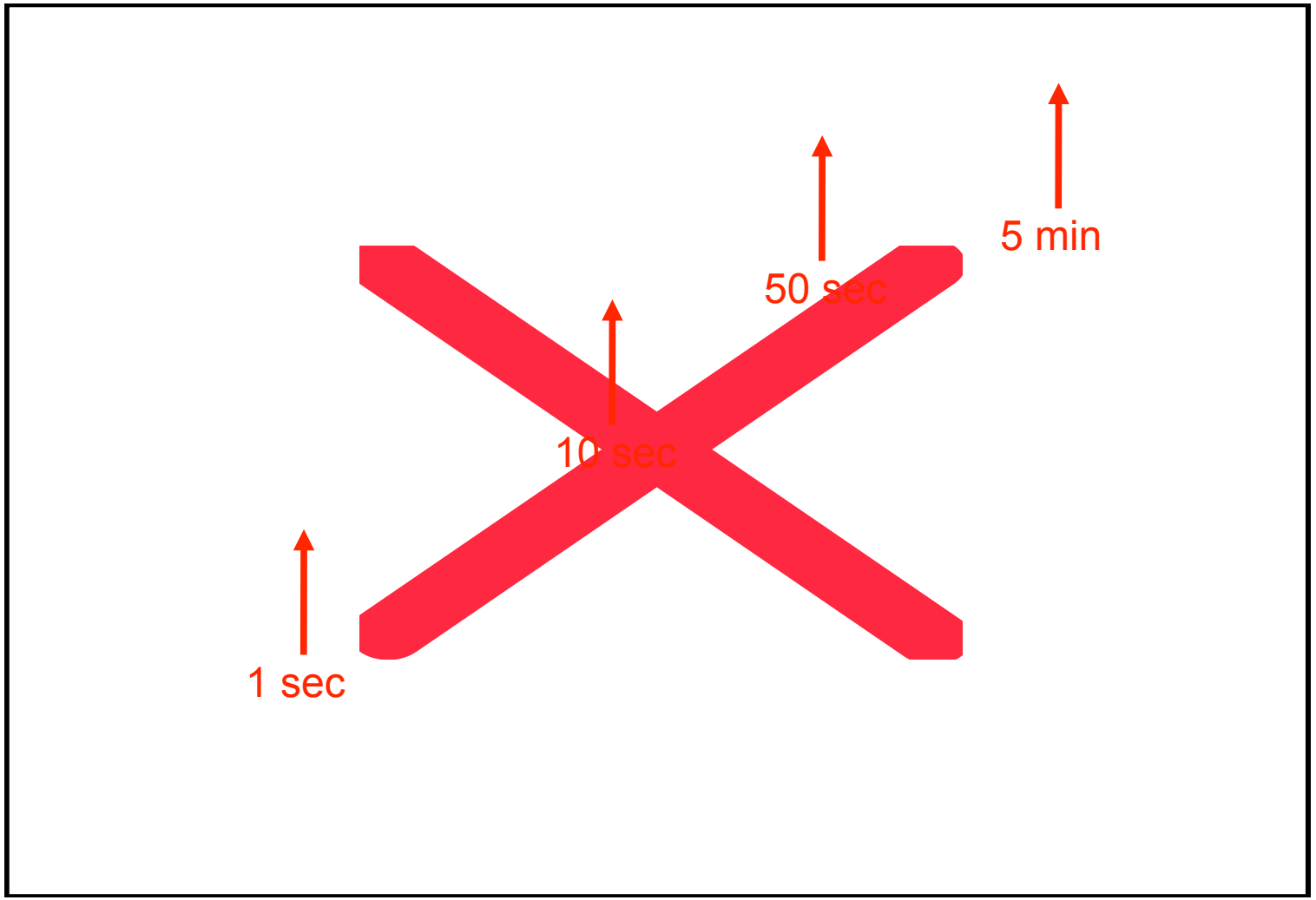
Traditional Concurrency Control



Problem

- Sensornet applications have the capability of exploiting high levels of concurrency
  - Must do so without threads (i.e no concept of an execution entity)
  - Require extreme low-power operation
- Traditional systems not well suited
  - Blocking application level I/O calls
  - Thread scheduling in the device driver


5 min
50 sec
10 sec
1 sec


5 min
50 sec
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1 sec