Solving the System Challenges of Intermittent Energy-harvesting Devices

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ABSTRACT Research Group - https://intermittent.systems

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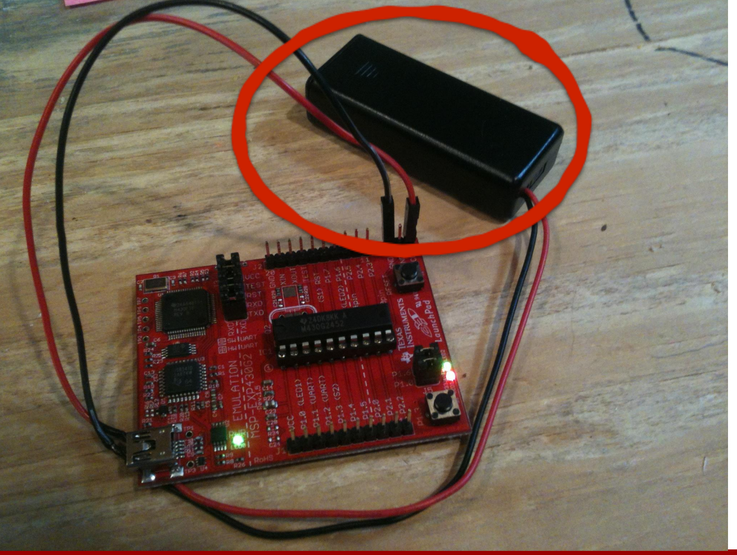
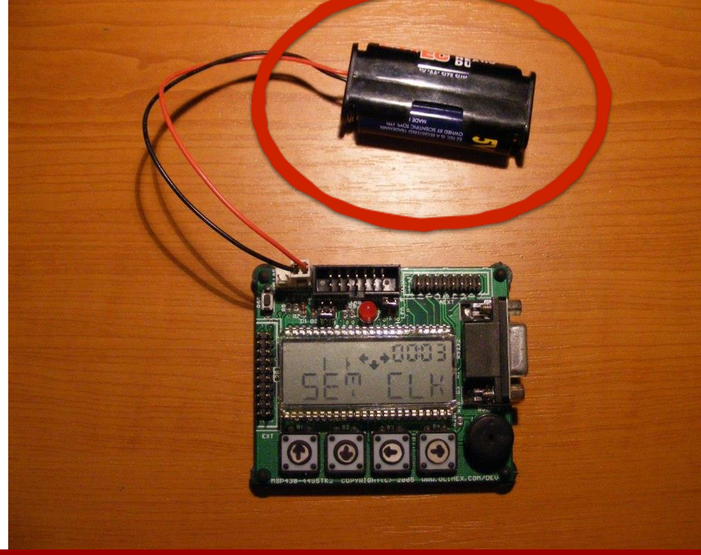
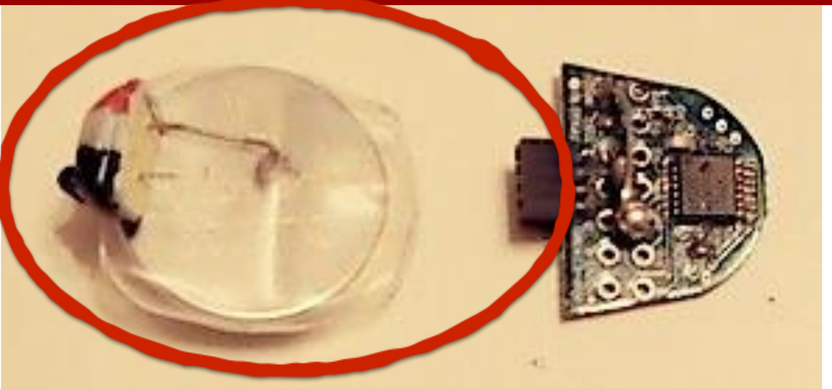
Emerging Devices Everywhere

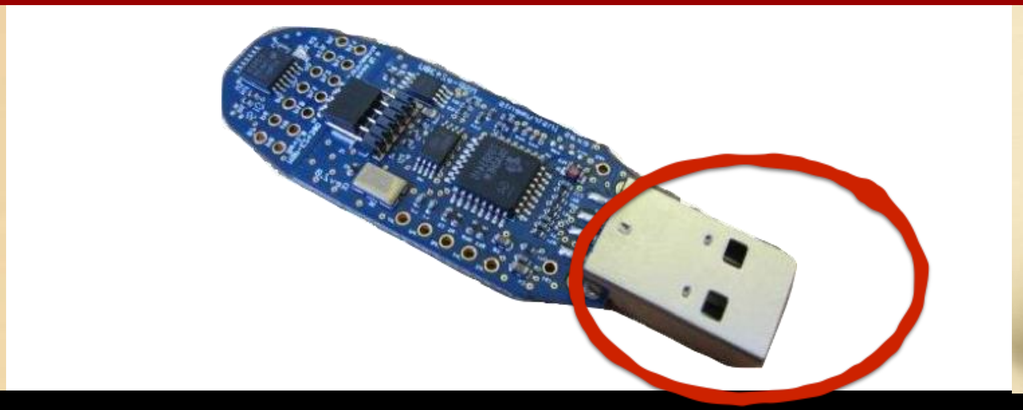
Wearables, sensors, “Internet of Things”, tiny satellites, medical implants, environmental monitoring, security, computational art, interactive clothing, smart furniture, smart carpets, smart toilet paper

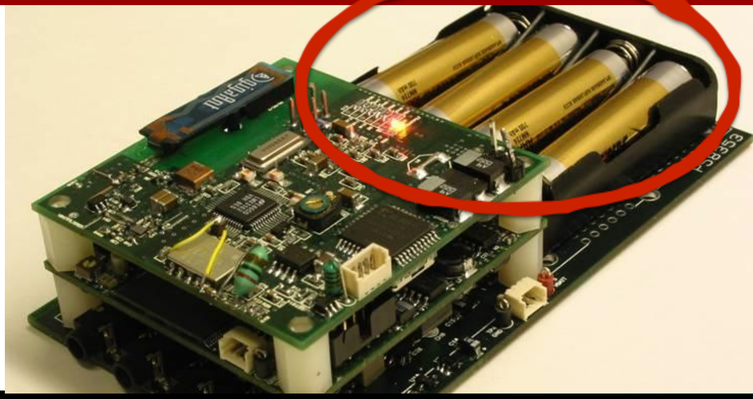


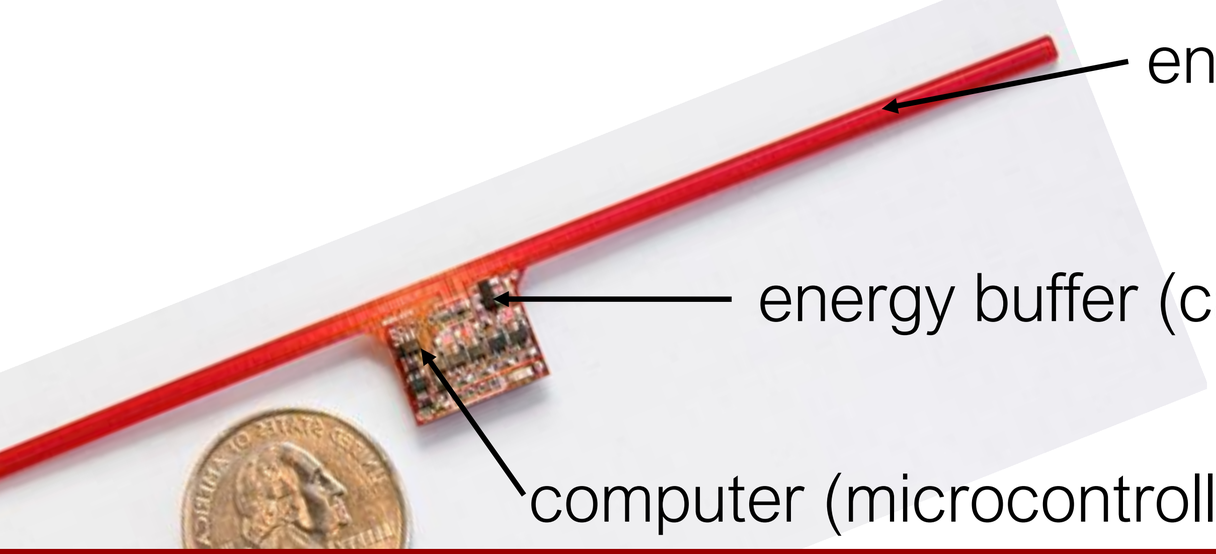


Tethered to a power source

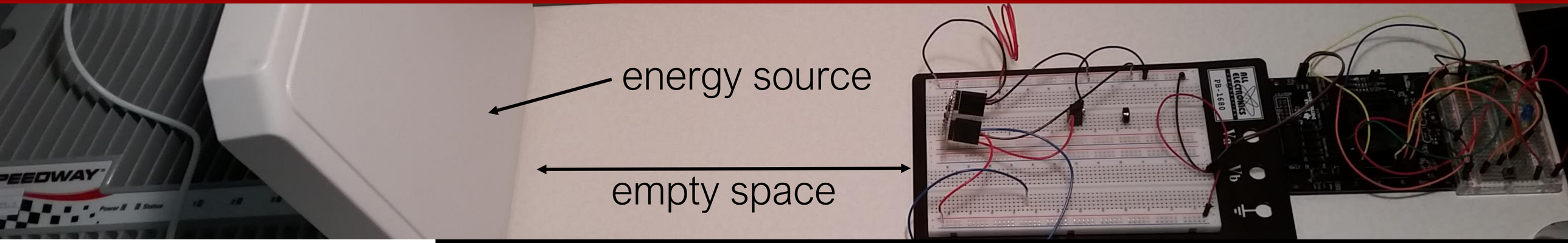


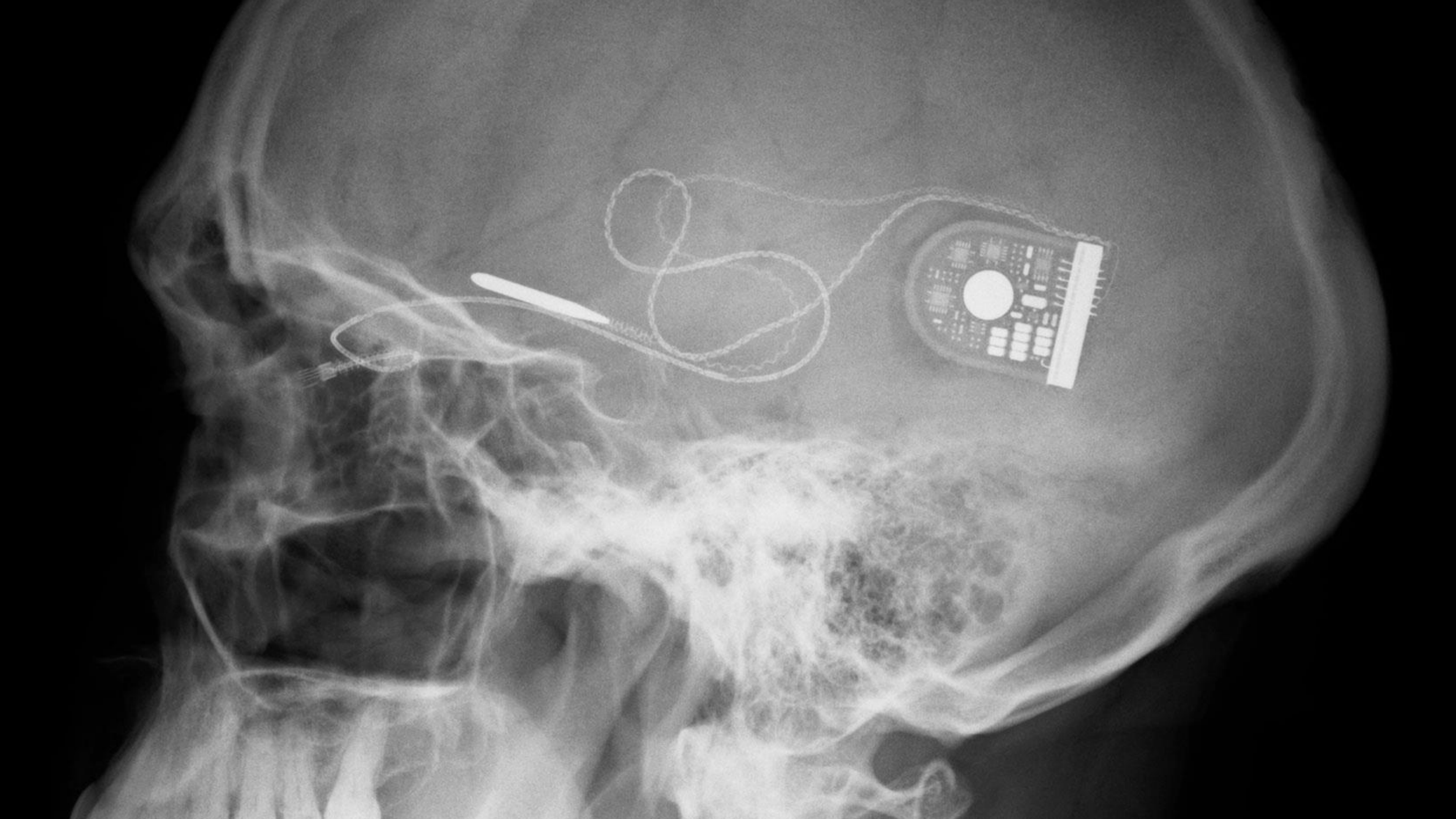


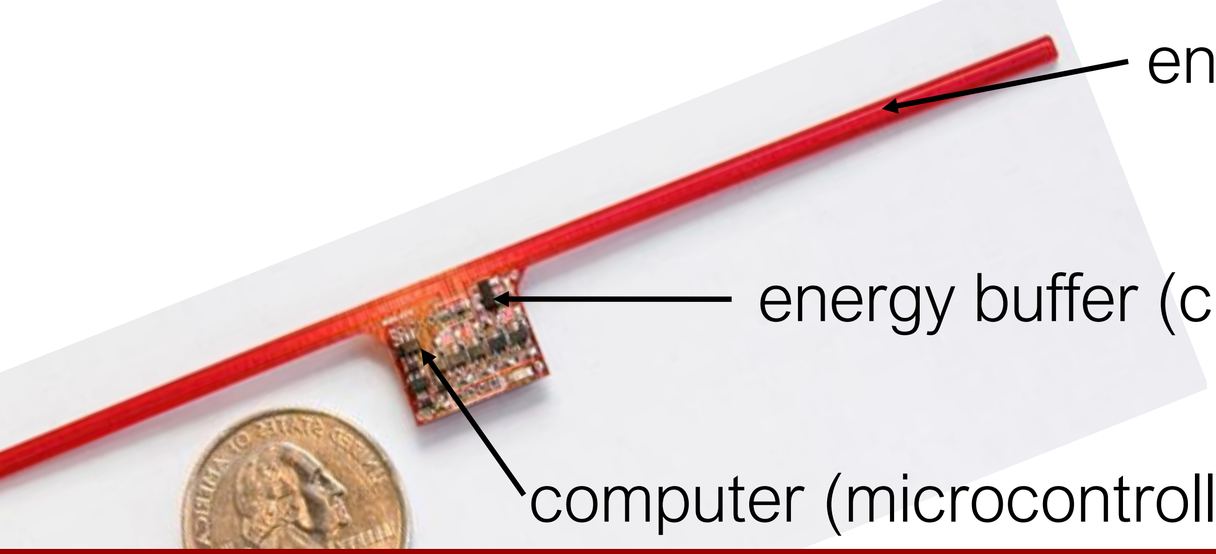




Energy harvesting untethers devices



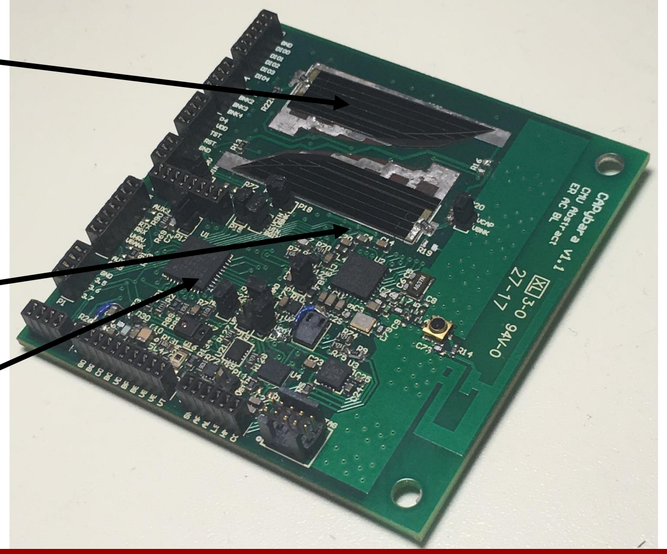




energy receiver

energy buffer (capacitor)

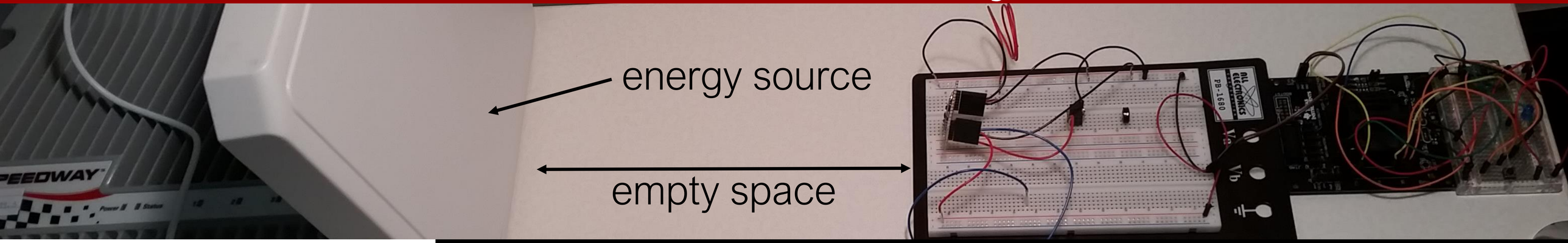
computer (microcontroller)



…but energy is **intermittent**

—and as a result—

software becomes **inherently unreliable.**



energy source

empty space

The Intermittent Execution Model

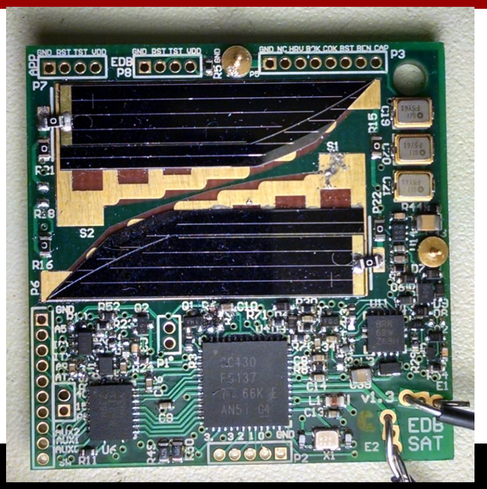
Reasoning About Intermittently-powered Devices

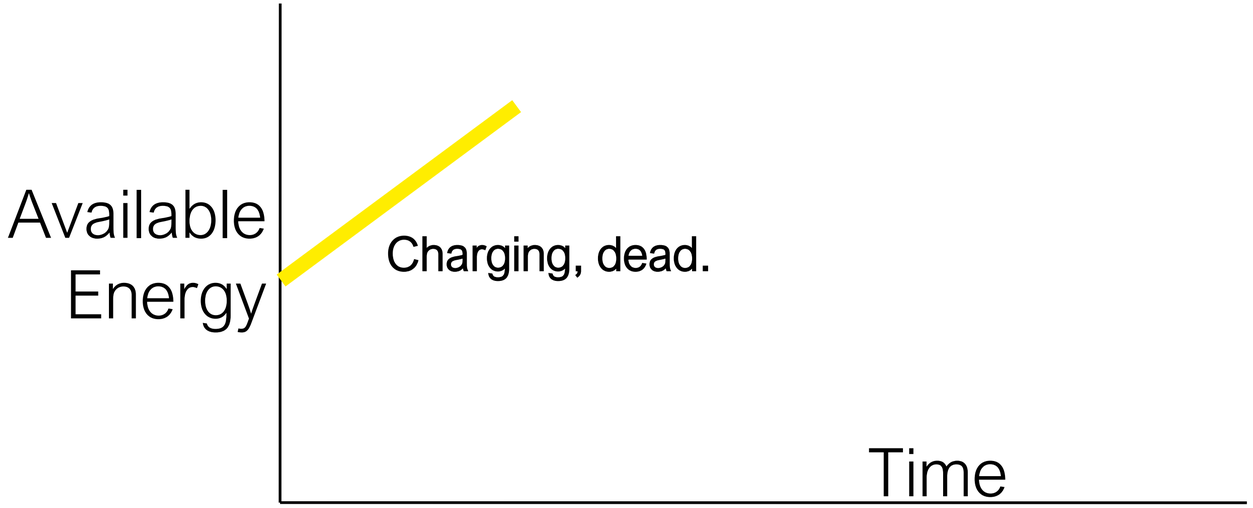
Designing for Intermittence

System Support for Reliable Intermittence

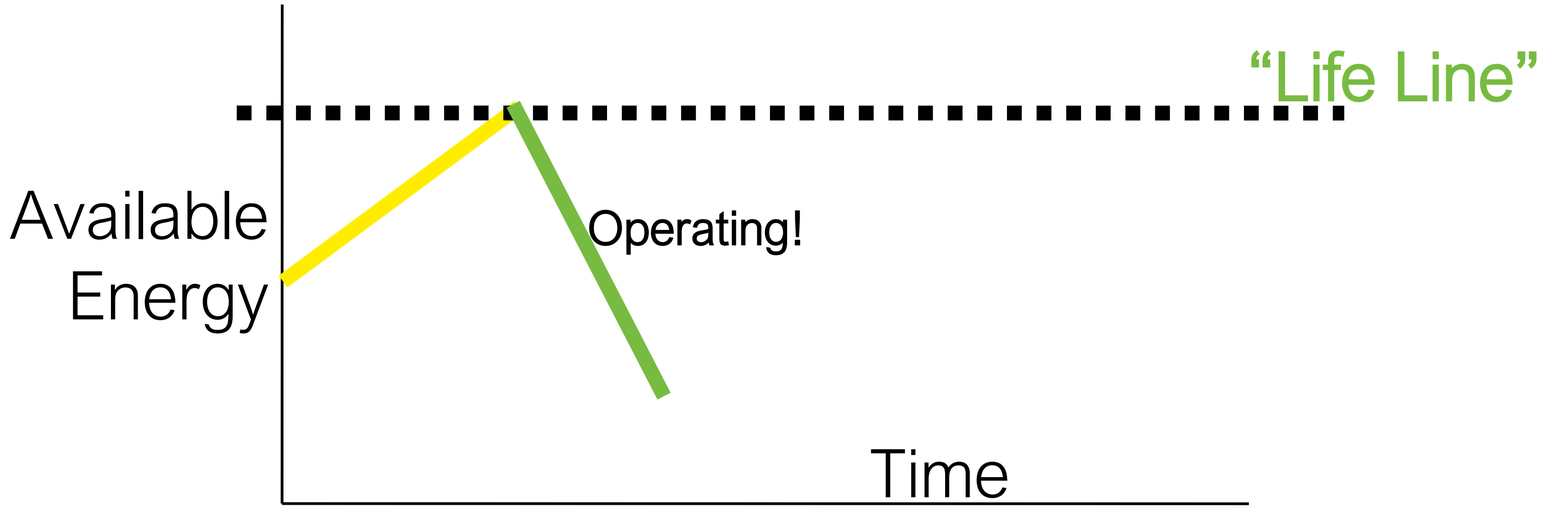
Intermittent Computing Platforms

Hardware, Programming Models, System Software





Running on intermittent energy



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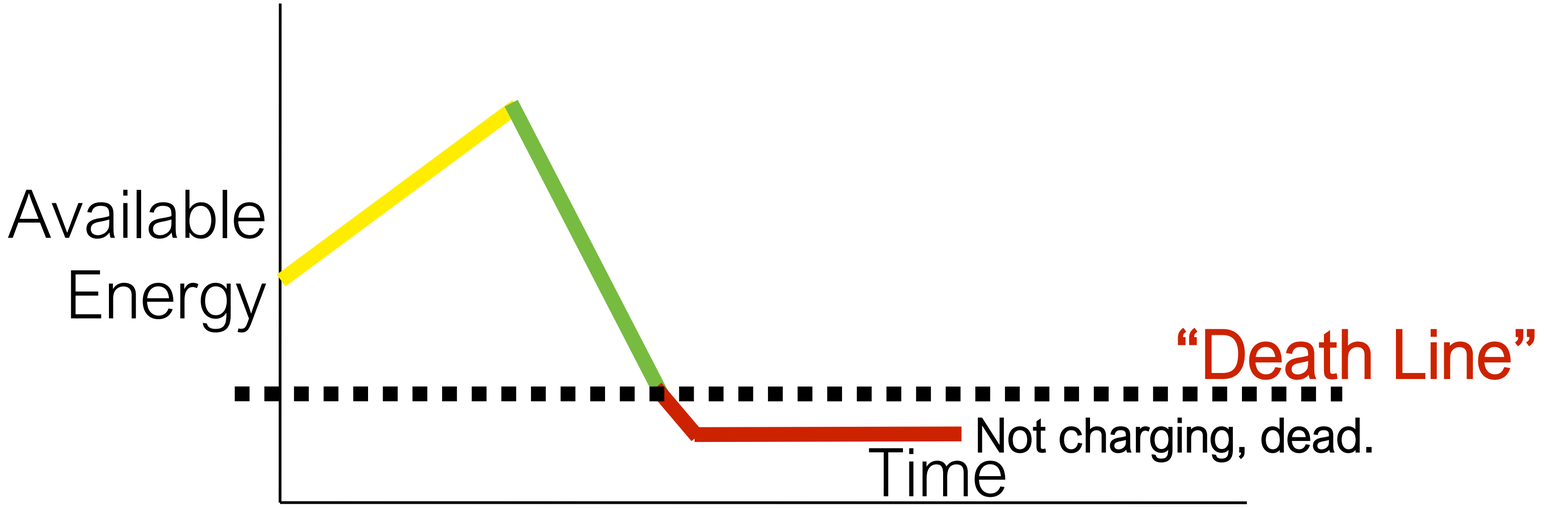
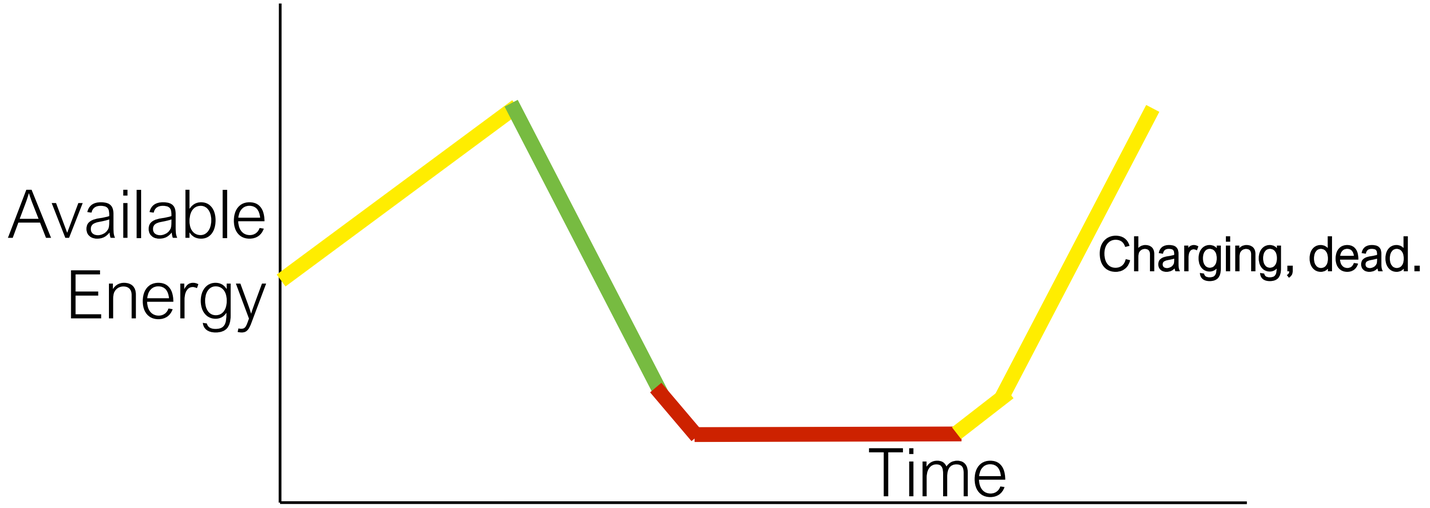
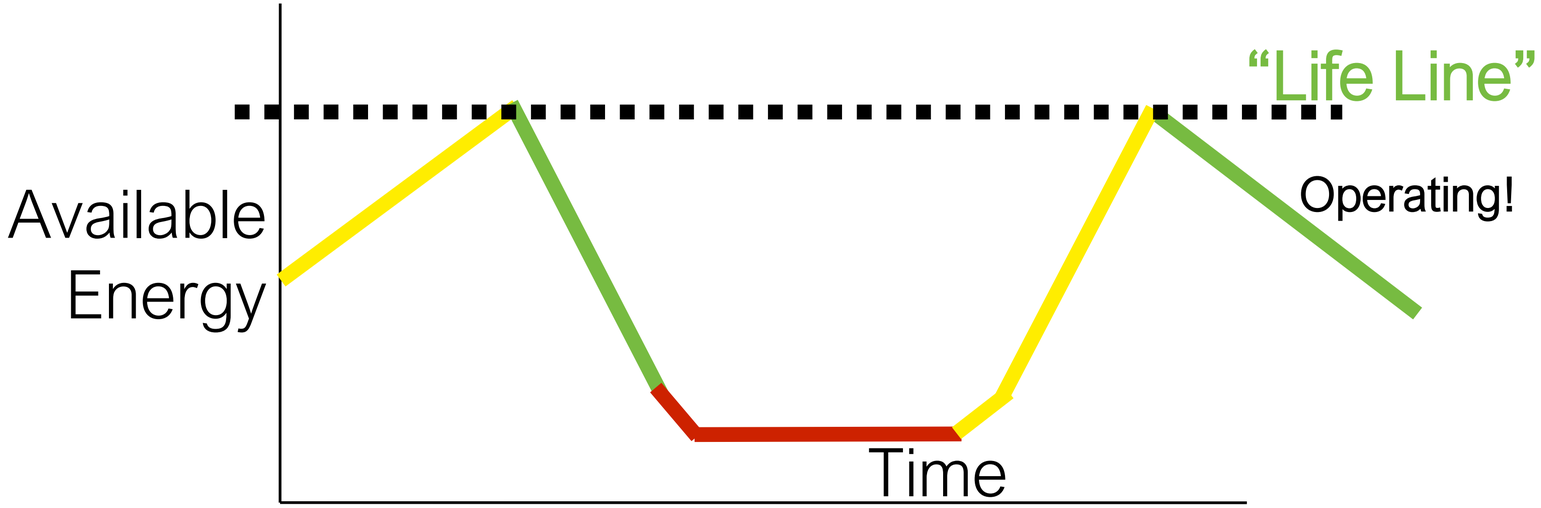


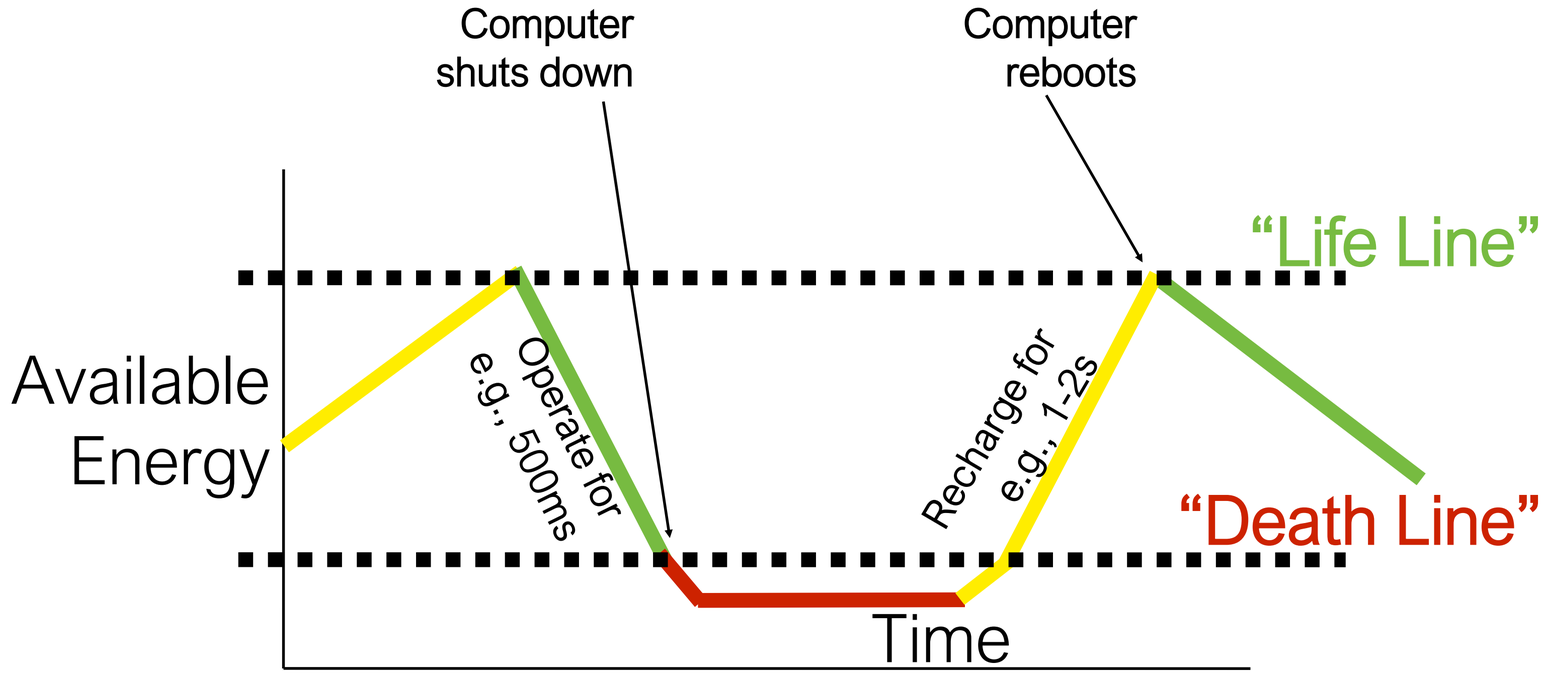
Running on intermittent energy



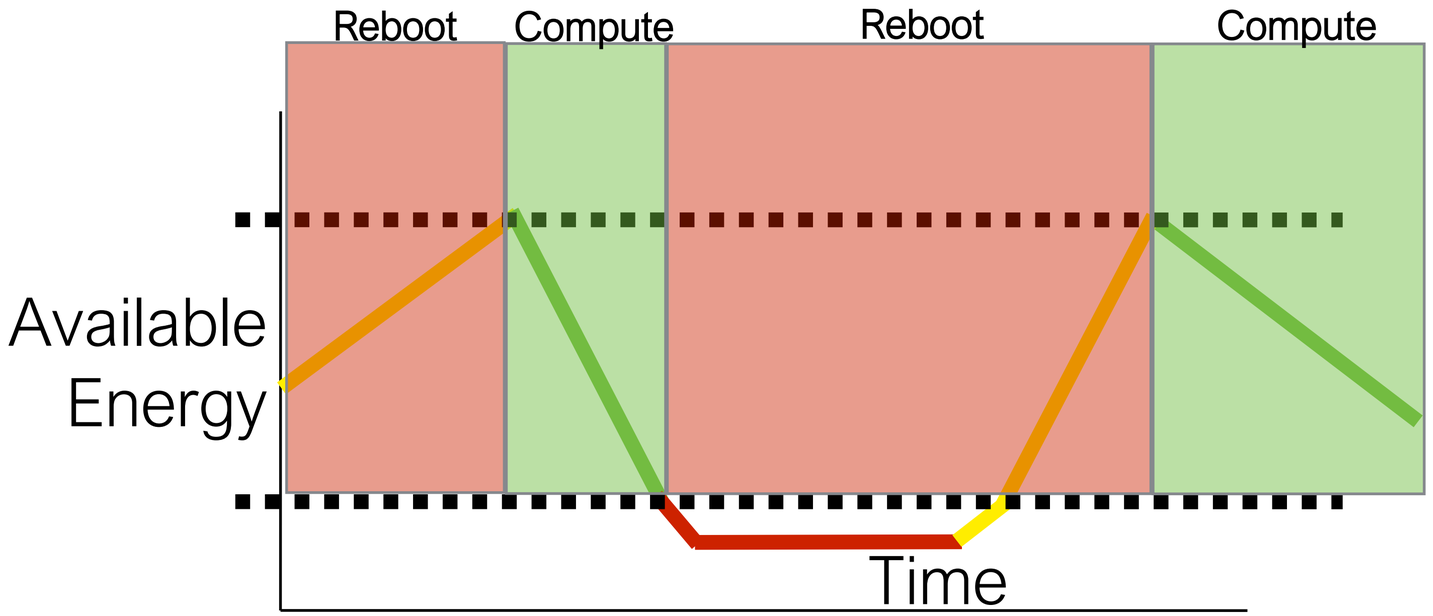
Running on intermittent energy



Running on intermittent energy

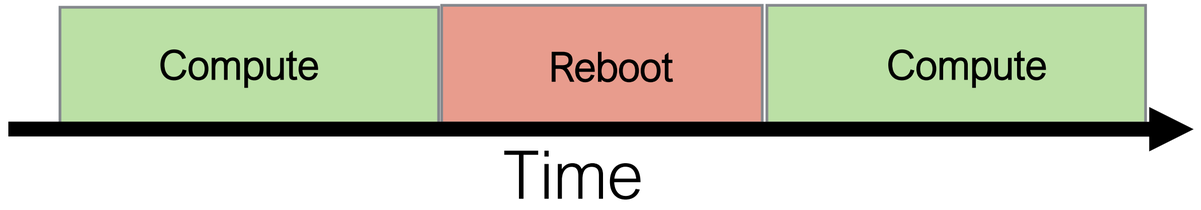


Intermittent Operation on Harvested Energy


Reboot
Compute
Reboot
Compute
Available
Energy
Time

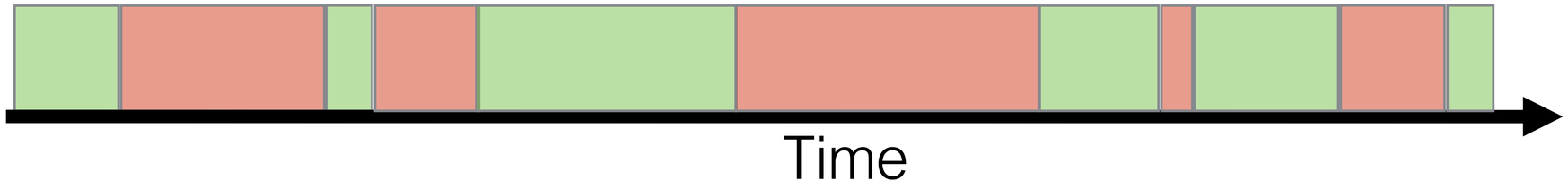
The Intermittent Execution Model

[PLDI '15]



The Intermittent Execution Model

[PLDI '15]



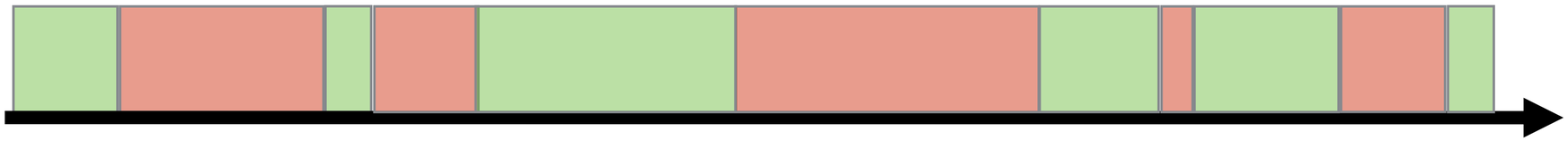
Goal: Run programs that take longer than one green box

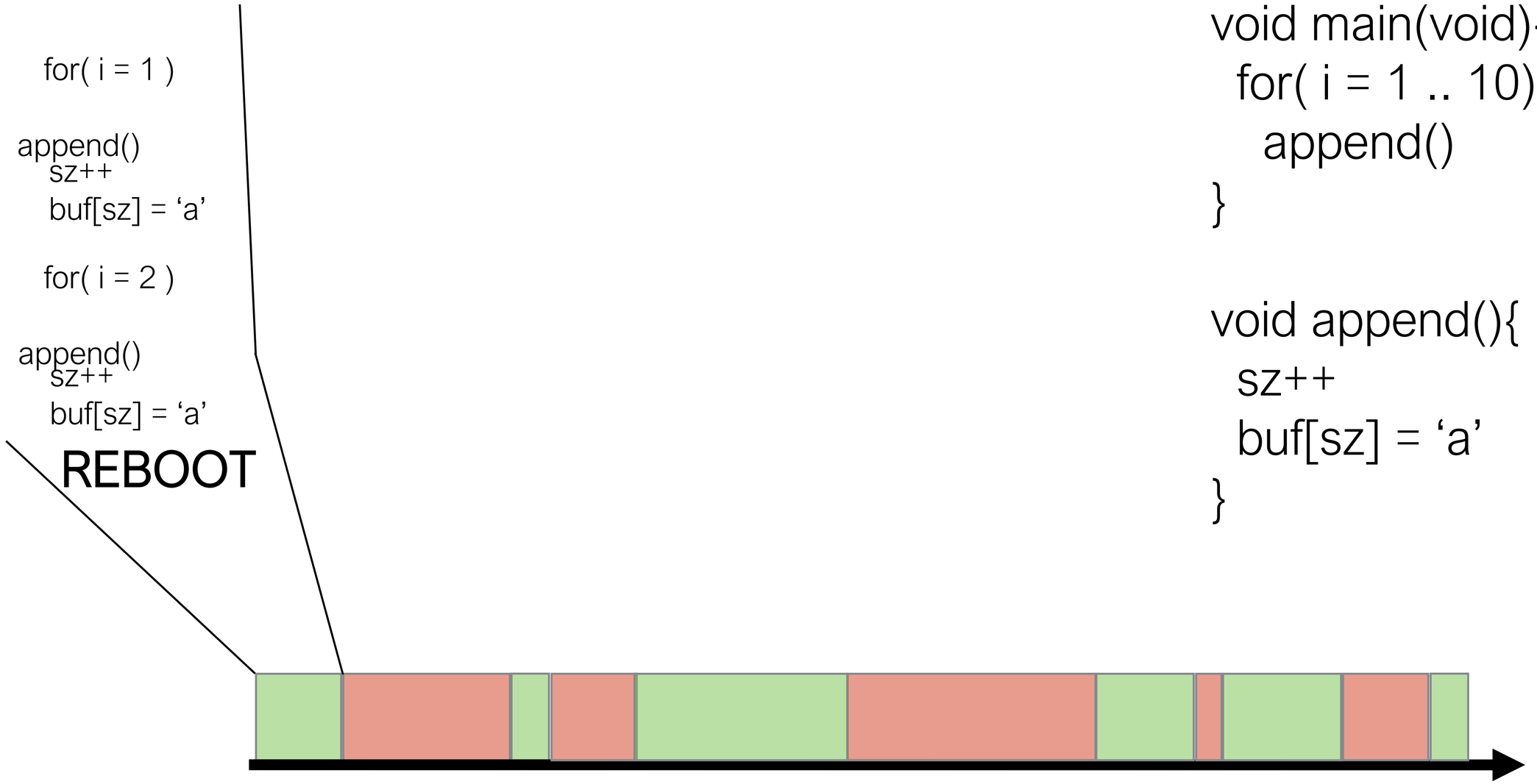
```
void main(void){
  for( i = 1 .. 10)
    append()
}

void append(){
  sz++
  buf[sz] = ‘a’
}
```

*/*Store 10 letters ‘a’ in the buffer*/*

*/*Store a letter ‘a’ in buf[sz] and increase sz by one*/*



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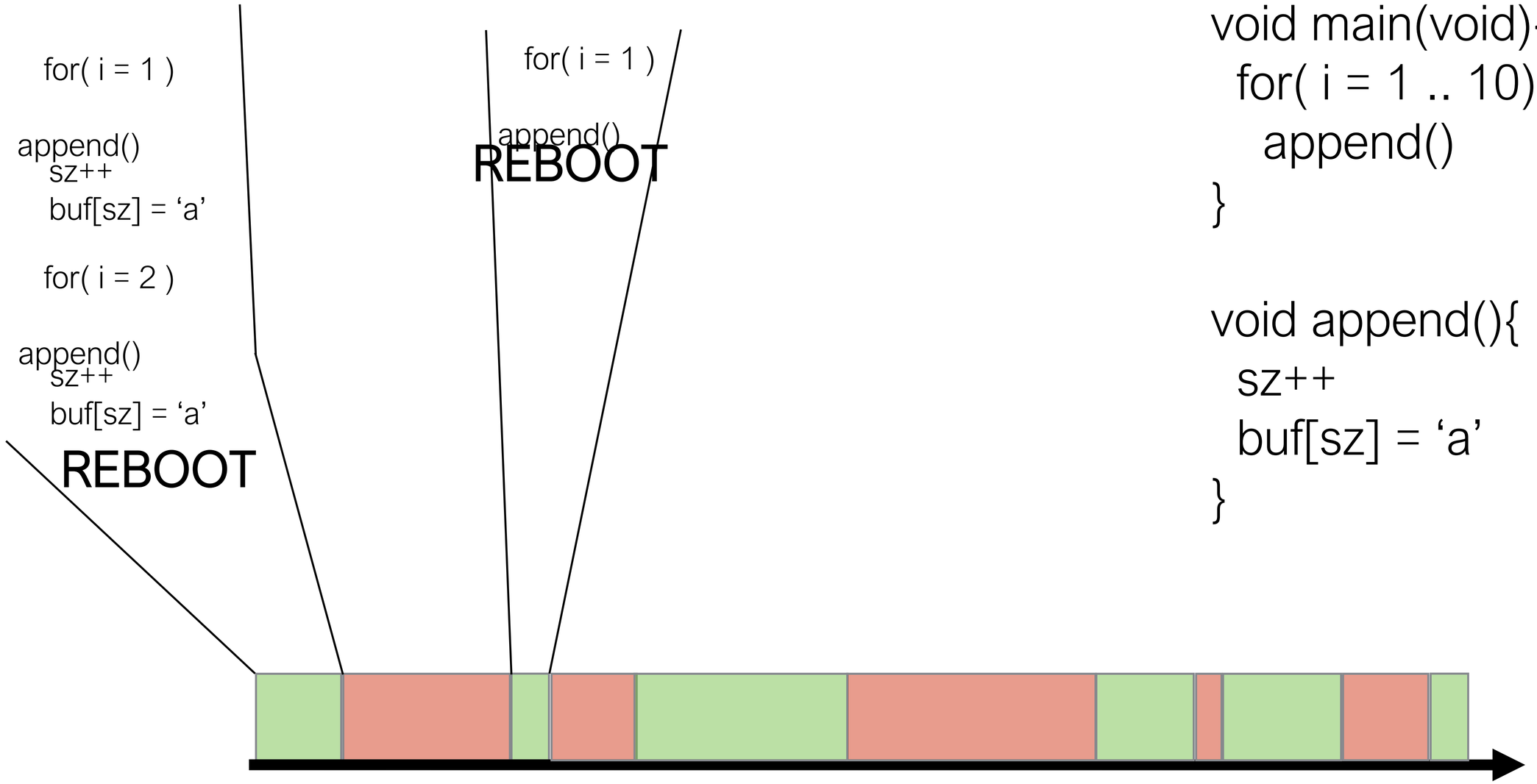


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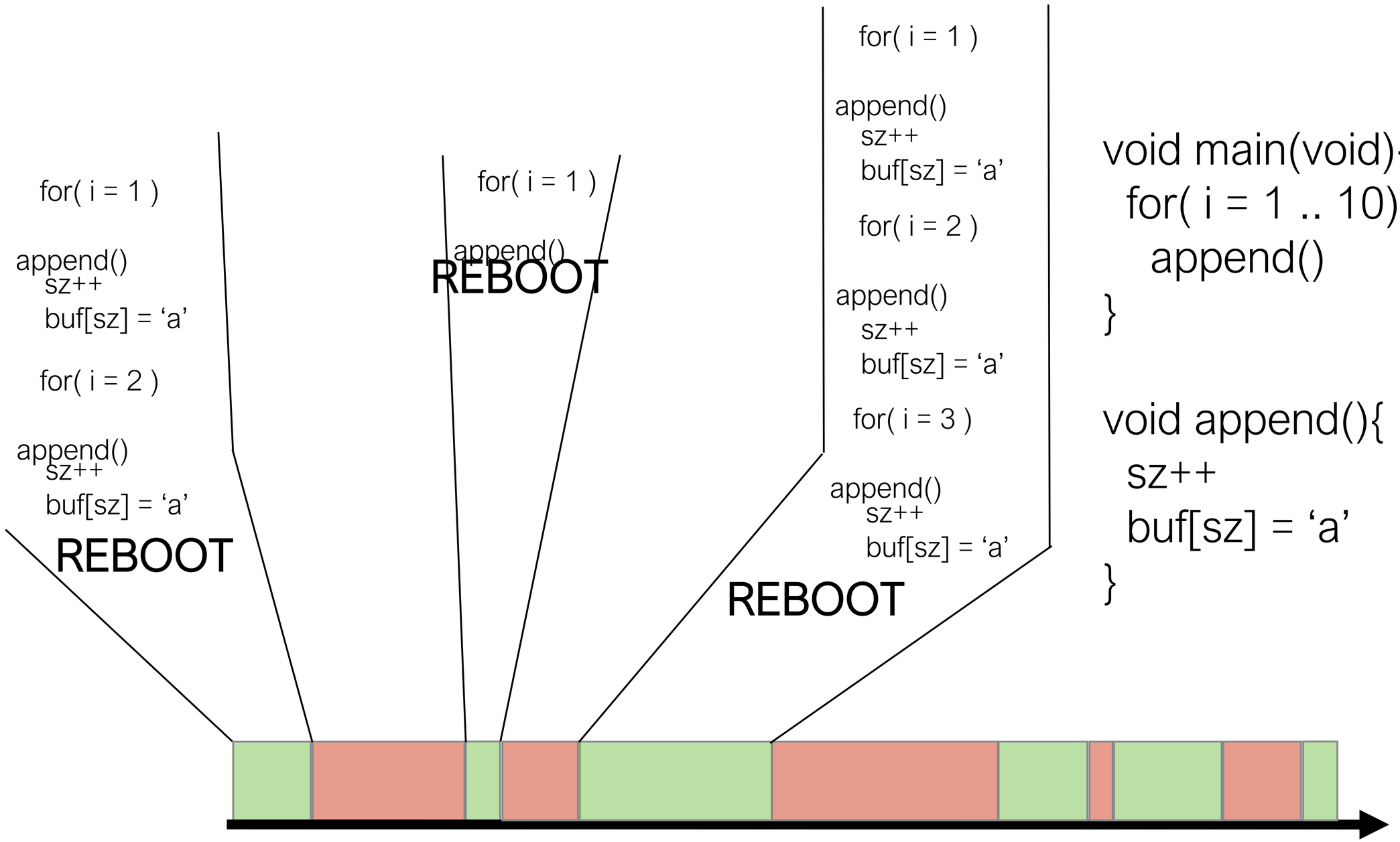


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}
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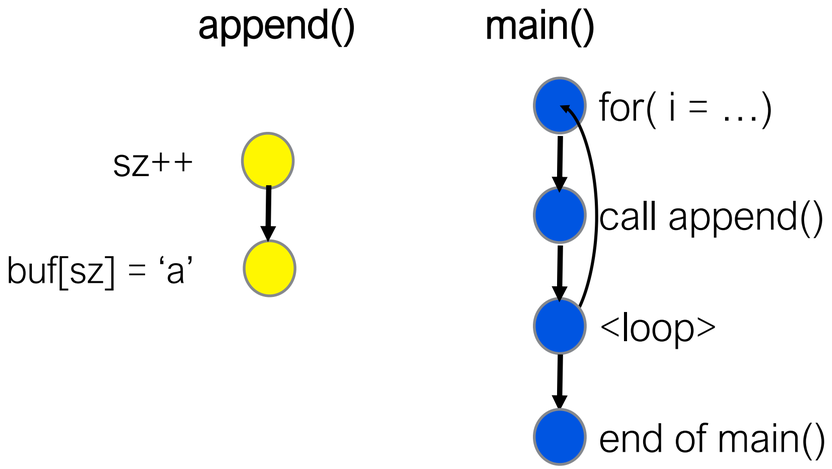
Control-flow Graph




```
void main(void){
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}

void append(){
  sz++
  buf[sz] = ‘a’
}
```
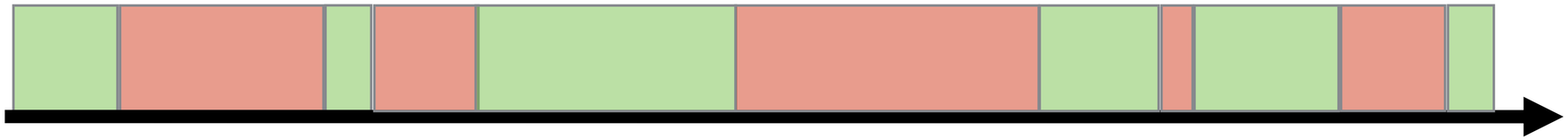
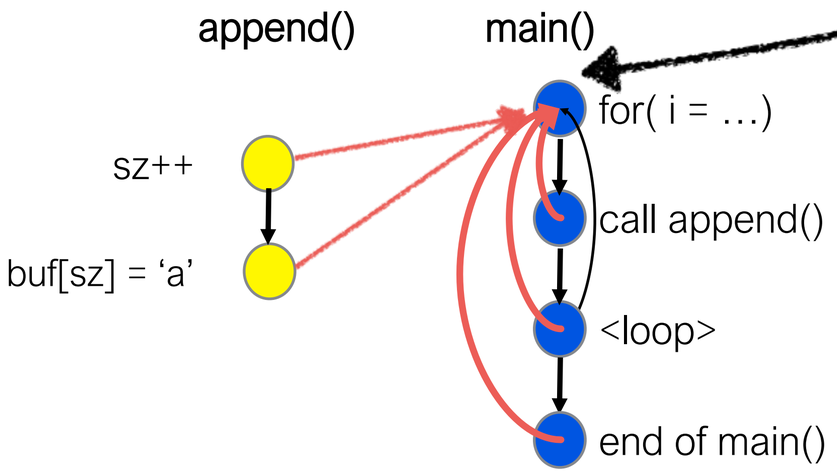

We can model intermittence as a control-flow problem



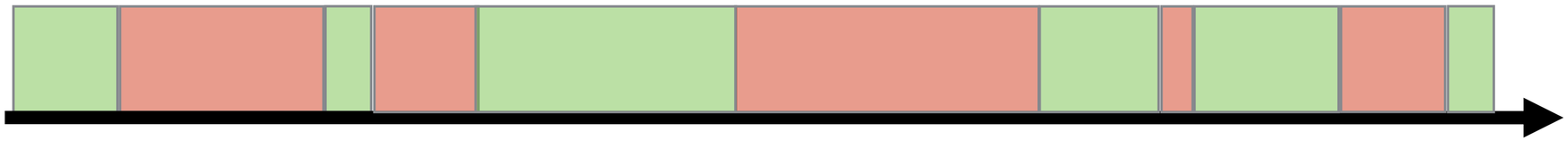
Back in time!

Control-flow Graph

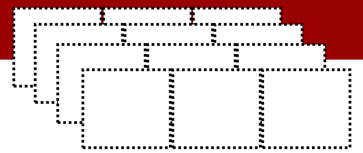


Intermittent Execution Challenge:
Implicit control-flow “back in time” on reboot.

Failure Induces
Implicit Control-flow

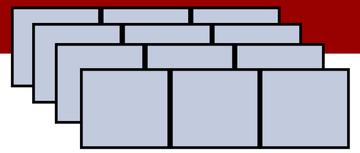


Mixture of Volatile & Non-volatile State



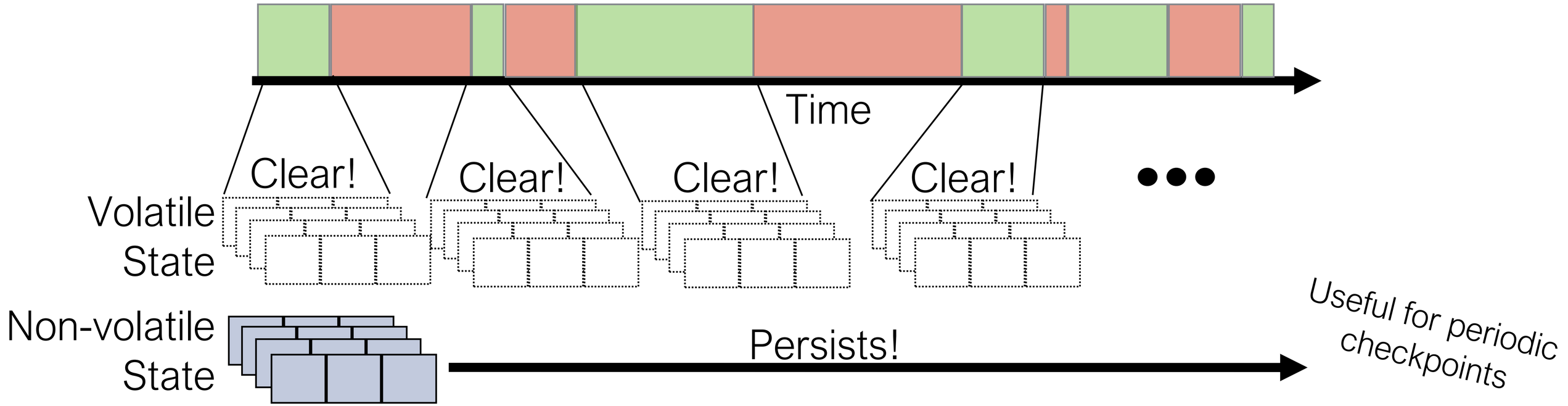
volatile memory (e.g., DRAM, SRAM registers)

Access latencies growing similar w/ new technology

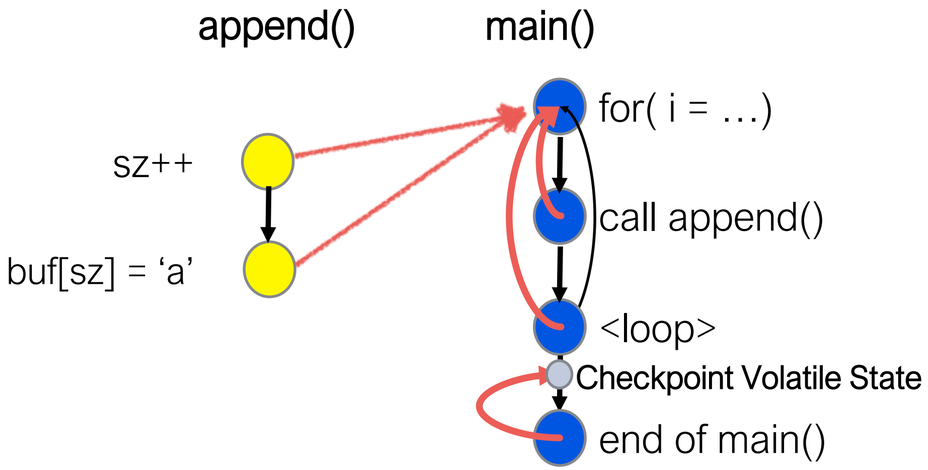


non-volatile memory (e.g., Flash, FRAM)

Reboots **clear** volatile state and **preserve** non-volatile state

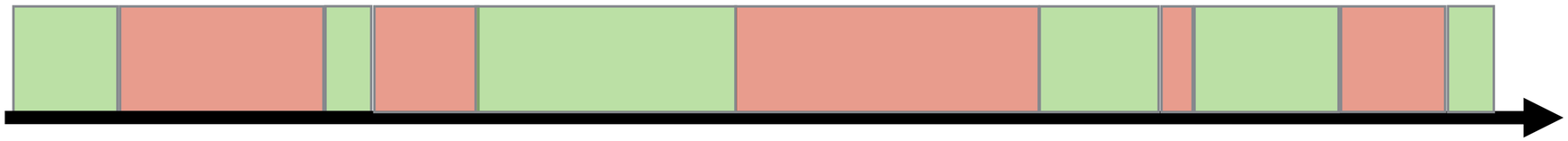


Control-flow Graph



Intermittent Execution Challenge:
Implicit control-flow “back in time” on reboot.

Checkpoint introduce **more complex** implicit control-flow



The Big Idea

for(i = 1)

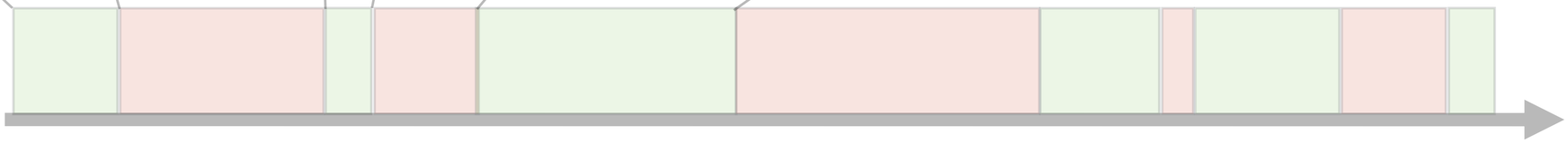
append()
sz++
buf[sz] = ‘a’

REBOOT

for(i = 2)

void main(void){
for(i = 1 .. 10)
append()
}

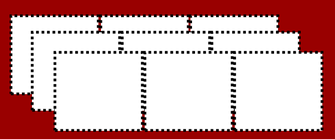
The way we think about software does work with the intermittent execution model



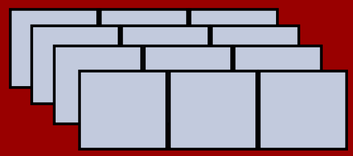
Challenge: *Intermittence Bugs*

Software that is **correct** with continuous power can be **incorrect** due to intermittent execution

especially when we combine non-volatile and volatile memory!

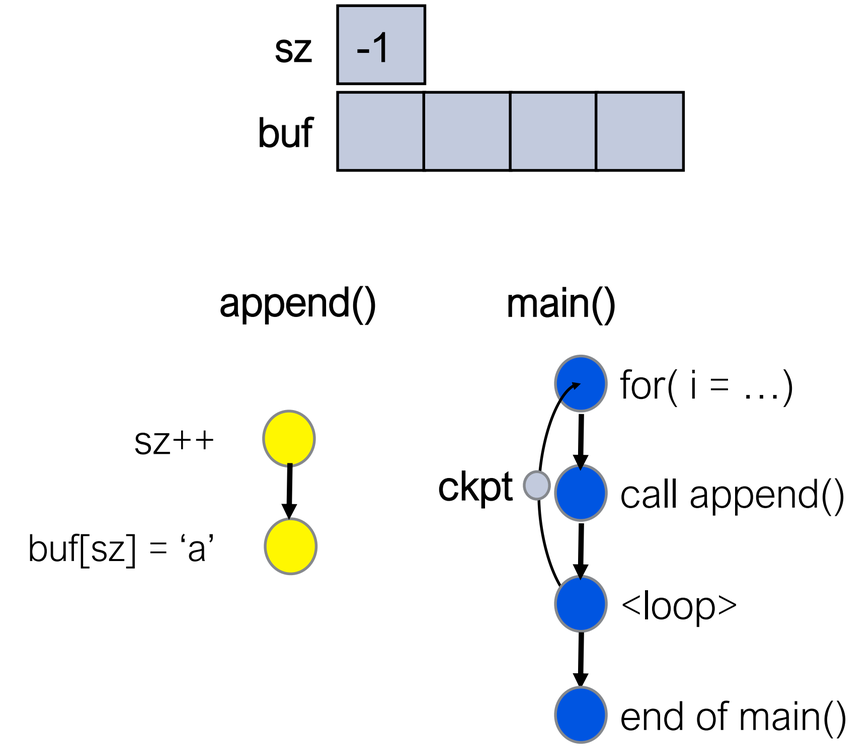


+



Intermittence Bug: Out-of-thin-air Values

[MSPC '14; PLDI '15]



Intermittence Bug: Out-of-thin-air Values

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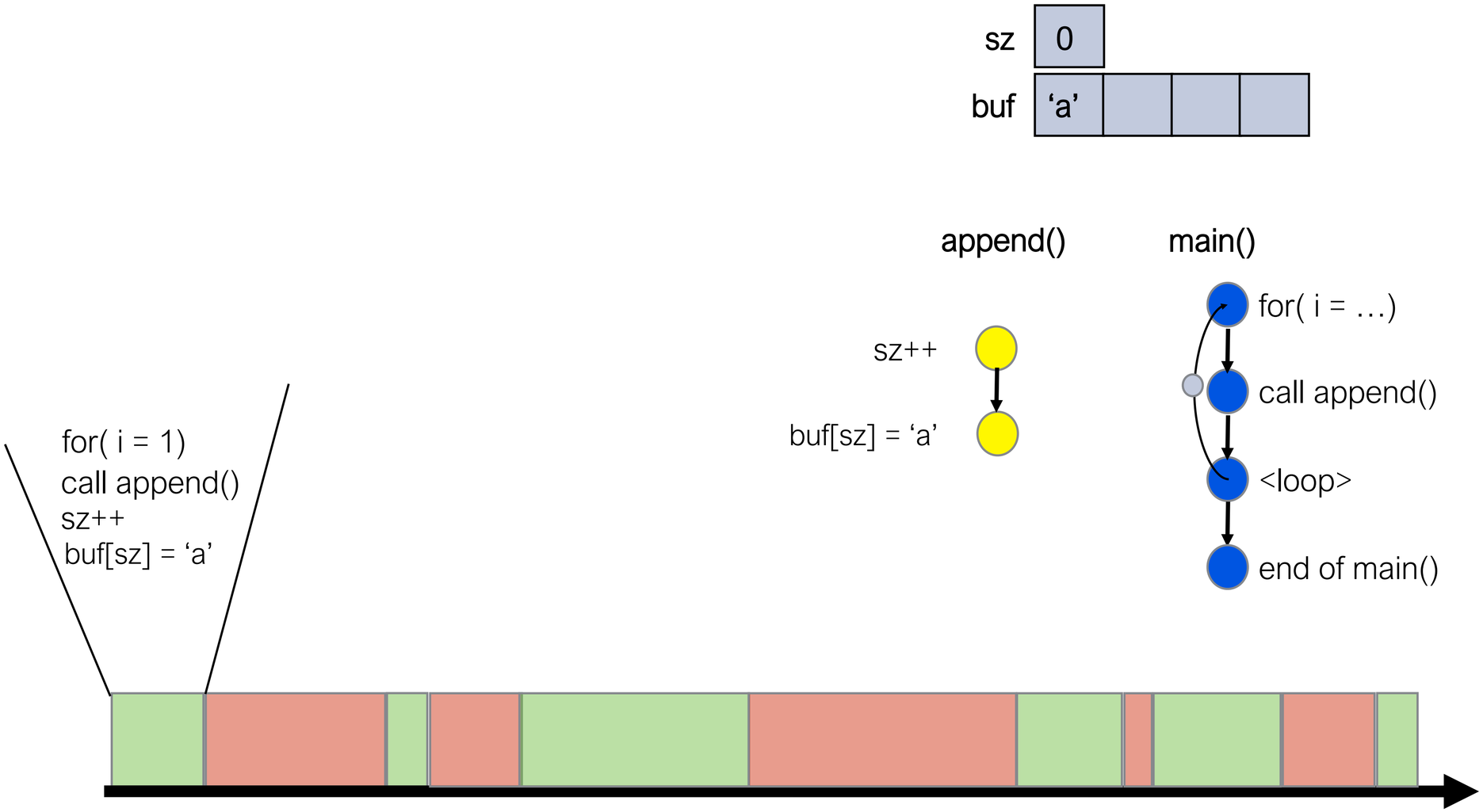

Intermittence Bug: Out-of-thin-air Values

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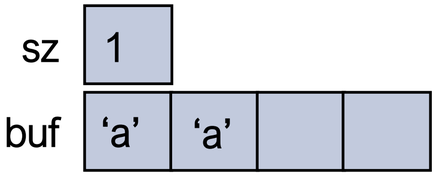
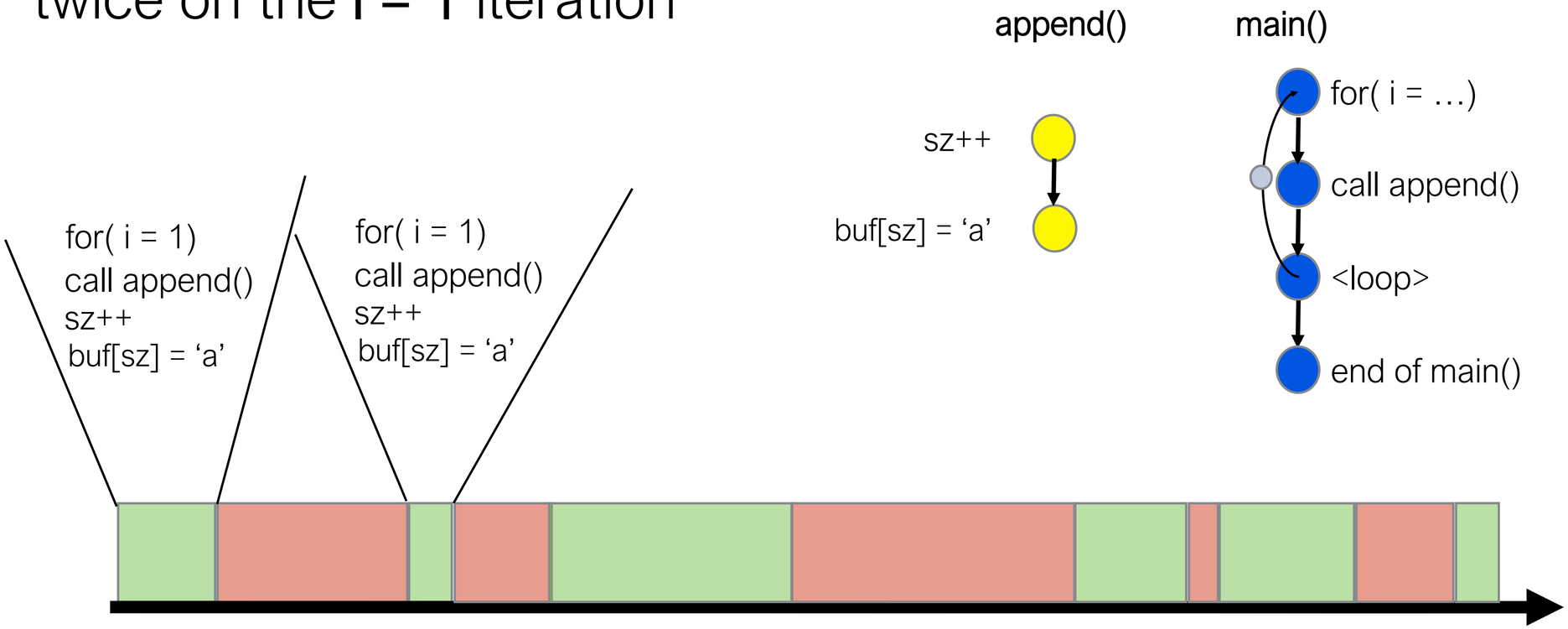


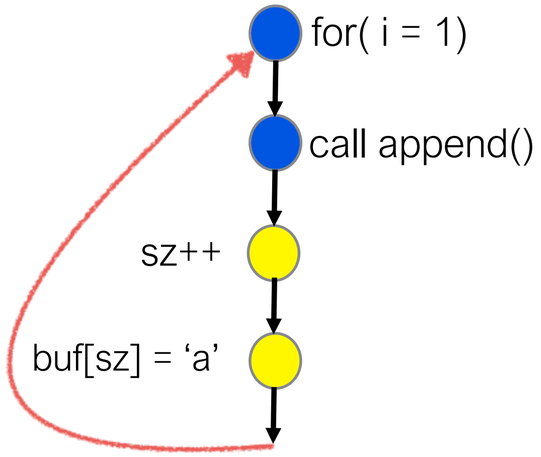
Error: 'a' is appended to **buf** twice on the **i = 1** iteration

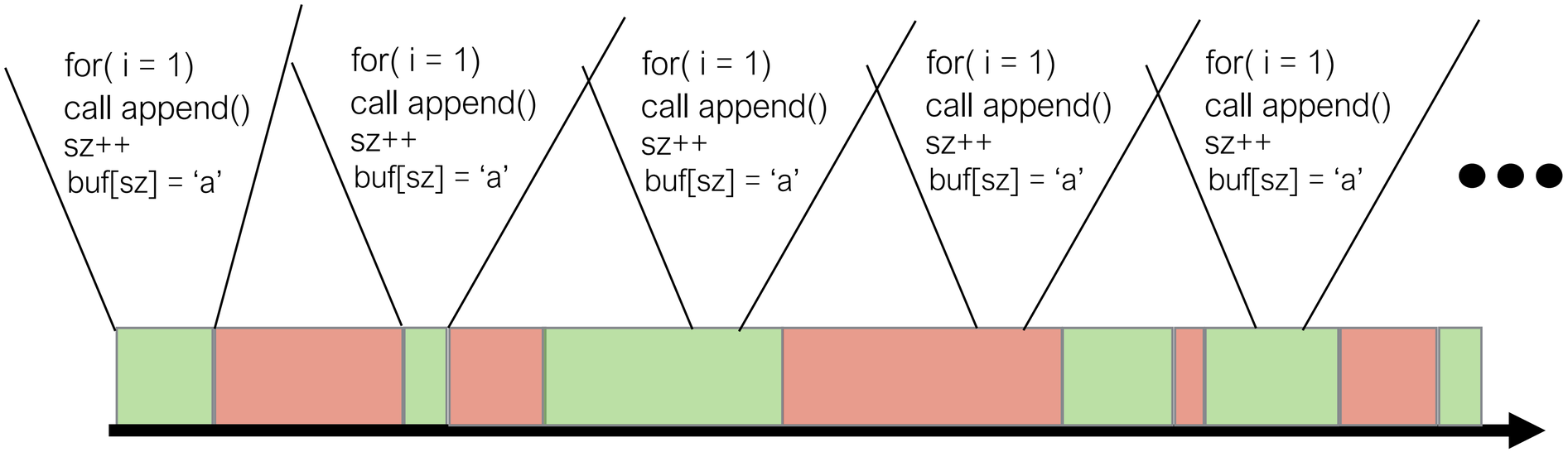


Intermittence Bug: Out-of-thin-air Values

[MSPC '14; PLDI '15]

Stuck in an implicit loop for **i = 1**





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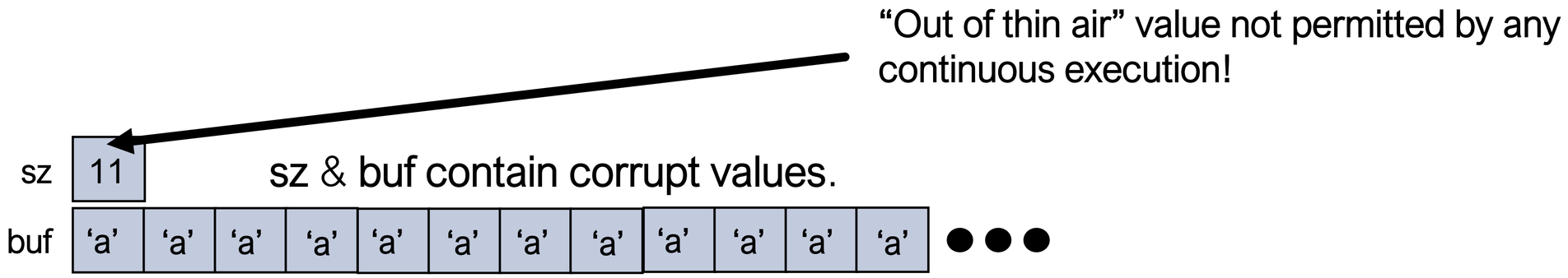
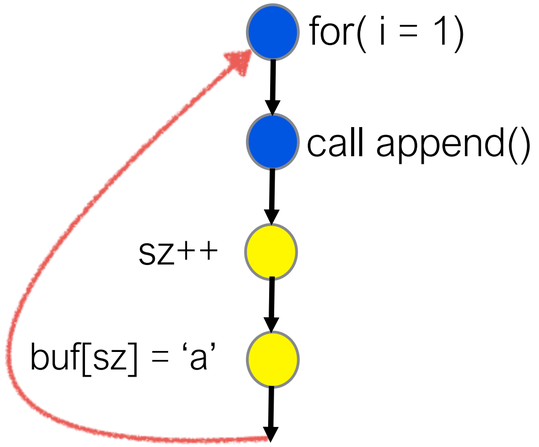


Memory contents depend on the *availability of harvestable energy* ***and*** *capacitor size*!

Stuck in an implicit loop for **i = 1**

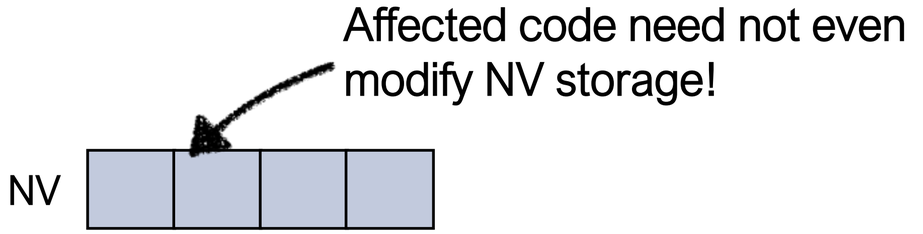


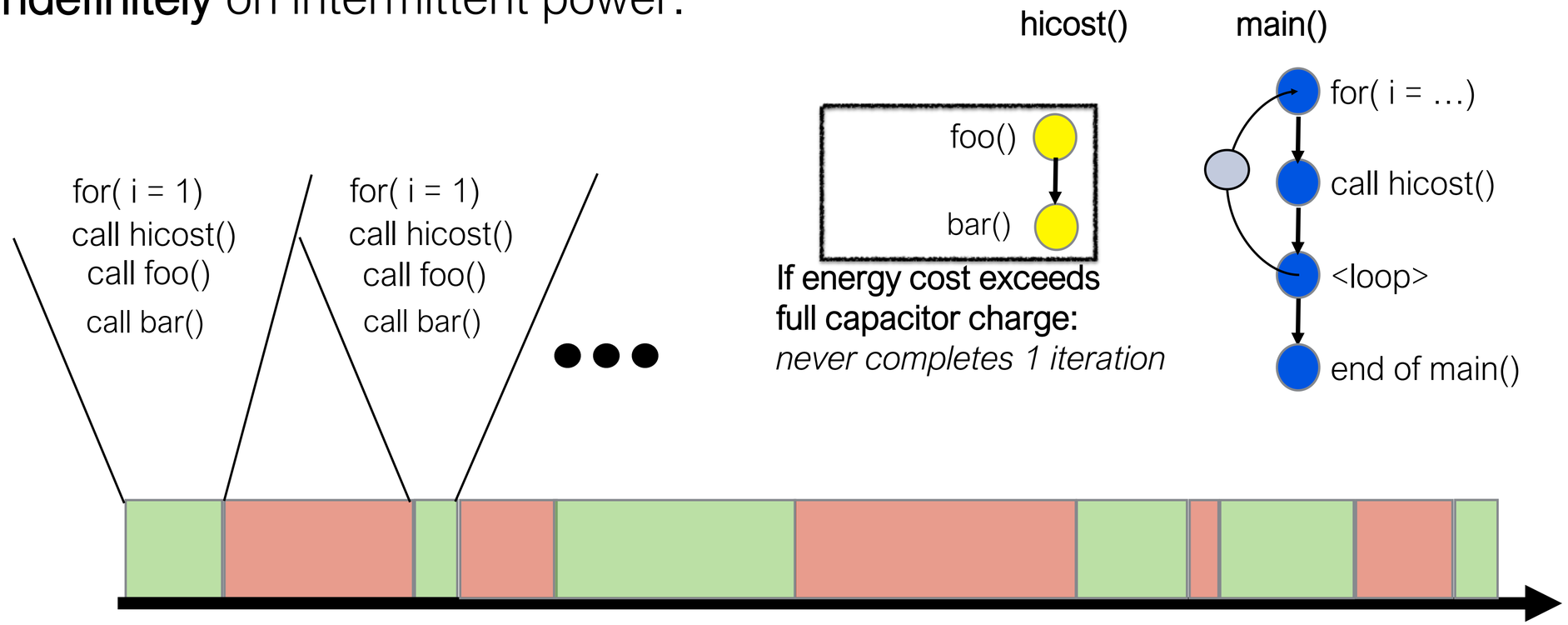
Intermittence Bug: Livelock & Non-termination

[Colin, et al. CASES '15, ASPLOS '16]

Energy cost atomic span exceeds energy capacity

Code that is **correct** with continuous power
reboots indefinitely on intermittent power.



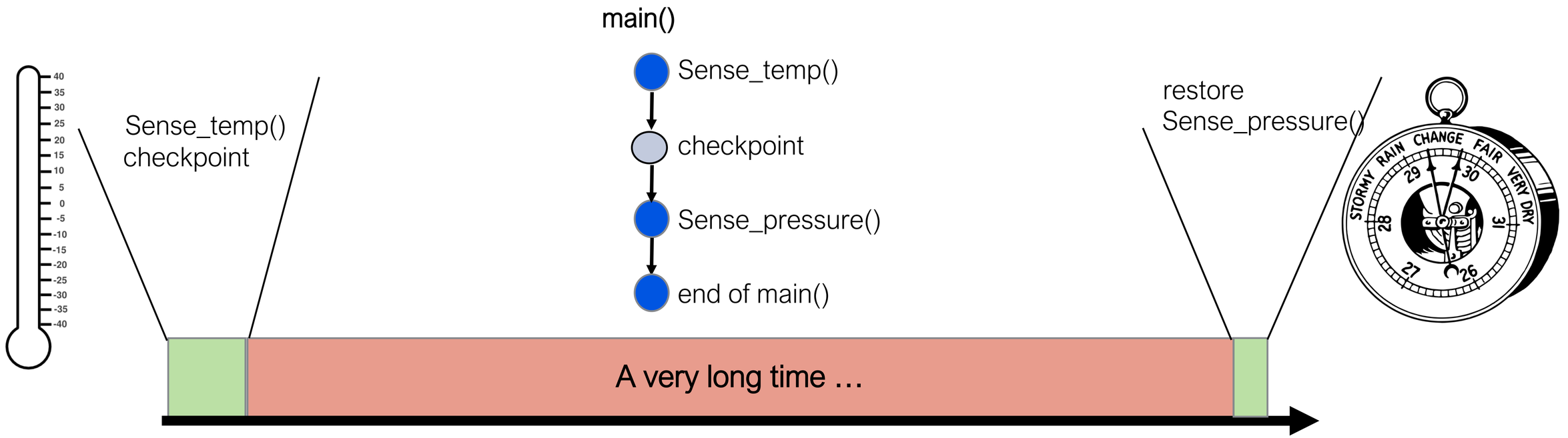


Intermittence Bug: I/O Atomicity

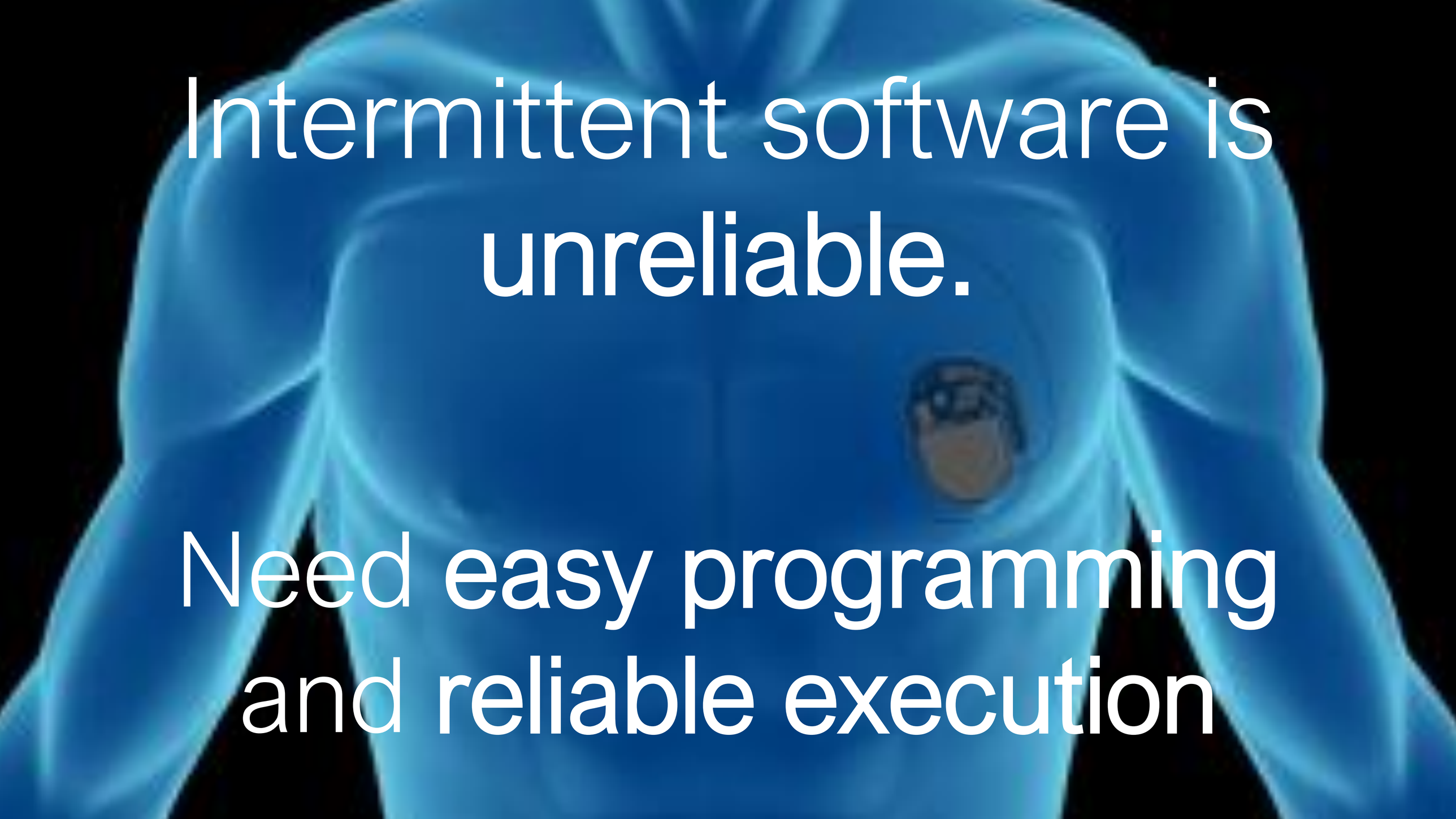
[Colin OOPSLA '16, Maeng OOPSLA '17, Hester et al SenSys '17]

Checkpoint between I/O operations that should execute together leaves I/O inconsistent

No atomicity control w/ automatic checkpoints

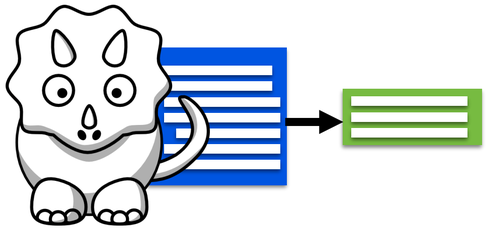


Inconsistent data read at different moments in time


Intermittent software is unreliable.
Need easy programming and reliable execution

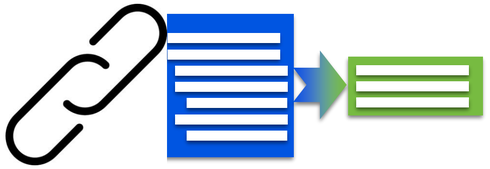
Reliable Intermittent Execution

Task-based Programming Models



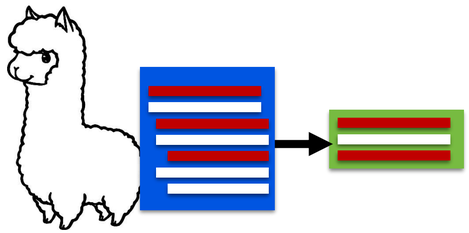
Dino

Arbitrary Task-based Intermittent Programming [PLDI'15]



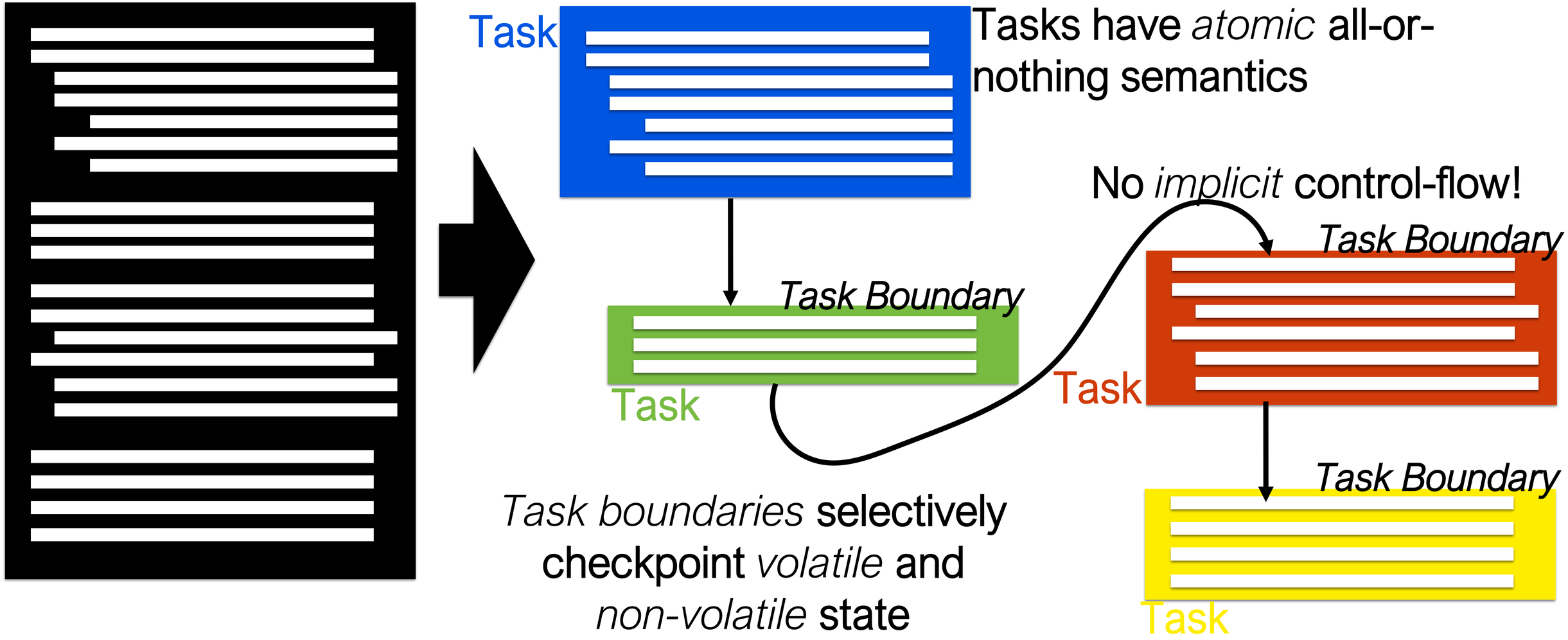
Chain

Task-based Intermittence w/ Static Data Duplication [OOPSLA'16]



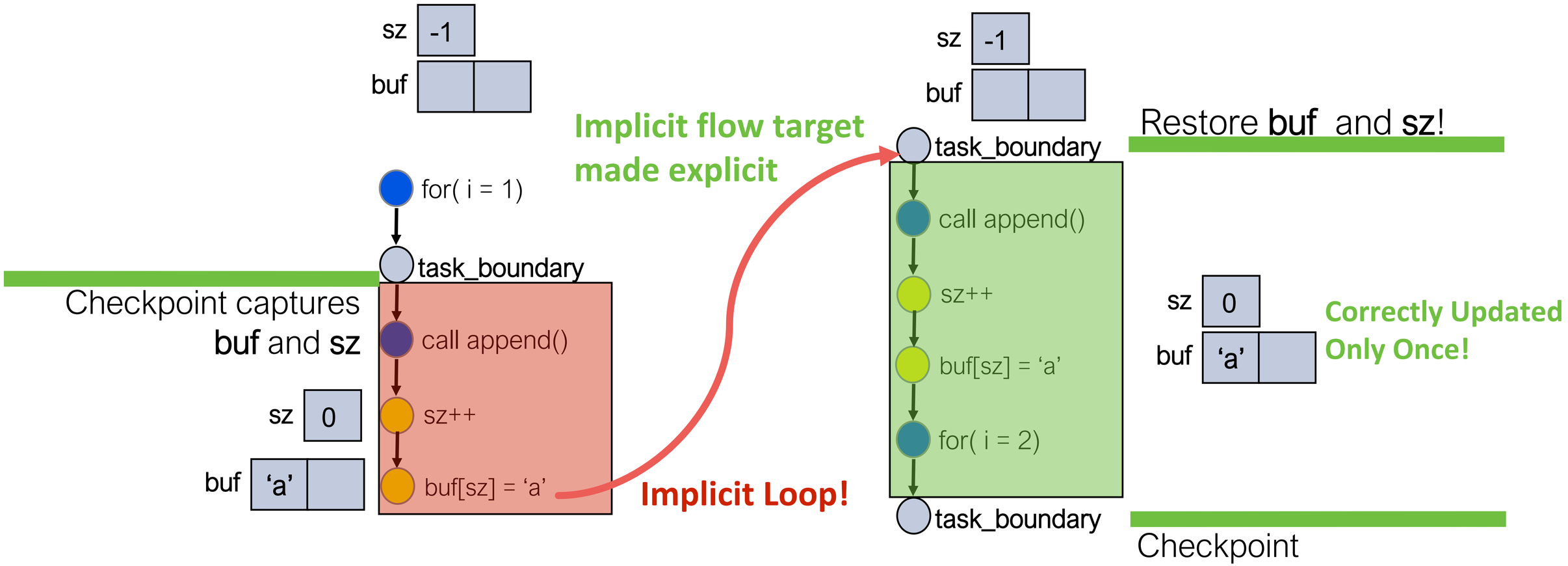
Alpaca

Task-based Intermittence w/ Dynamic Privatization [OOPSLA'17]



Task-atomic Execution in **DINO**

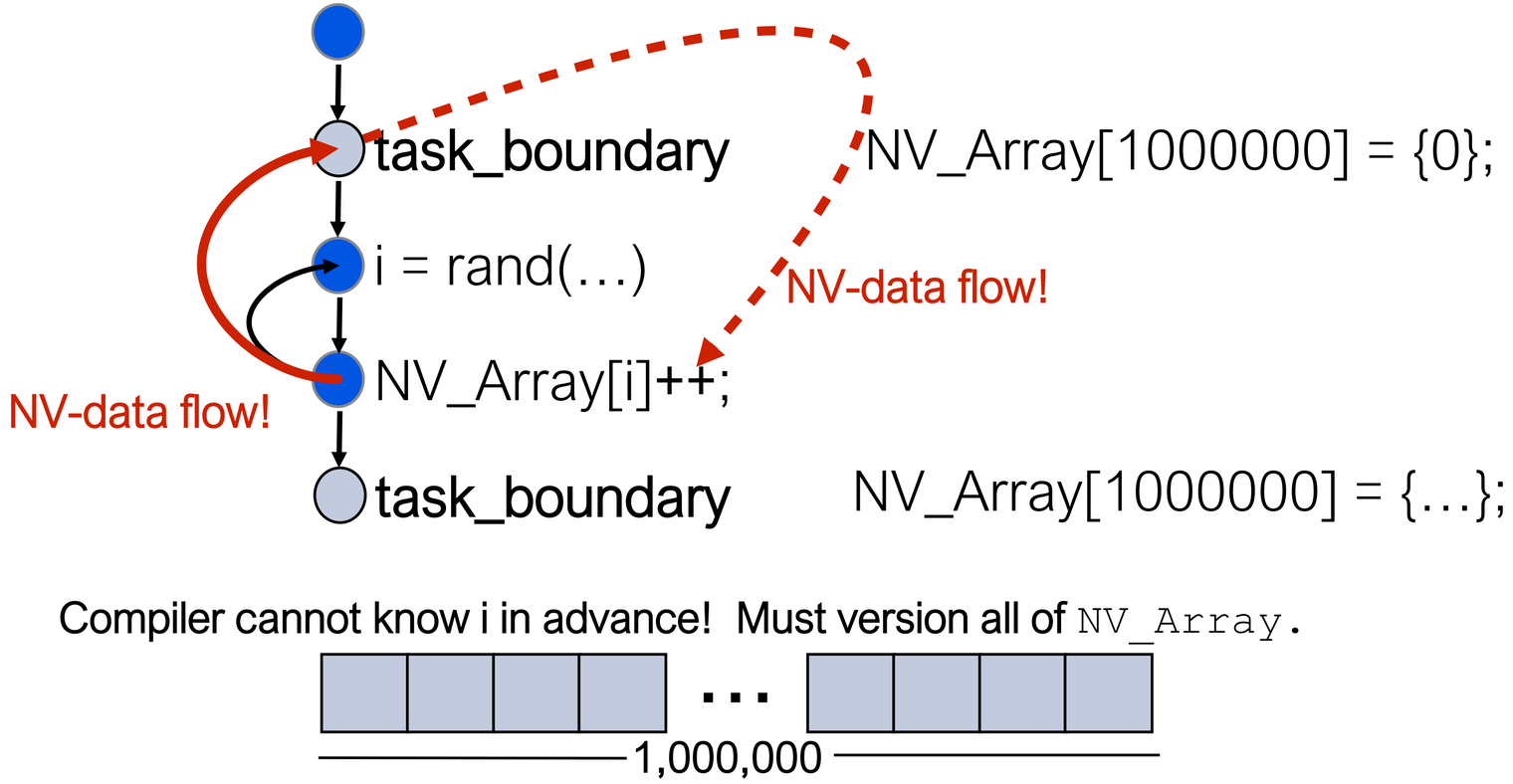
[PLDI '15]



DINO Eliminates OoTA Values

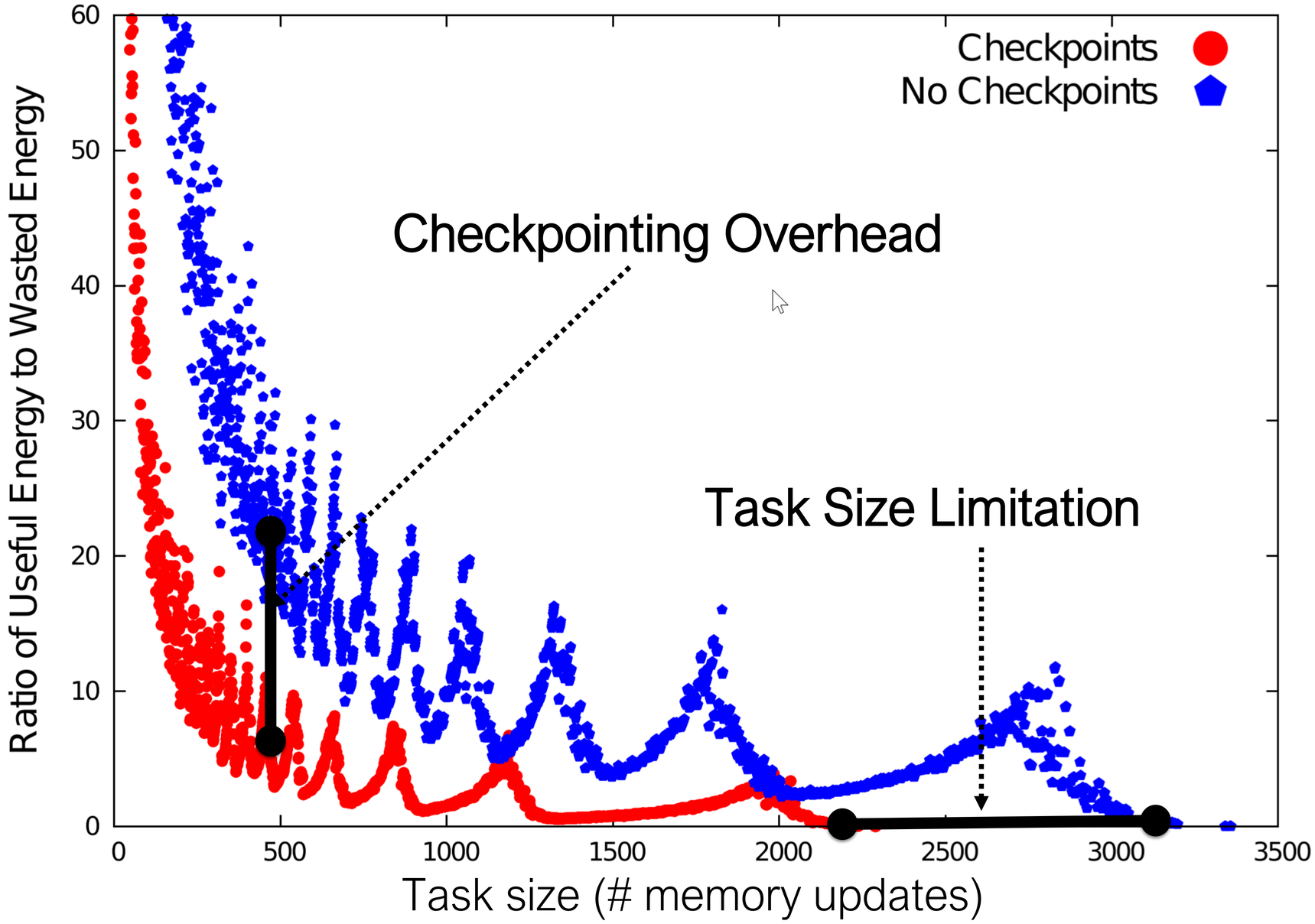
[PLDI ’15]

```
int NV_Array[1000000];
task_boundary
i = rand(1000000);

  NV_Array[i]++;

task_boundary
```



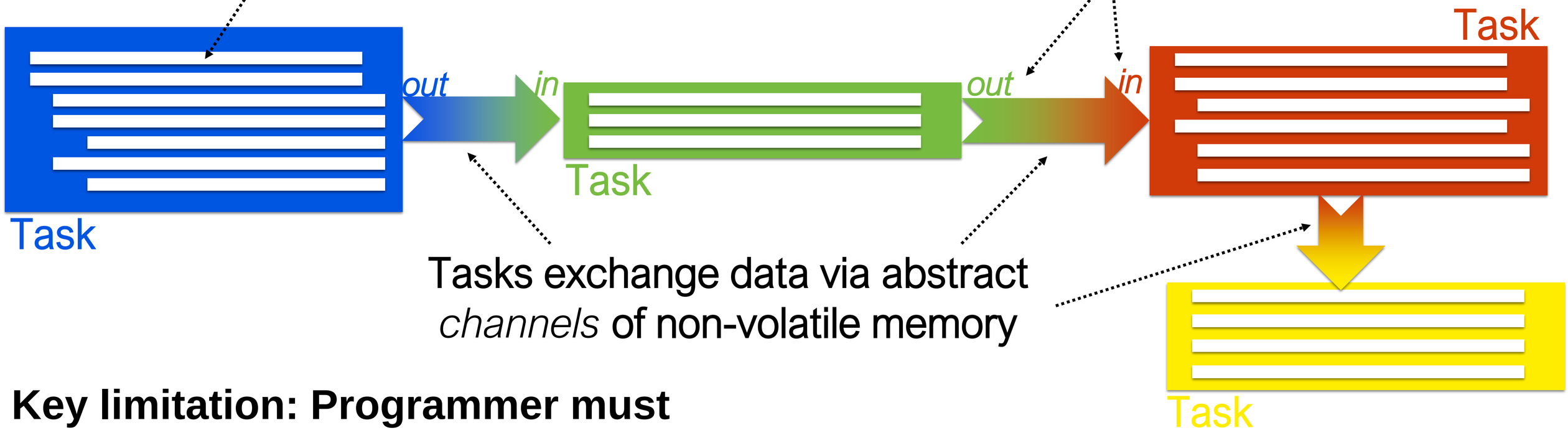
What data to include in checkpoint?

All NV data that **may** be accessed before a reboot, **plus volatile**.


Checkpoints
No Checkpoints
Checkpointing Overhead
Task Size Limitation
Ratio of Useful Energy to Wasted Energy
Task size (# memory updates)
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
3000
3500

Programmer explicitly defines tasks and task-flow graph in code

Channels *statically multiversion* data separating inputs from outputs



Tasks exchange data via abstract *channels* of non-volatile memory

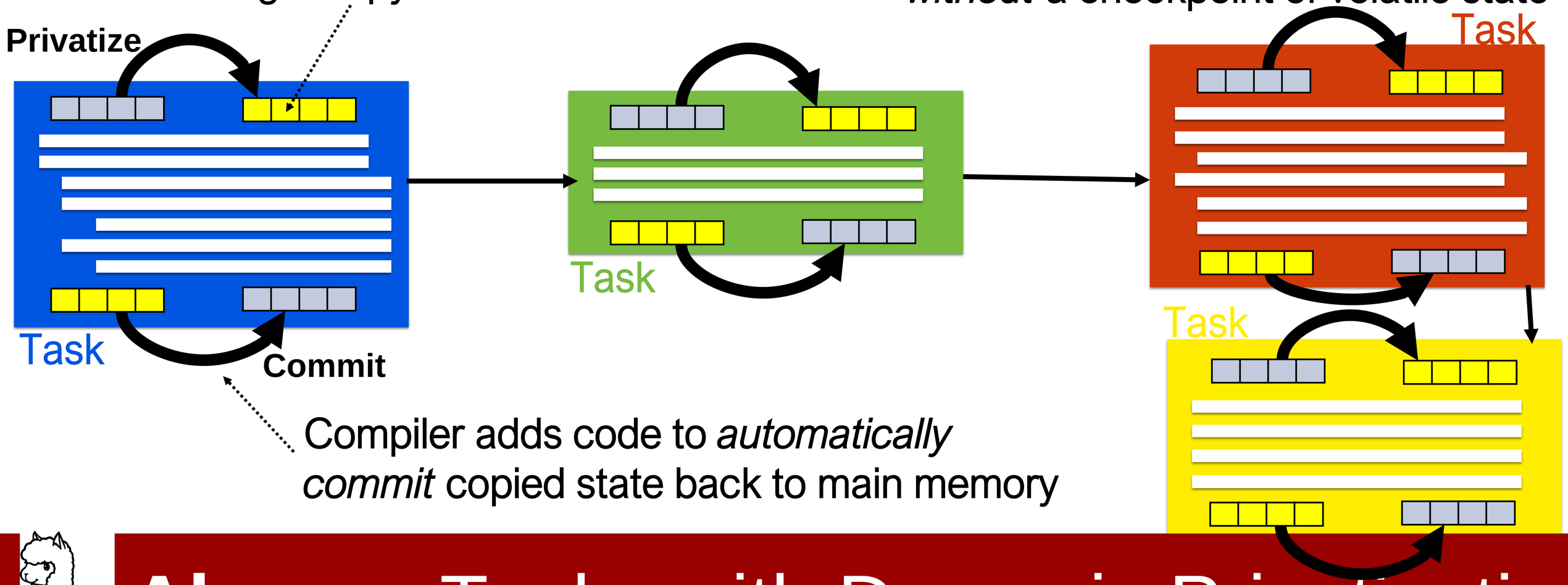
Key limitation: Programmer must learn new programming model

Chain: Static data multi-versioning

[Colin, et al OOPSLA '16]

Compiler *automatically privatizes* data creating a copy safe to use in a task.

Alpaca tasks are restartable *without* a checkpoint of volatile state

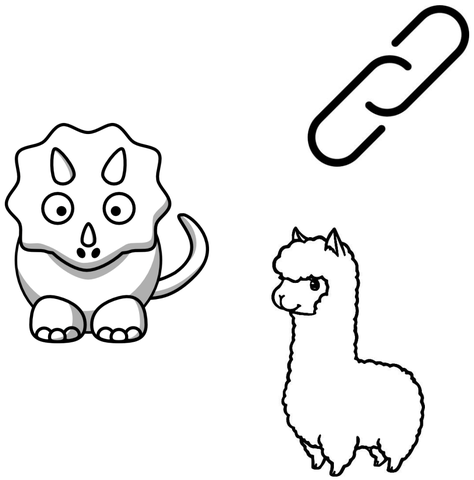


Compiler adds code to *automatically commit* copied state back to main memory

Alpaca: Tasks with Dynamic Privatization

[Maeng, et al OOPSLA '17]

DINO, Chain, Alpaca Programming Model



Task, Channel Definitions

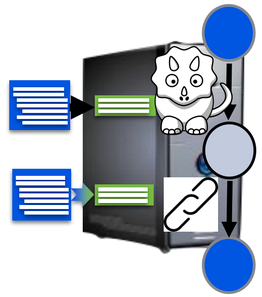
Task-aware Compiler

Task Data-flow Analysis

Link to Task Runtime

Channels, Versioning, Privatization

Runtime Library



DINO: Checkpoint & Recovery

Chain: Task Management

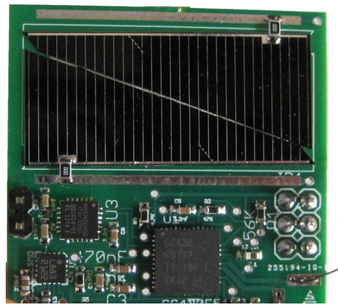
Alpaca: Privatization/Commit

Prototype Implementations

Energy-harvesting Platform Prototypes

WISP5 Energy-harvesting Device

RF Power Setup



Custom PCBs

Applications

Activity Recognition (accelerometer+ML)

MIDI Natural User Interface

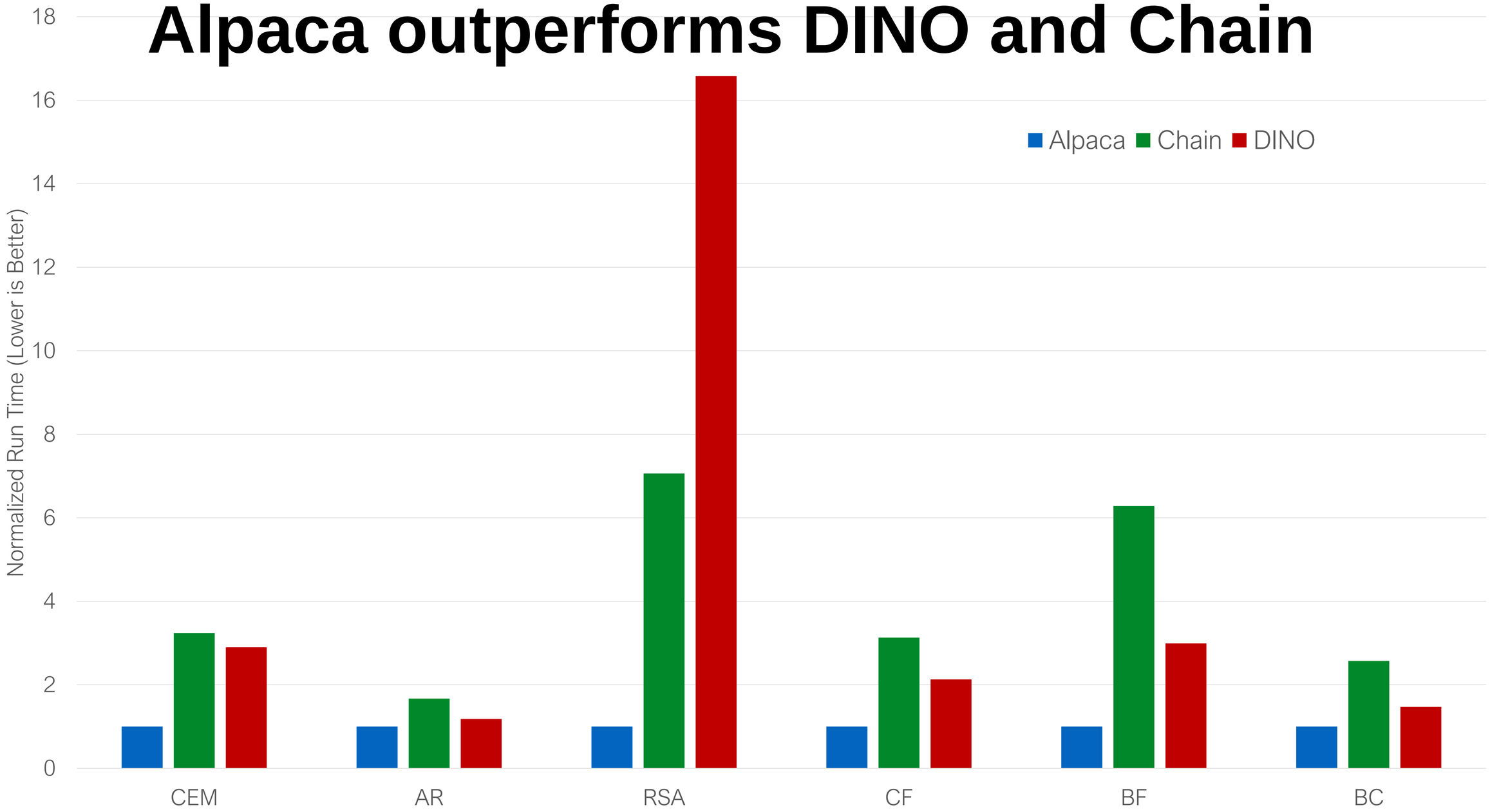
Cold-chain Equipment Monitor

Multi-granular Sensor Log

Key Result:

Applications suffer **errors** & **failures** without our system support for tasks

Alpaca outperforms DINO and Chain



Use Alpaca, Chain and DINO for your research!

http://intermittent.systems | http://github.com/CMUAbstract

https://cmuabstract.github.io/alpaca-landing-page/

Alpaca

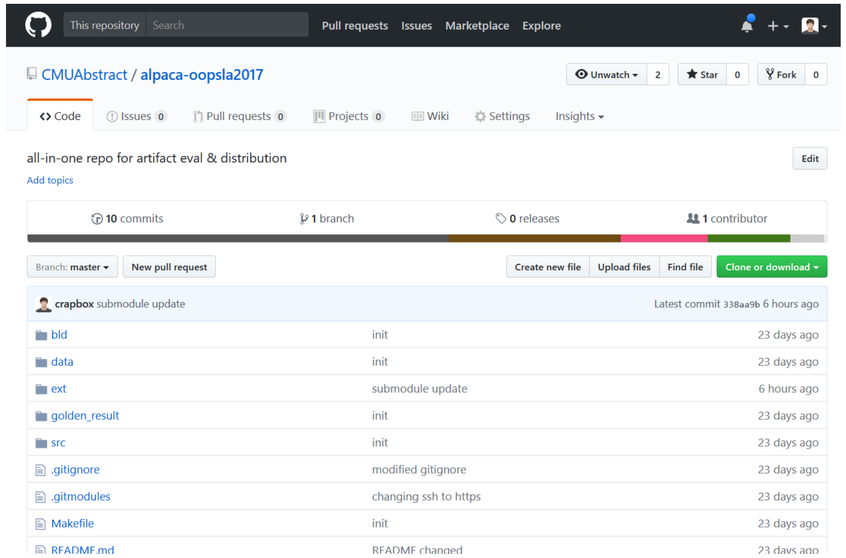
A programming language for writing reliable software for intermittent, energy-harvesting computer systems

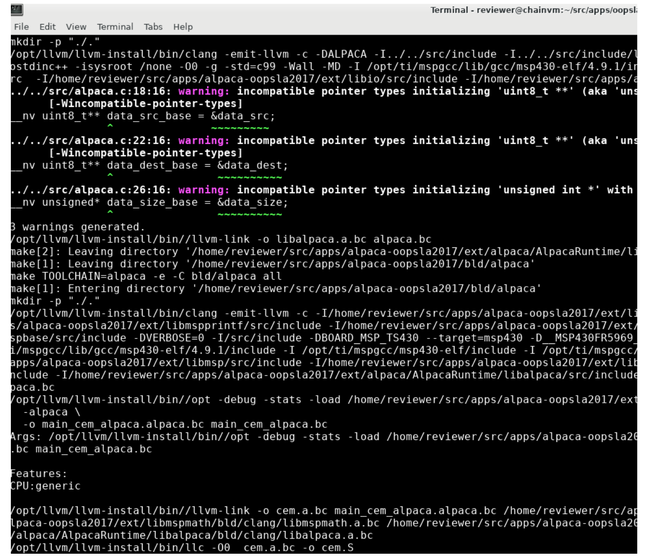
Download VM (10.67GB)

VM contains Alpaca and other previous state-of-the-art systems (Chain, DINO)
UserID: reviewer PW: review.

Pull source code from Github

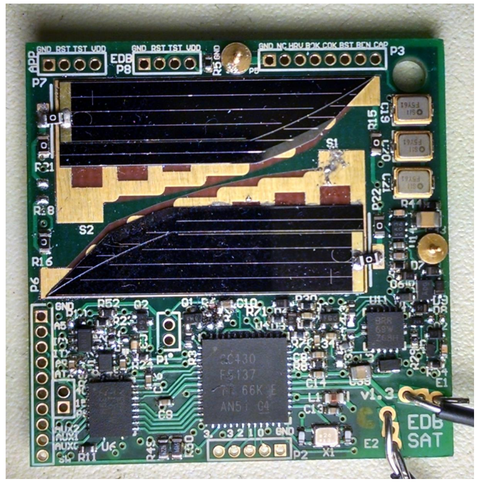
https://github.com/CMUAbstract/alpaca-oopsla2017



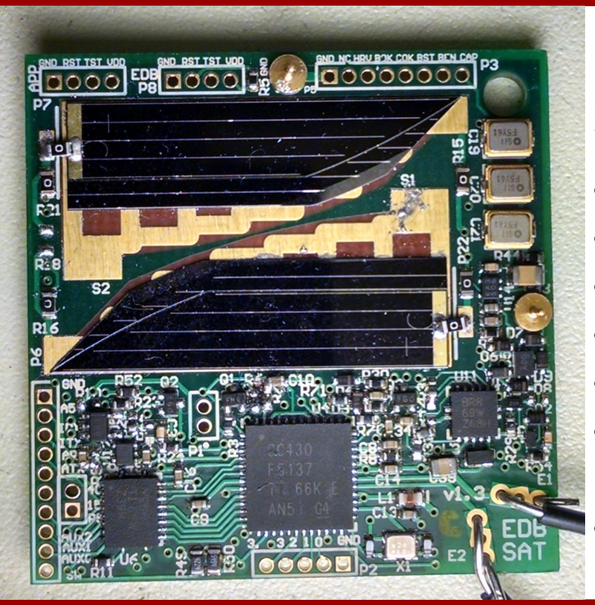


Intermittent Computing Platforms

Hardware, Programming Models, System Software

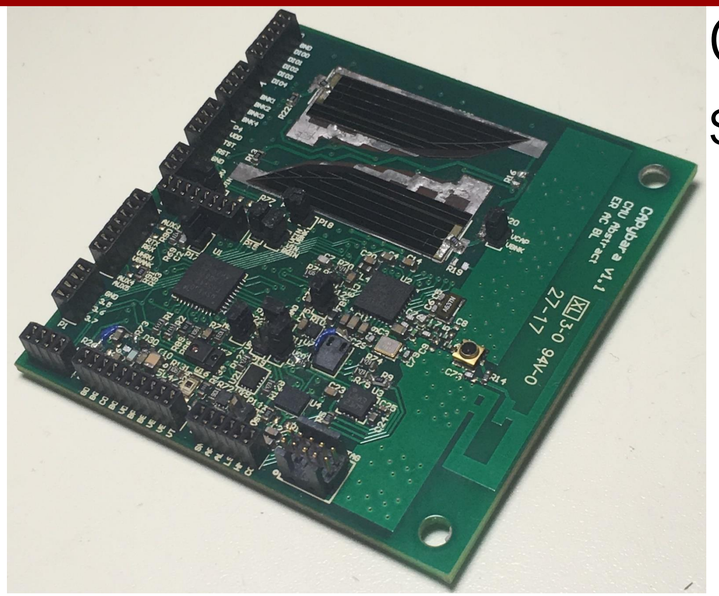


Intermittence-safe HW/SW Systems [ASPLOS 2018]



EDBSat Chip-scale satellite

- 3cmx3cmx4mm, solar power
- Magnetometer + gyro sensors
- Low-power radio (to earth)
- Custom “burst” power system
- Integrated HW/SW diagnostics
- Programmed in intermittence-safe Chain programming lang.
- Launch partner: KickSat/NASA



Capybara multi-sensor platform

- 5cmx5cm, solar/RF power
- 10 sensor array
- Bluetooth Low-energy Radio
- Software-switchable variable-capacity “burst” power system
- Integrated HW/SW diagnostics
- Supports Alpaca & Chain intermittent programming langs.

Key Insight: Co-design PL, OS, Arch, and power system for intermittent operation

The Intermittent Execution Model

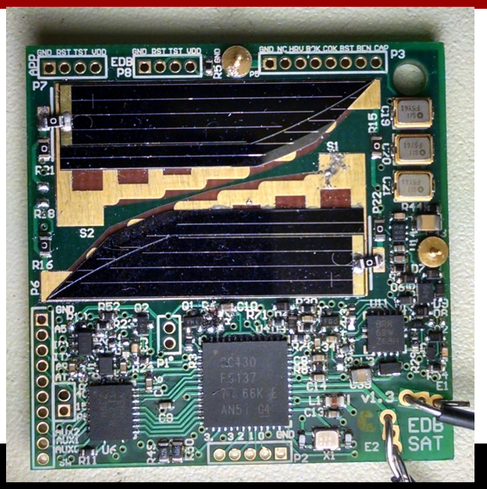
Reasoning About Intermittently-powered Devices

Designing for Intermittence

System Support for Reliable Intermittence

Intermittent Computing Platforms

Hardware, Programming Models, System Software



Solving the System Challenges of Intermittent Energy-harvesting Devices

Brandon Lucia | Assistant Professor, CMU ECE

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