# DYNAMIC BUFFER OVERFLOW DETECTION FOR GPGPUS

CHRIS ERB, MIKE COLLINS, JOE GREATHOUSE,
FEBRUARY 6, 2017

# CONSEQUENCES OF BUFFER OVERFLOWS

## DEGRADING USER EXPERIENCE, AND SECURITY RISKS

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Data Corruption

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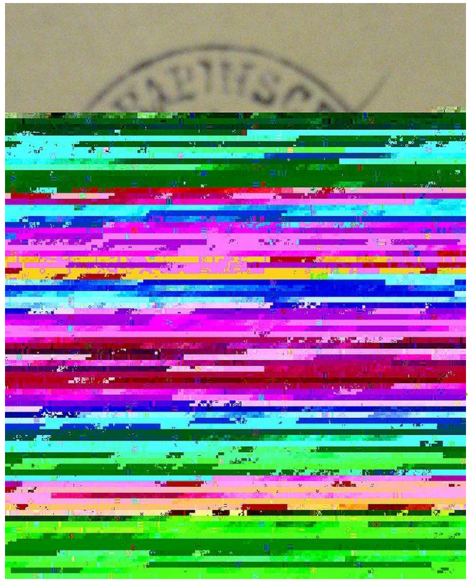

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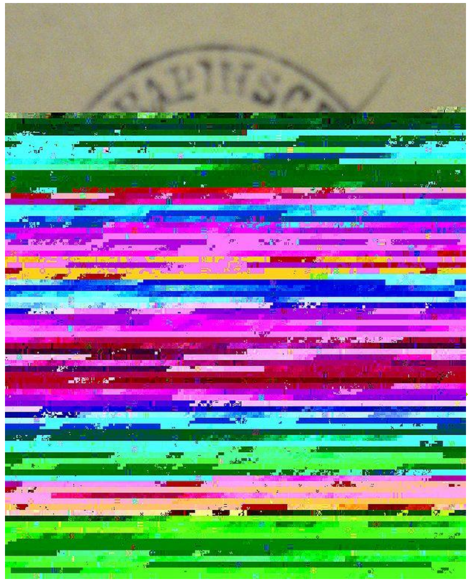

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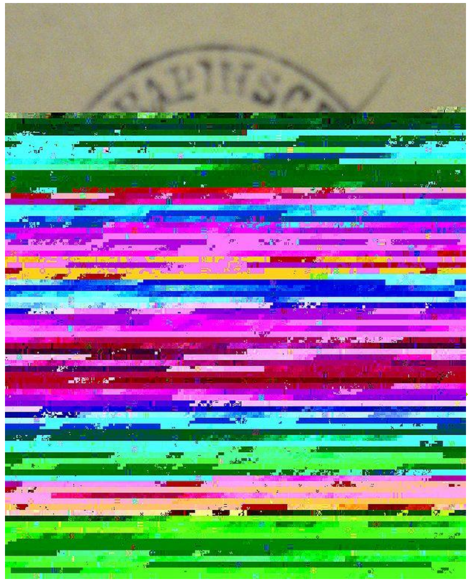

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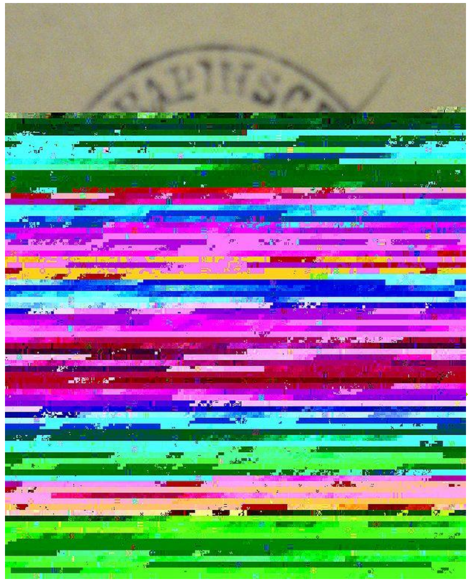

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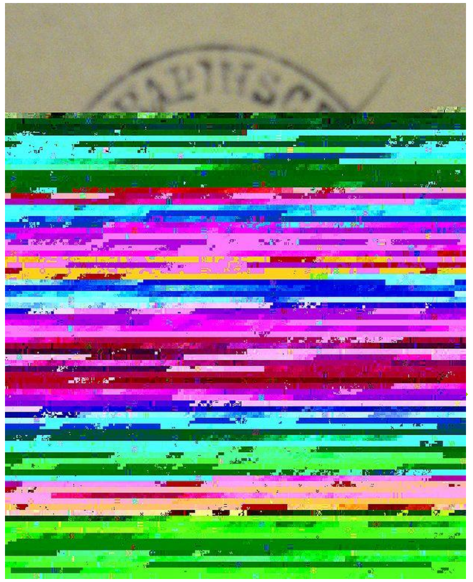

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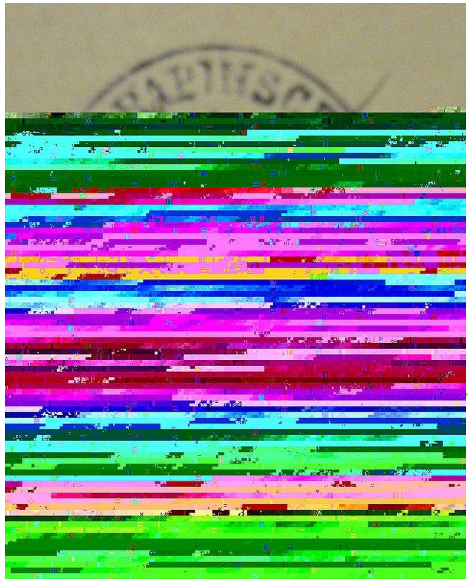

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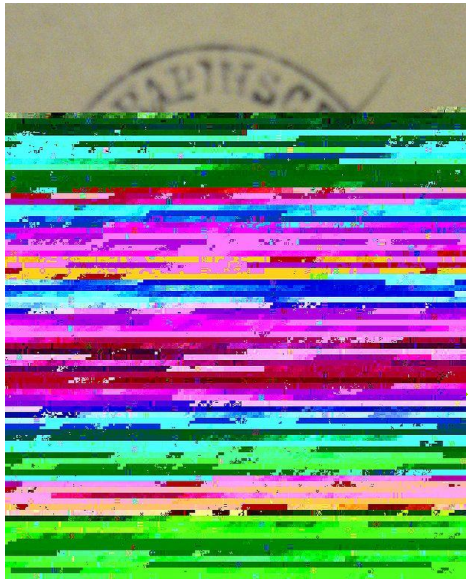

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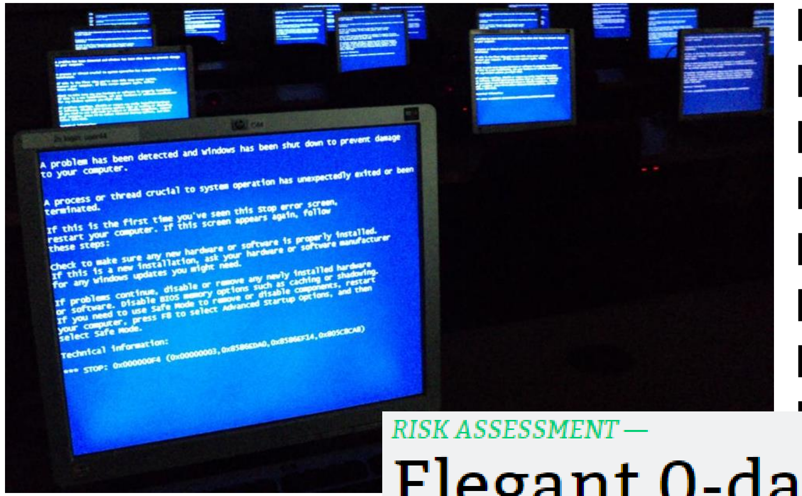


**Altered Control Flow**

**(Security Subversion)**

*RISK ASSESSMENT —*

Elegant 0-day unicorn underscores "serious concerns" about Linux security

Scriptless exploit bypasses state-of-the-art protections baked into the OS.

DAN GOODIN - 11/22/2016, 3:48 PM

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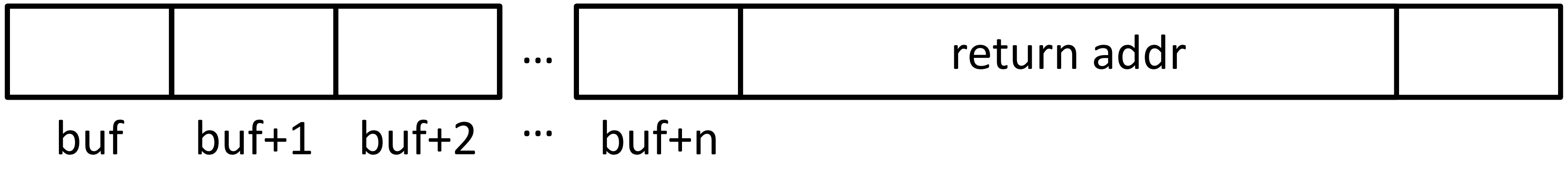

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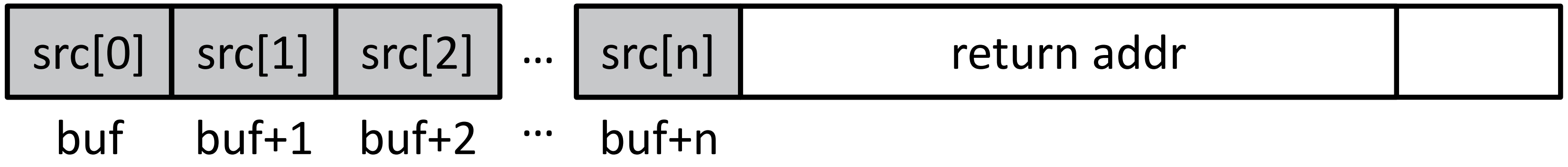
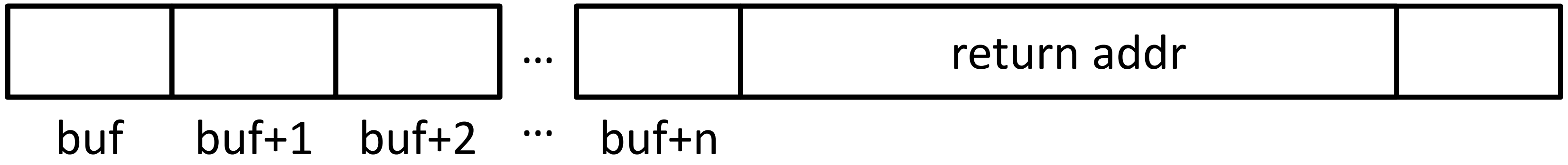


# BACKGROUND: BUFFER OVERFLOW

- buf[n+1]
- memcpy(buf, src, n+5)



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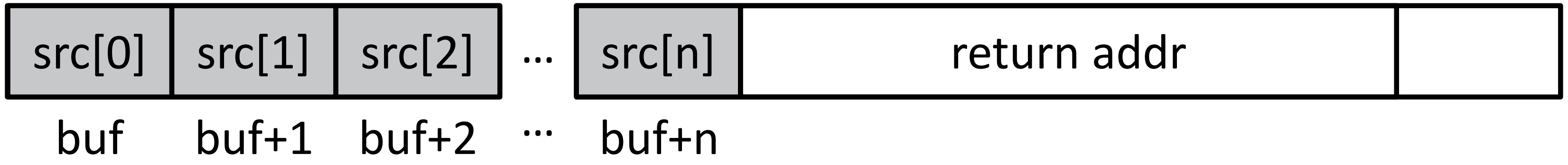

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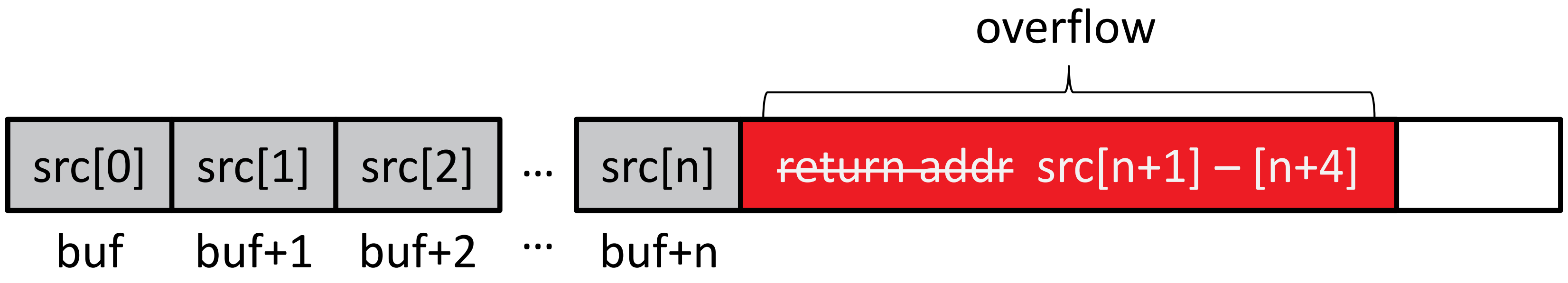

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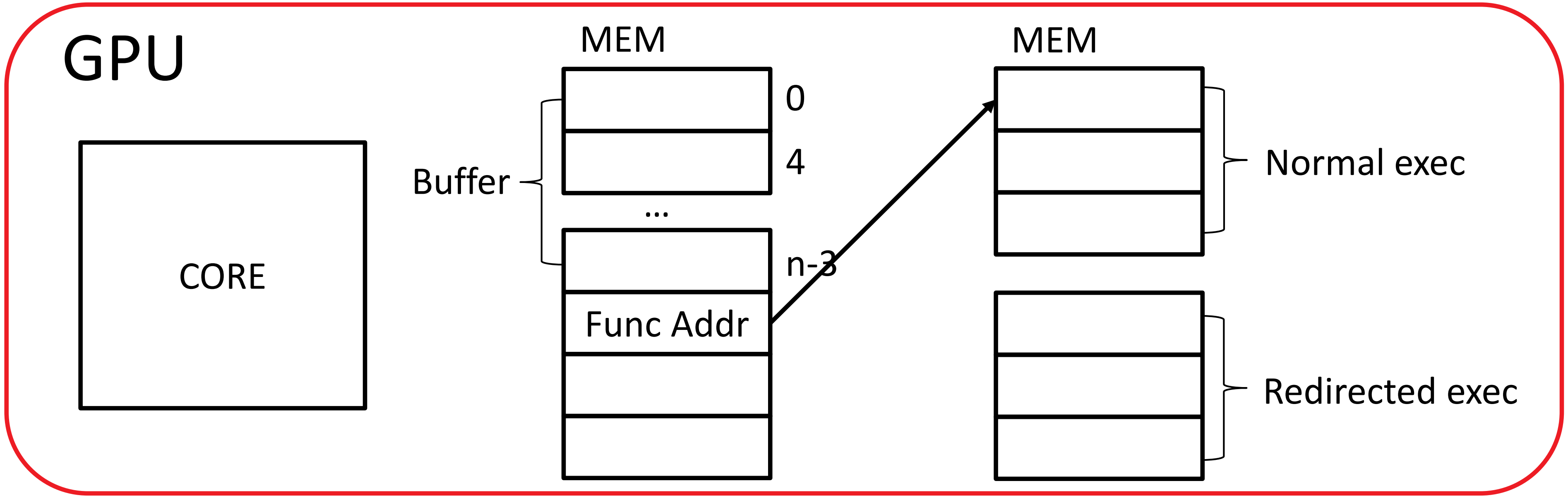

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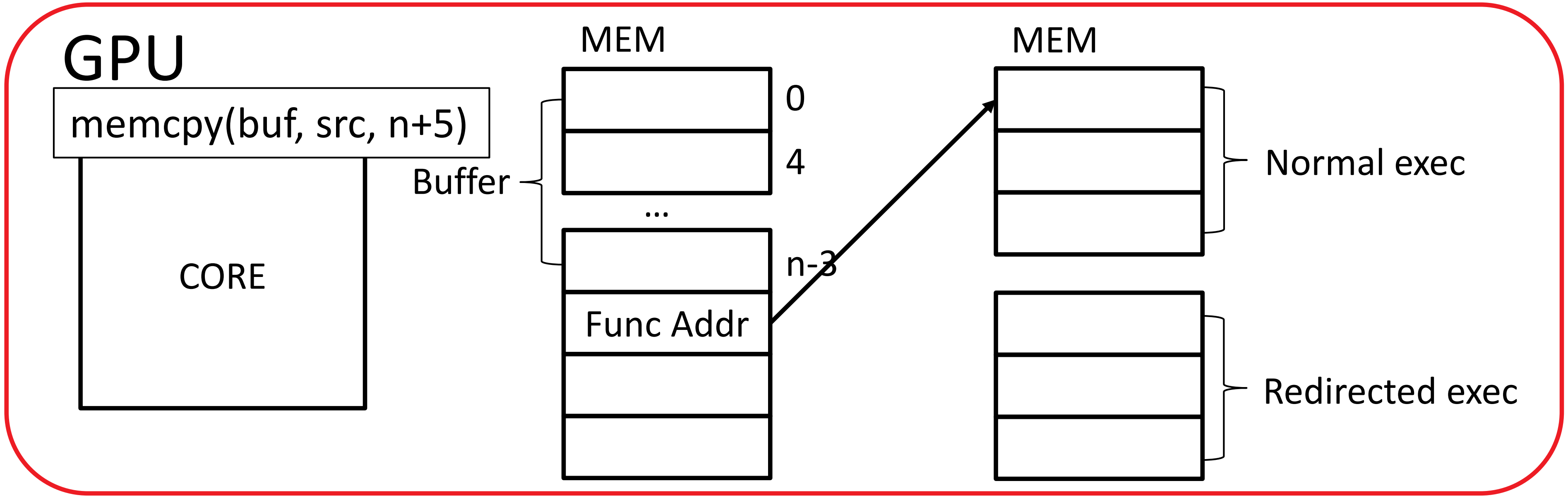

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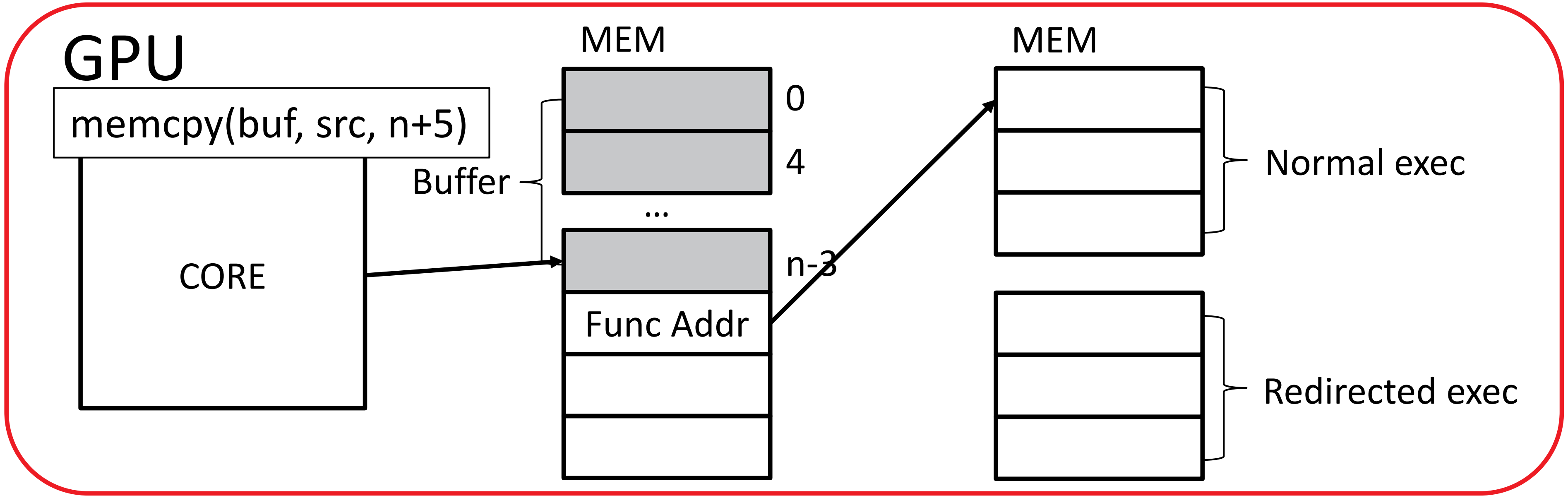

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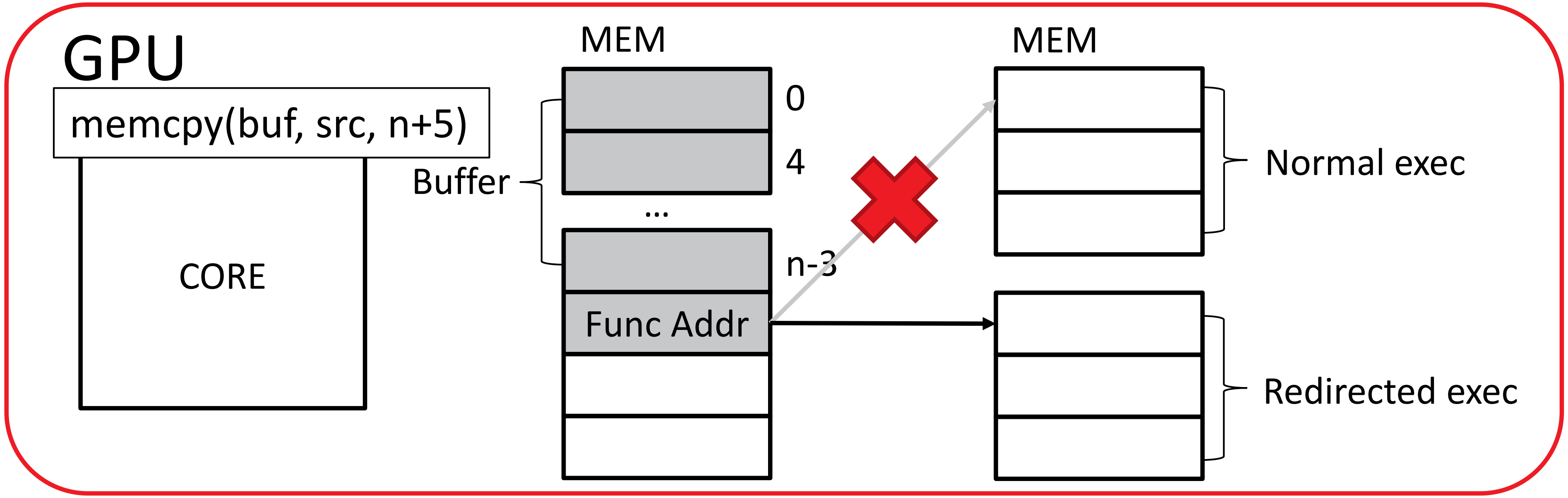

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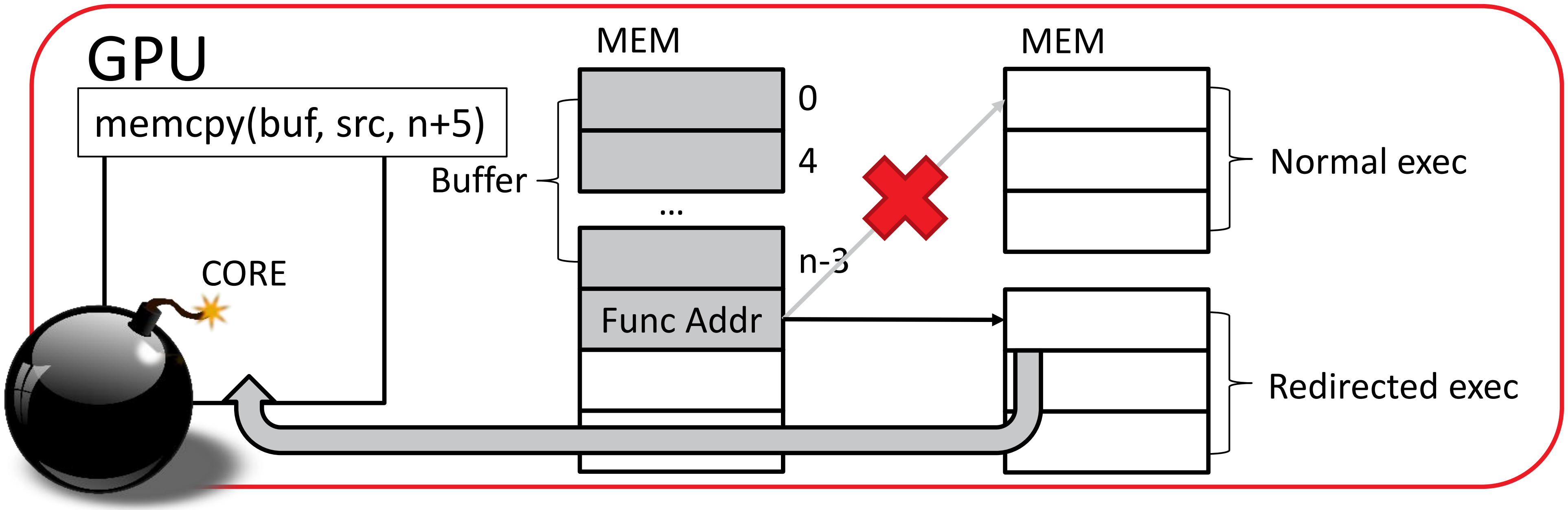

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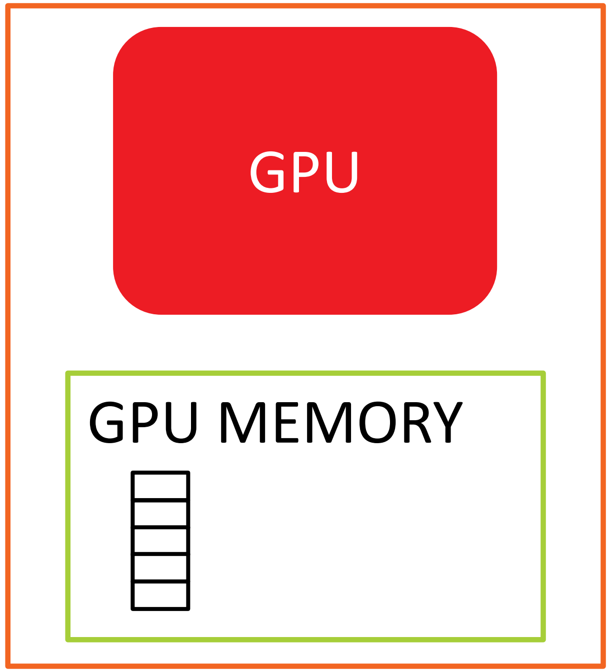

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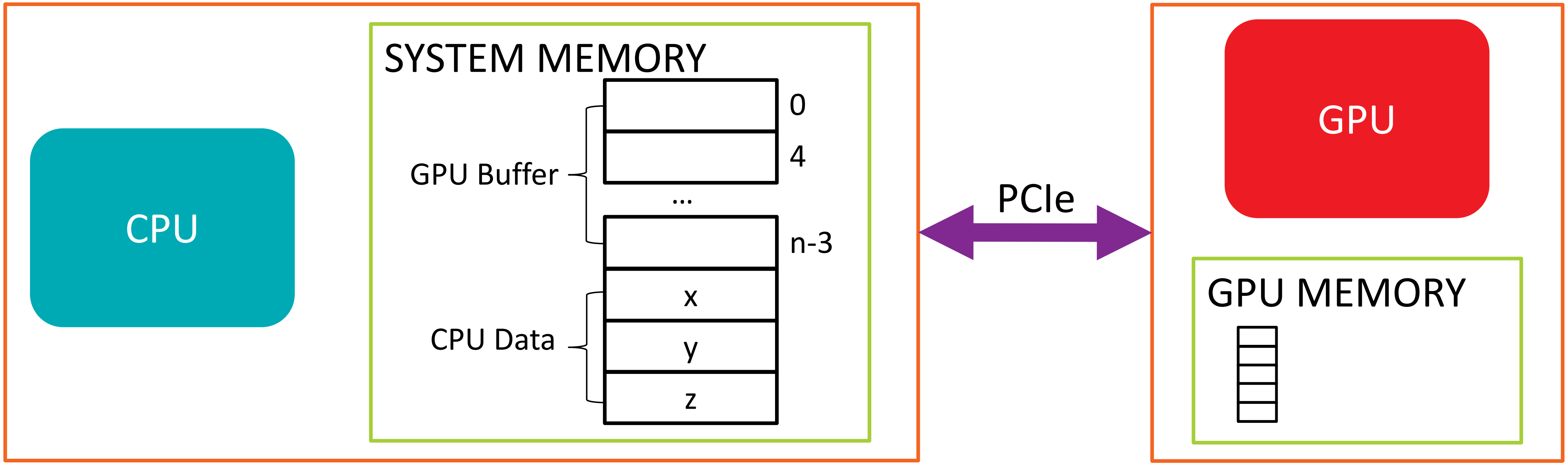

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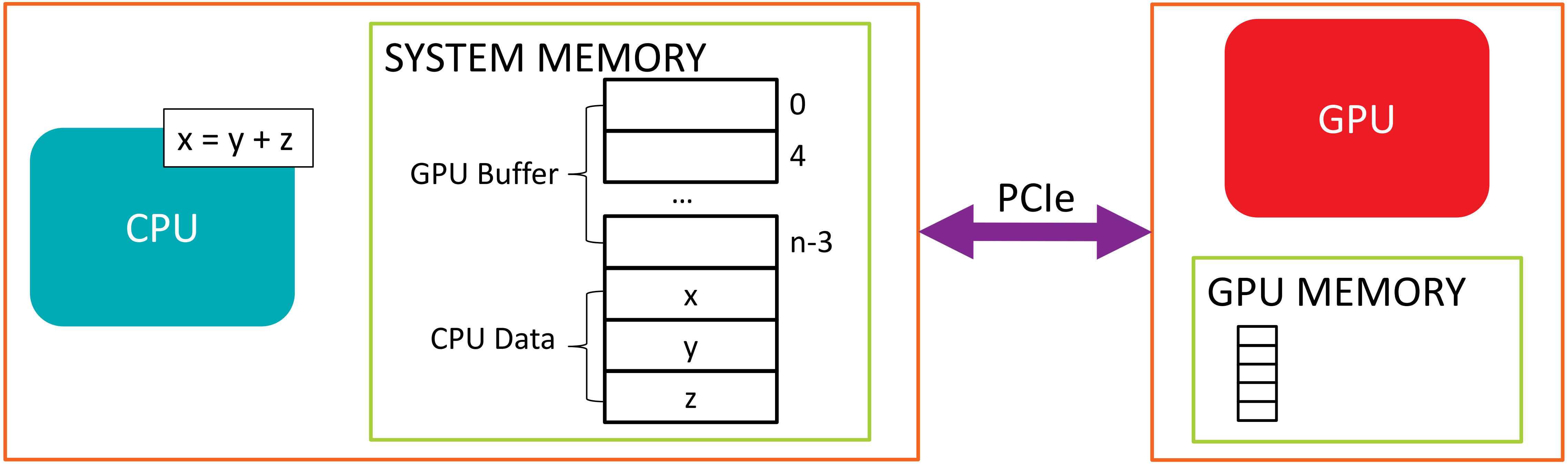

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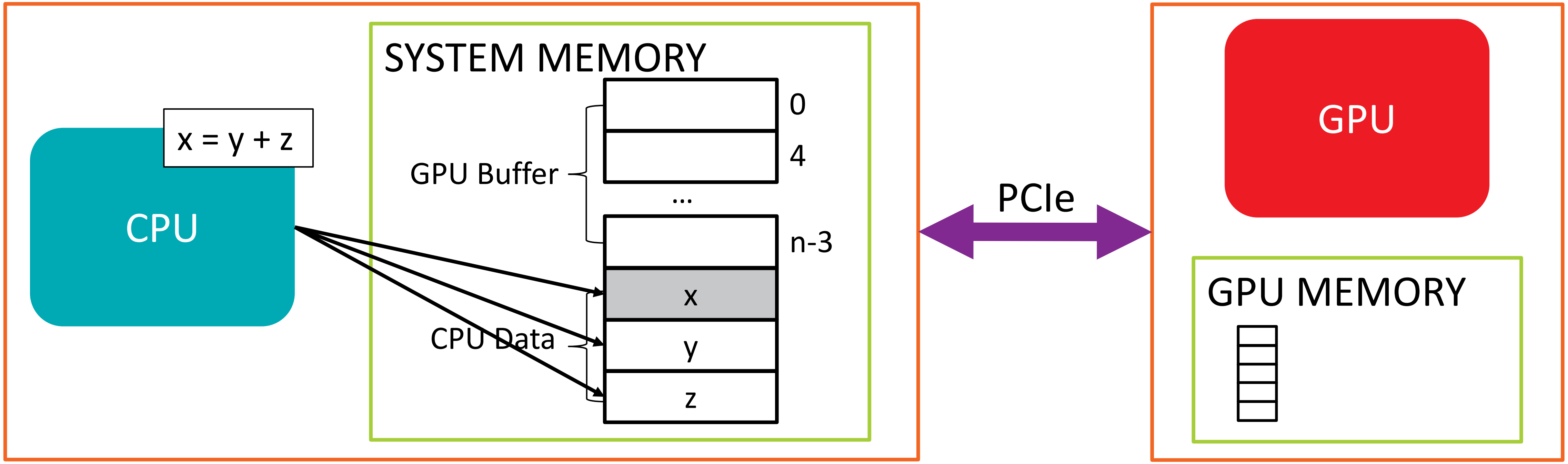

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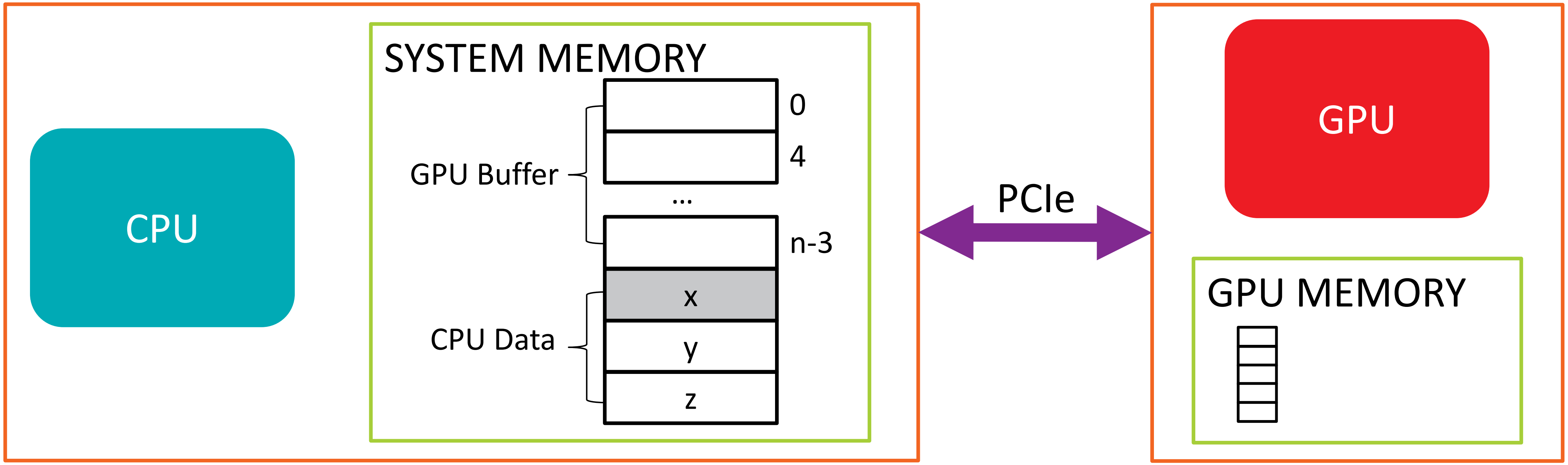

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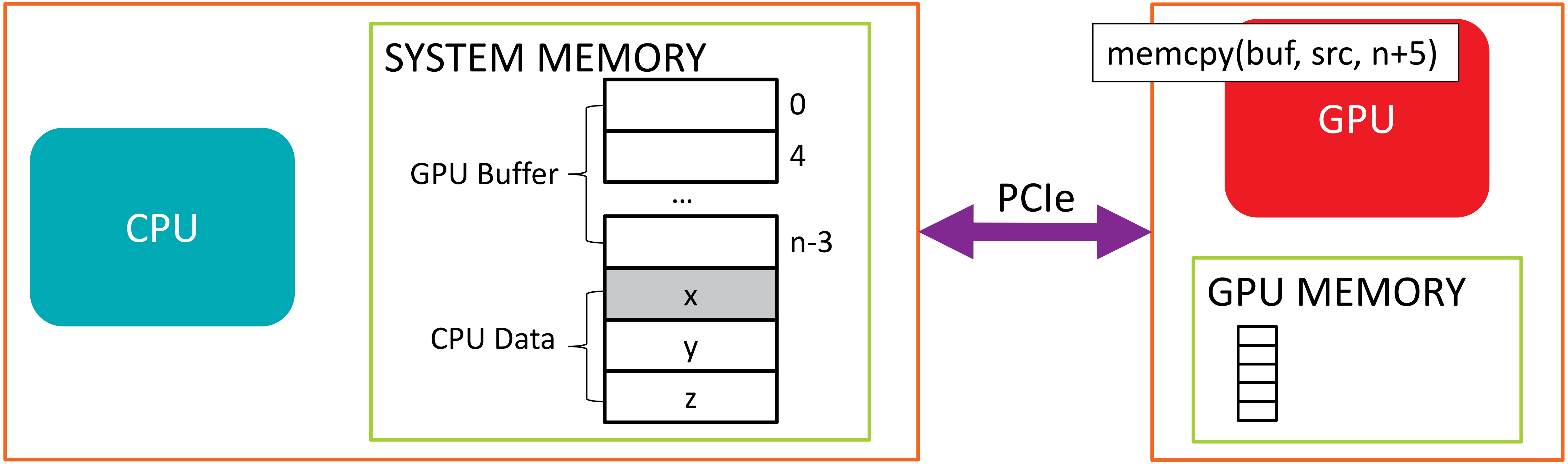

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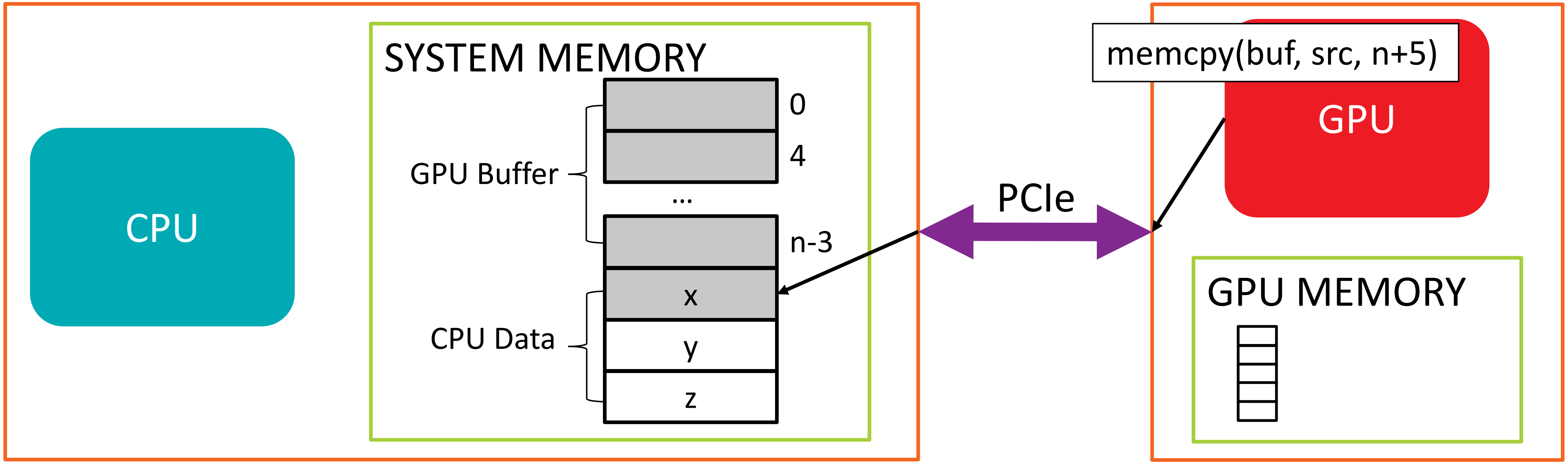

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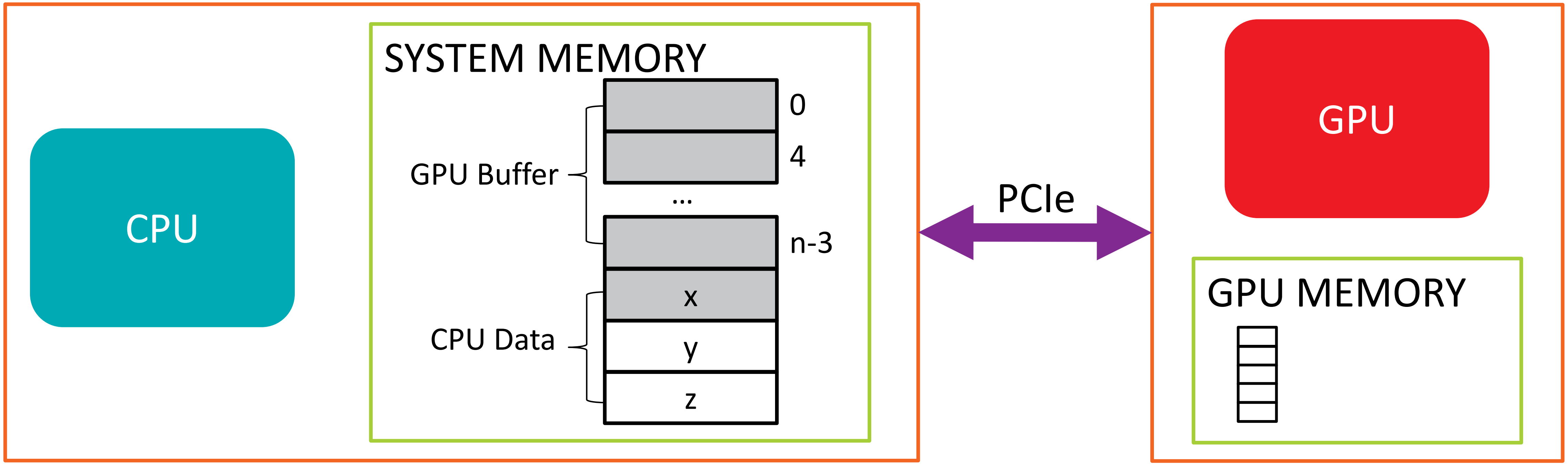

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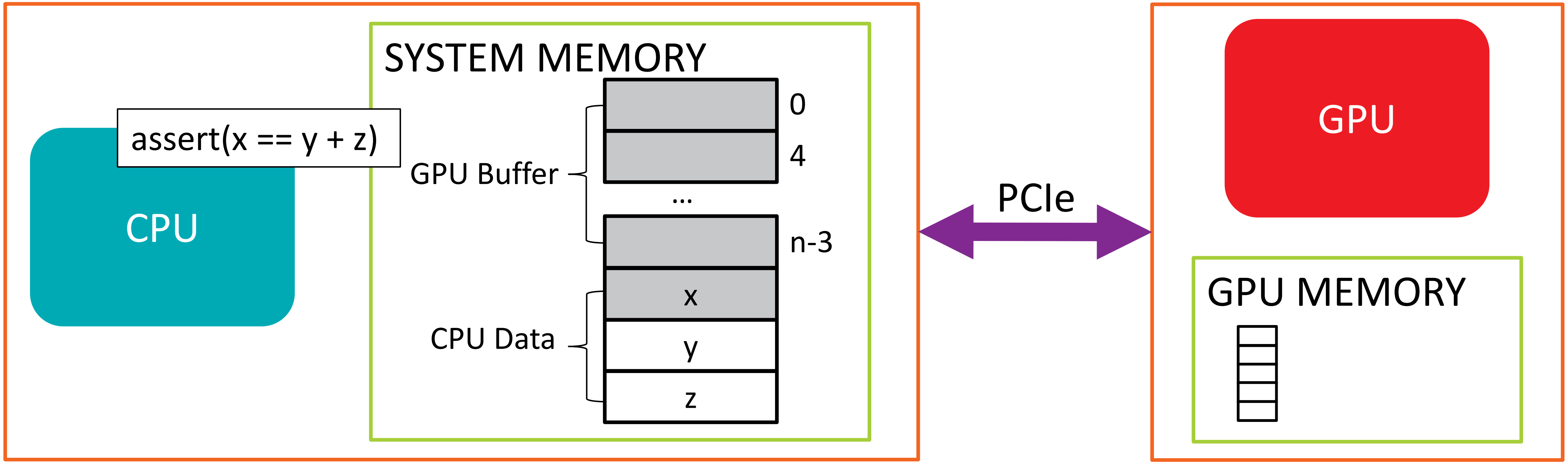

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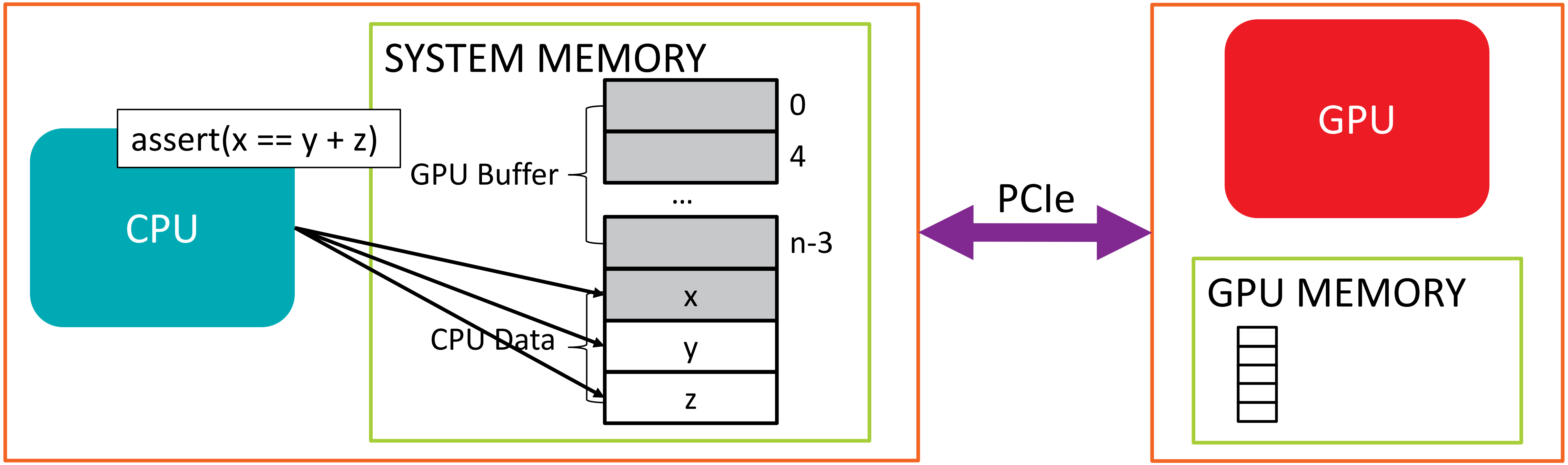

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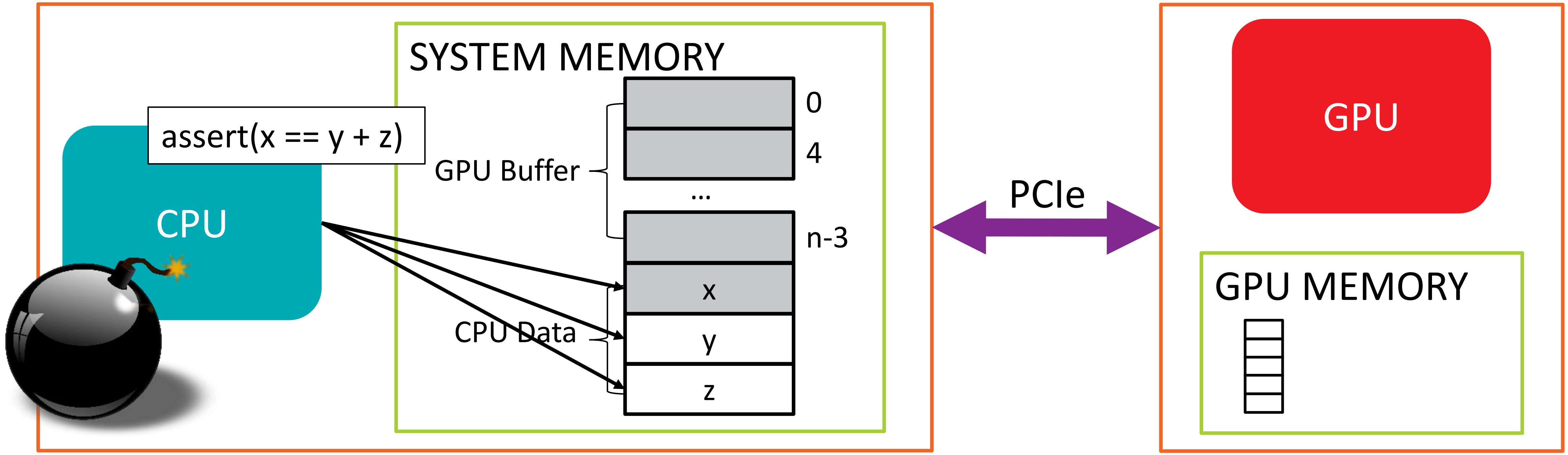

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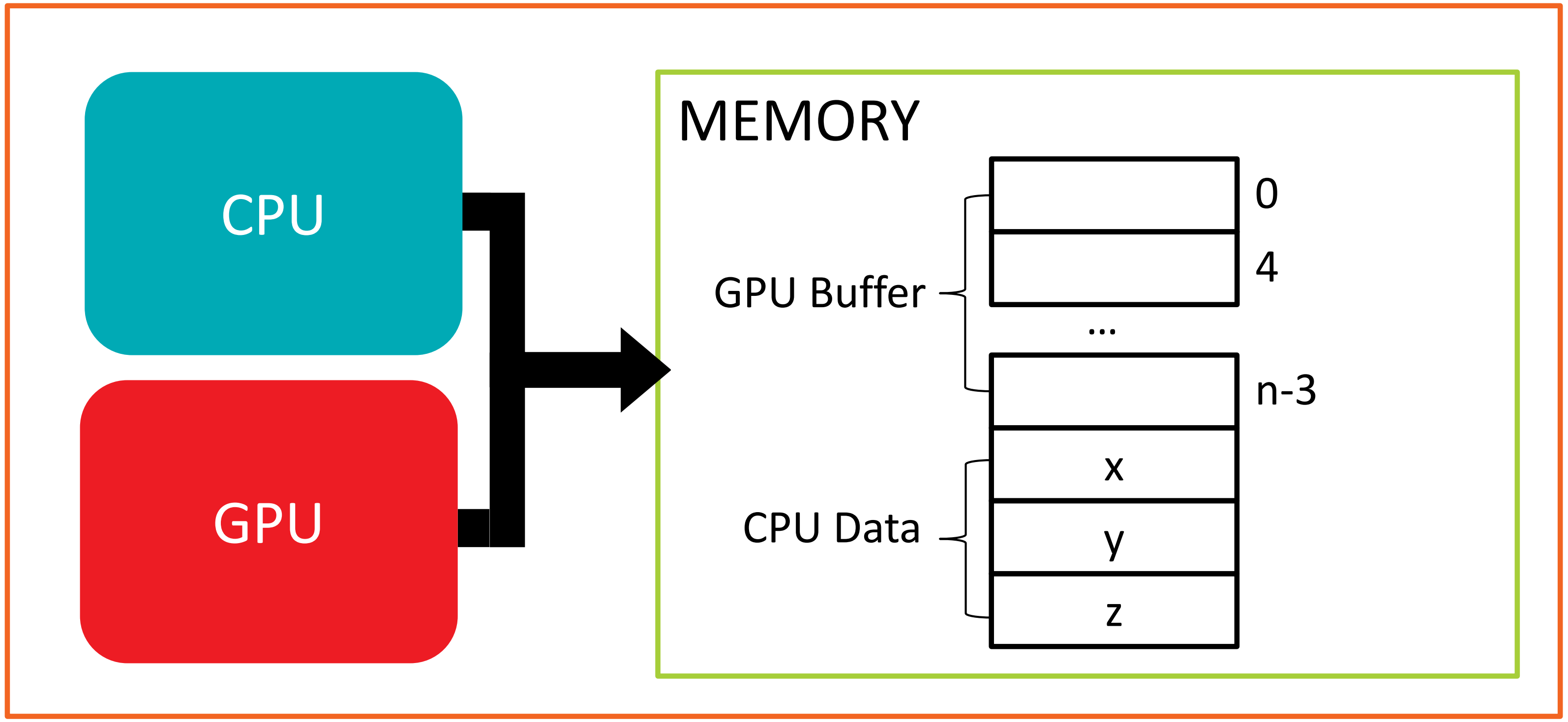

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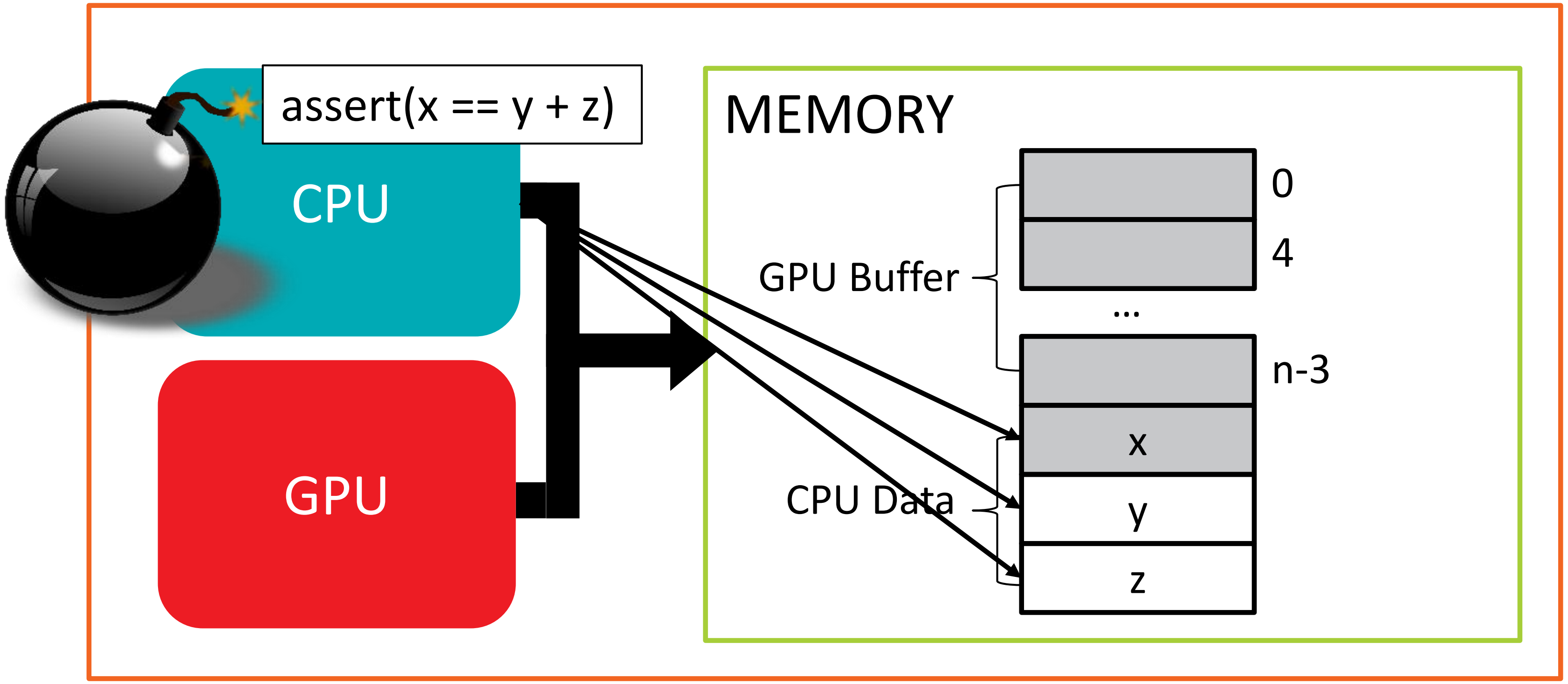

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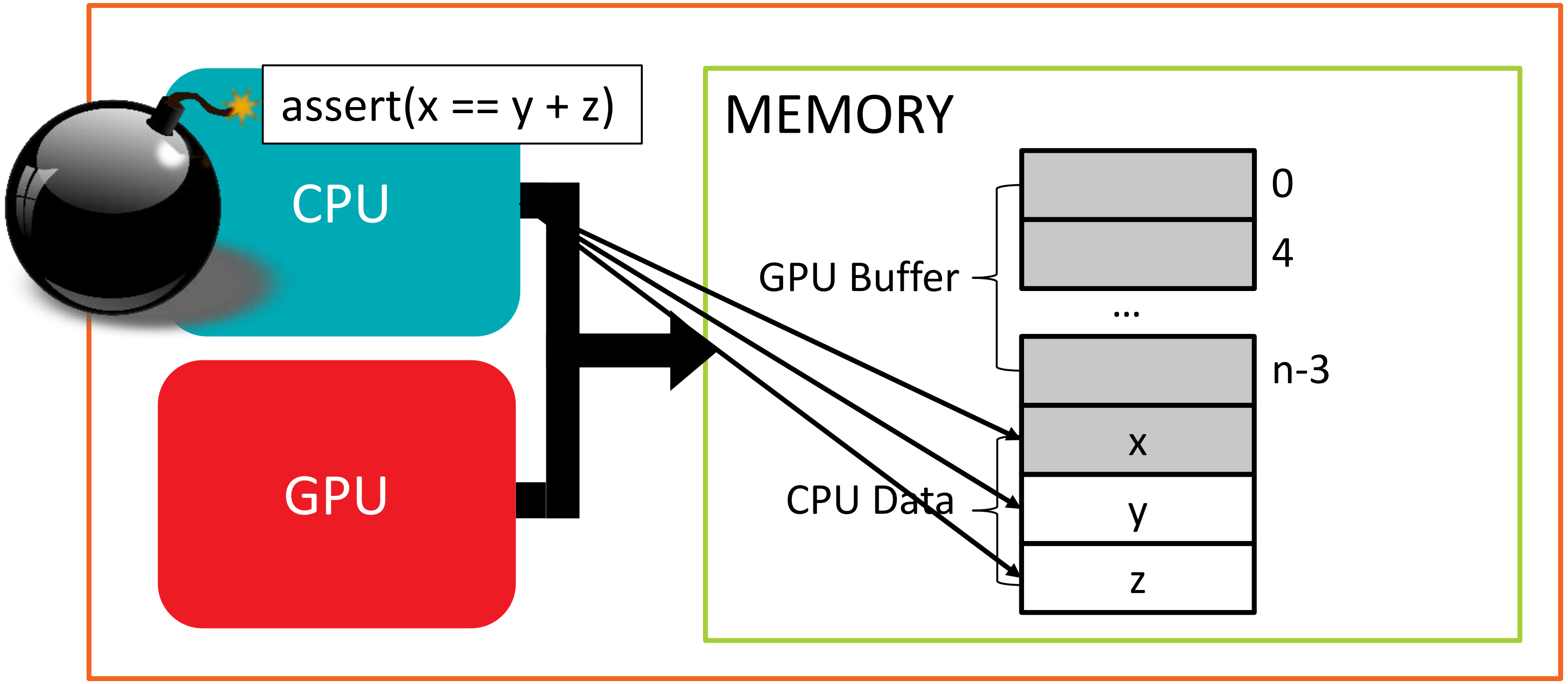

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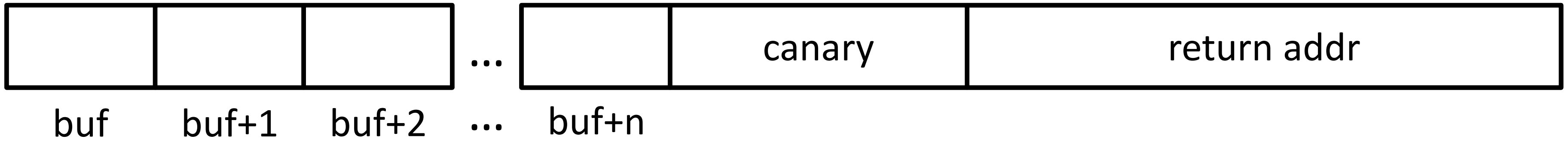


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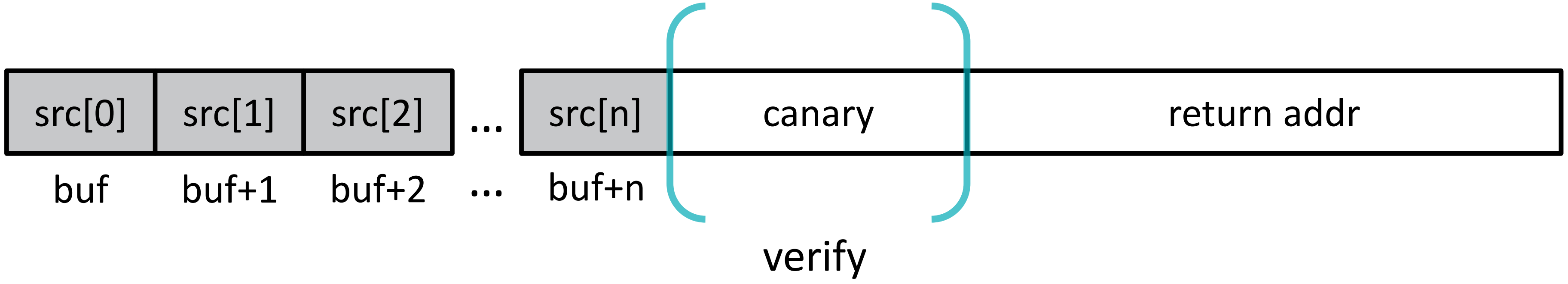


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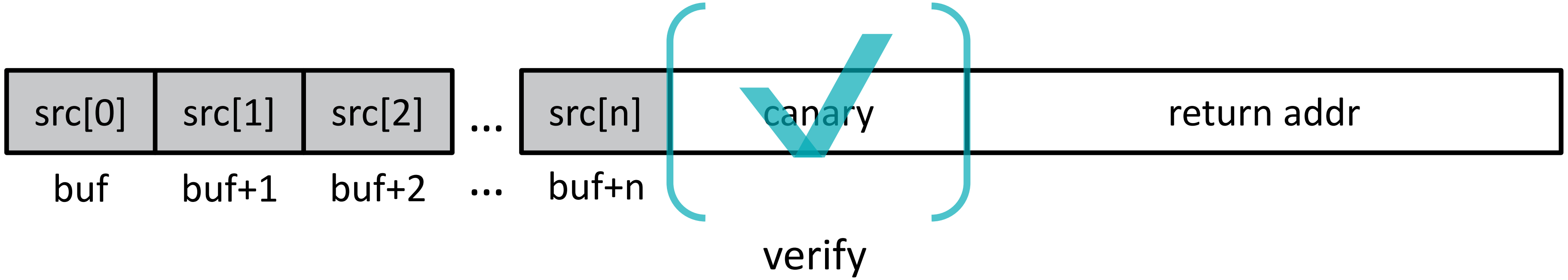


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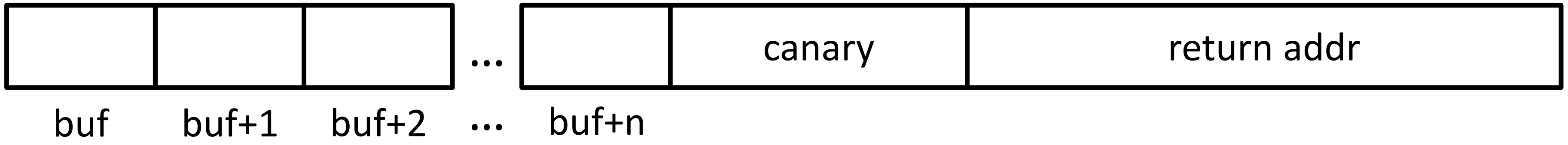


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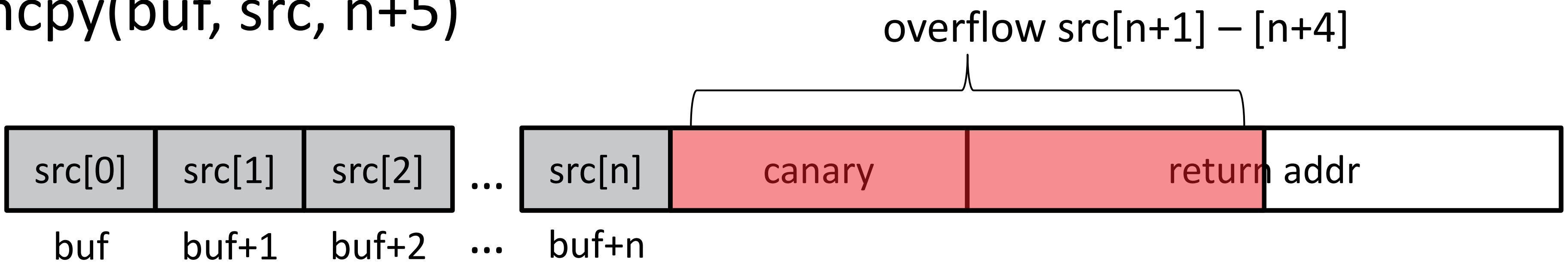


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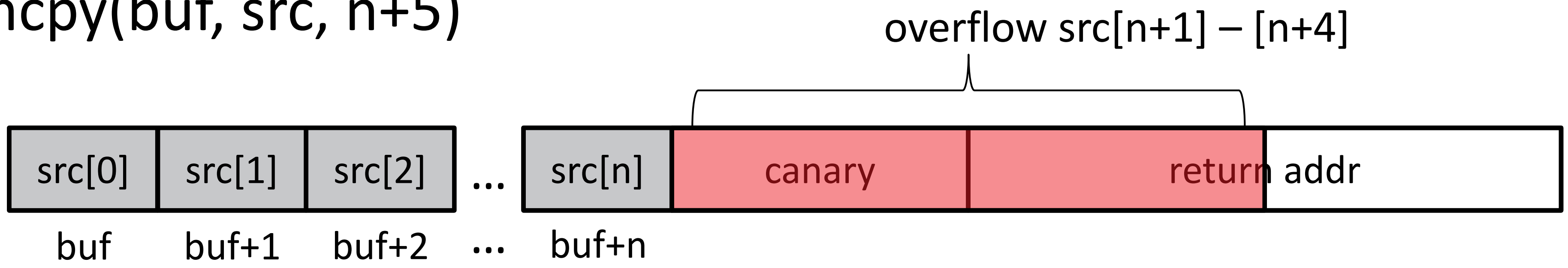


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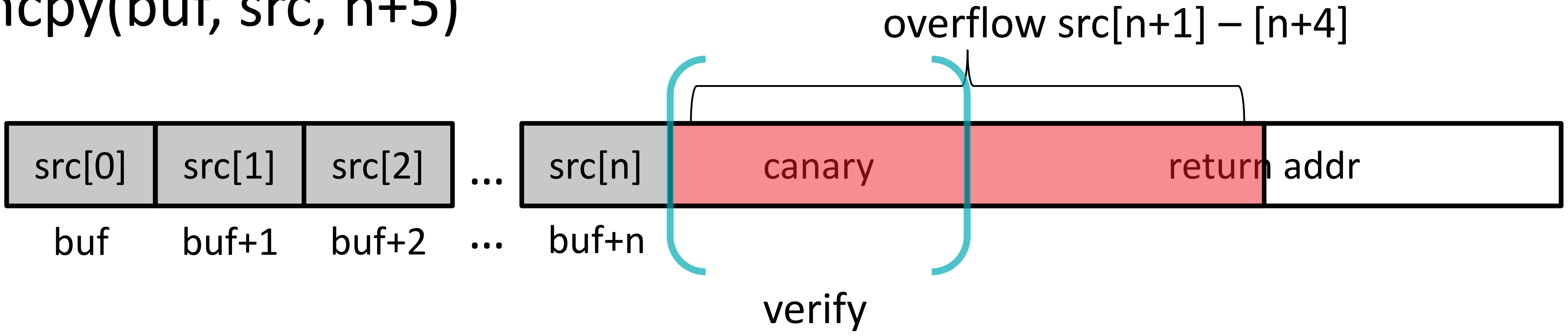


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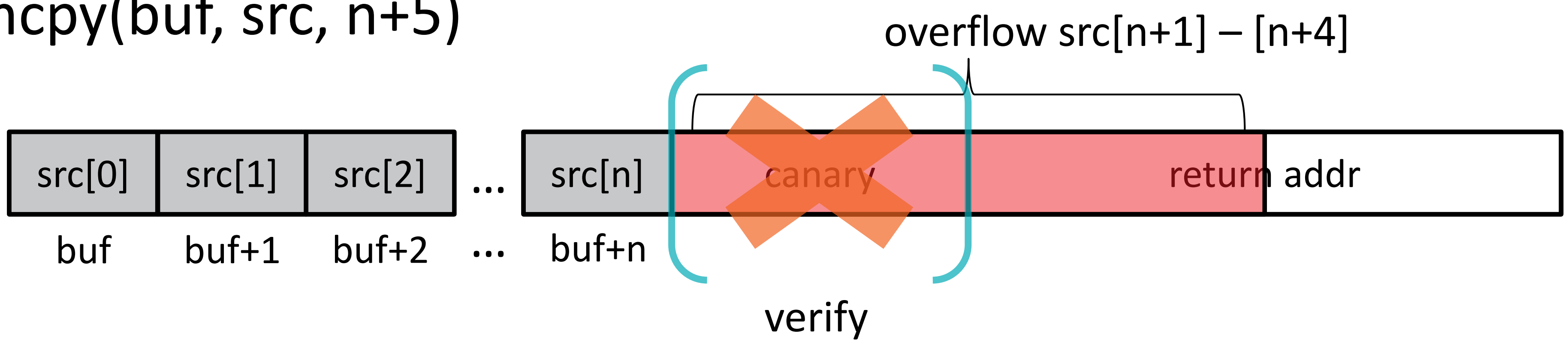


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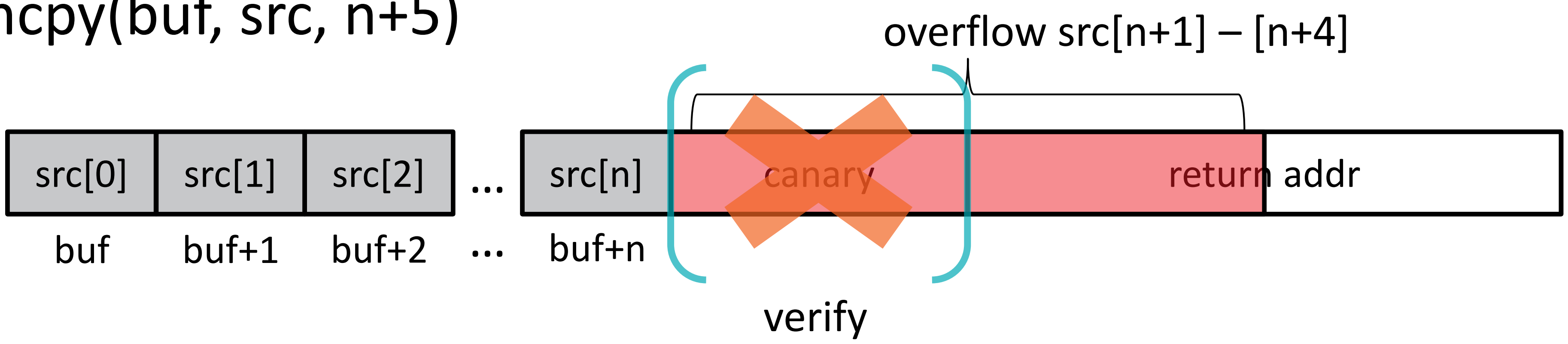


- Absence of known canary values alerts to invalid writes.

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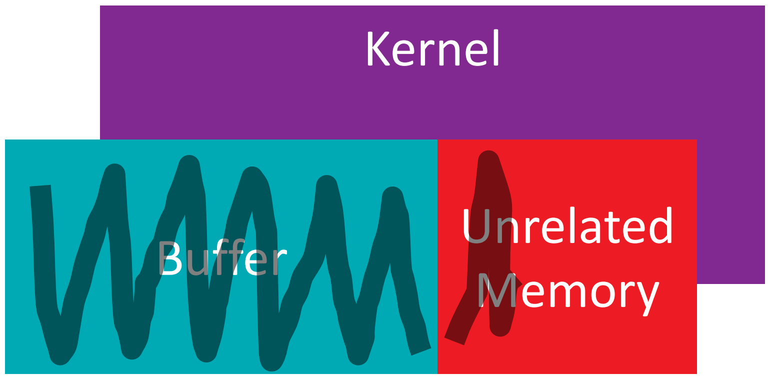

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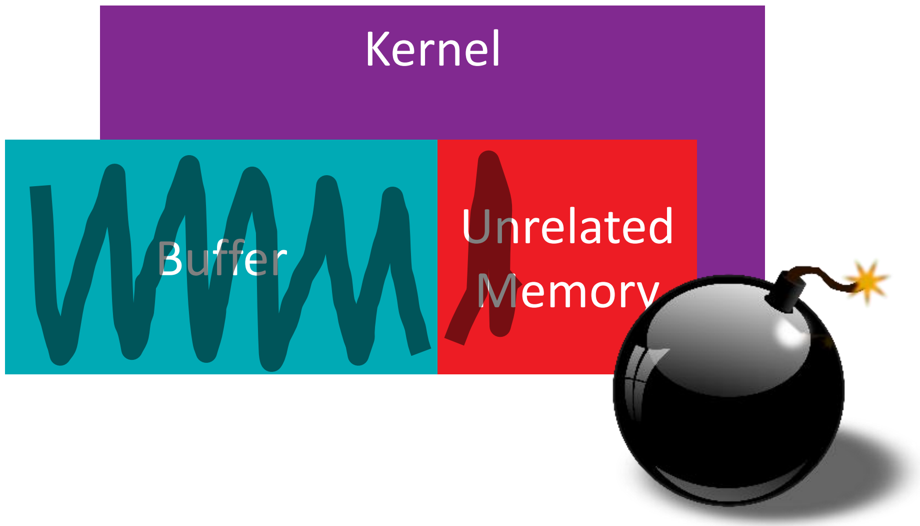

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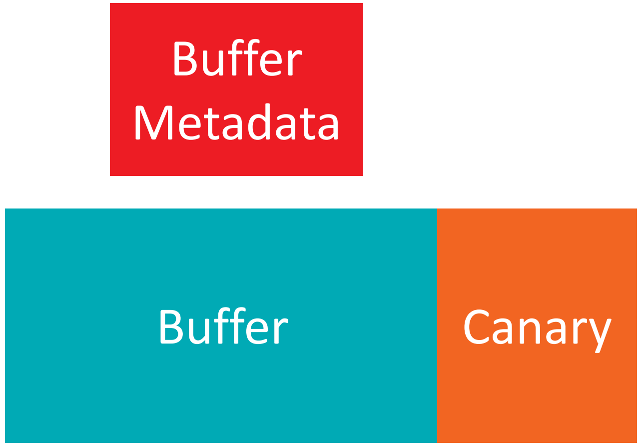

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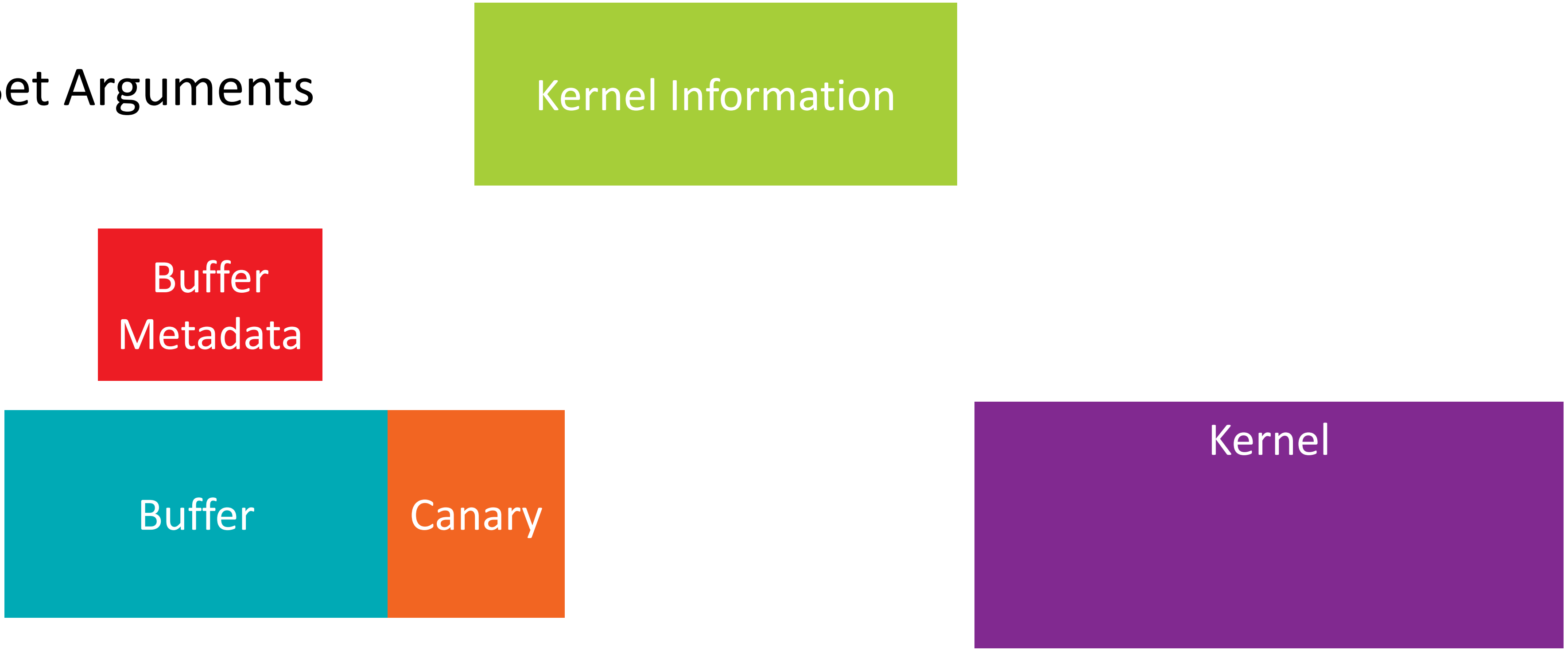

# LAUNCHING AN OPENCL™ WITH CLARMOR

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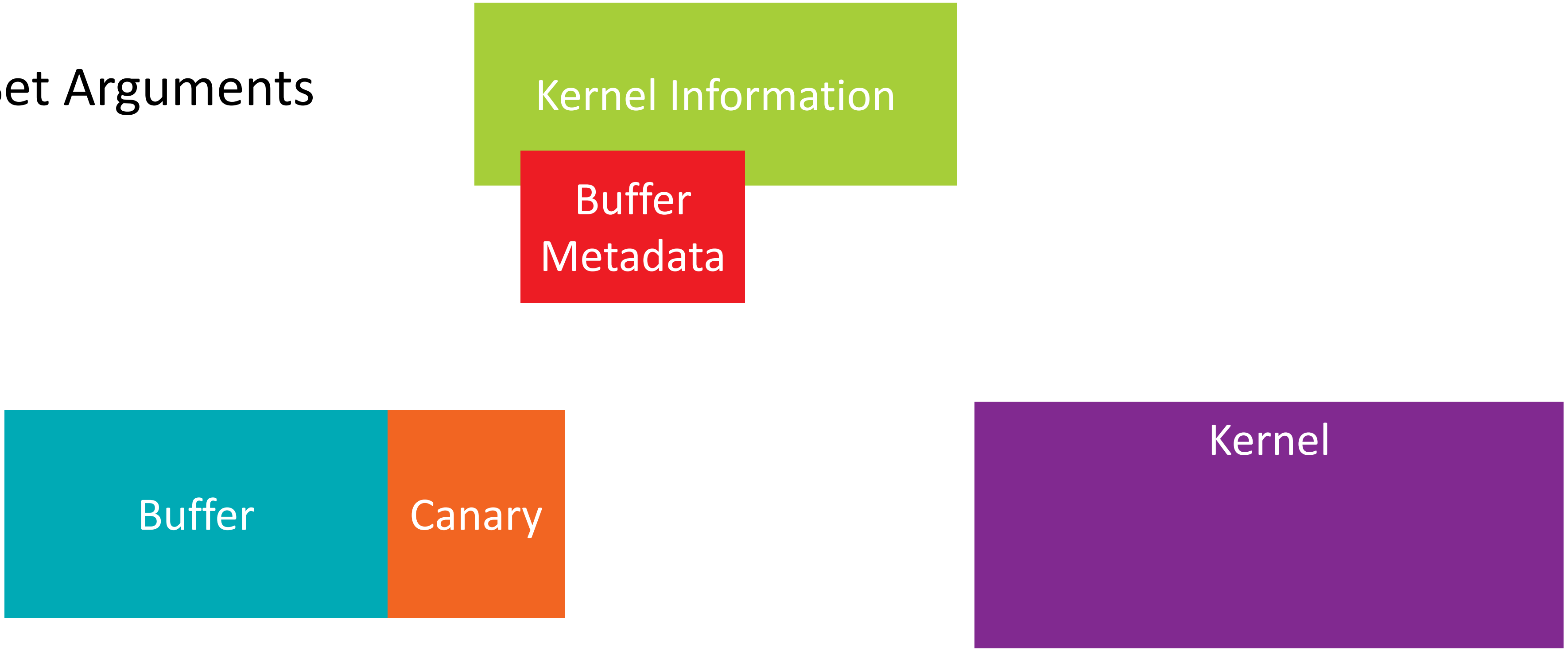

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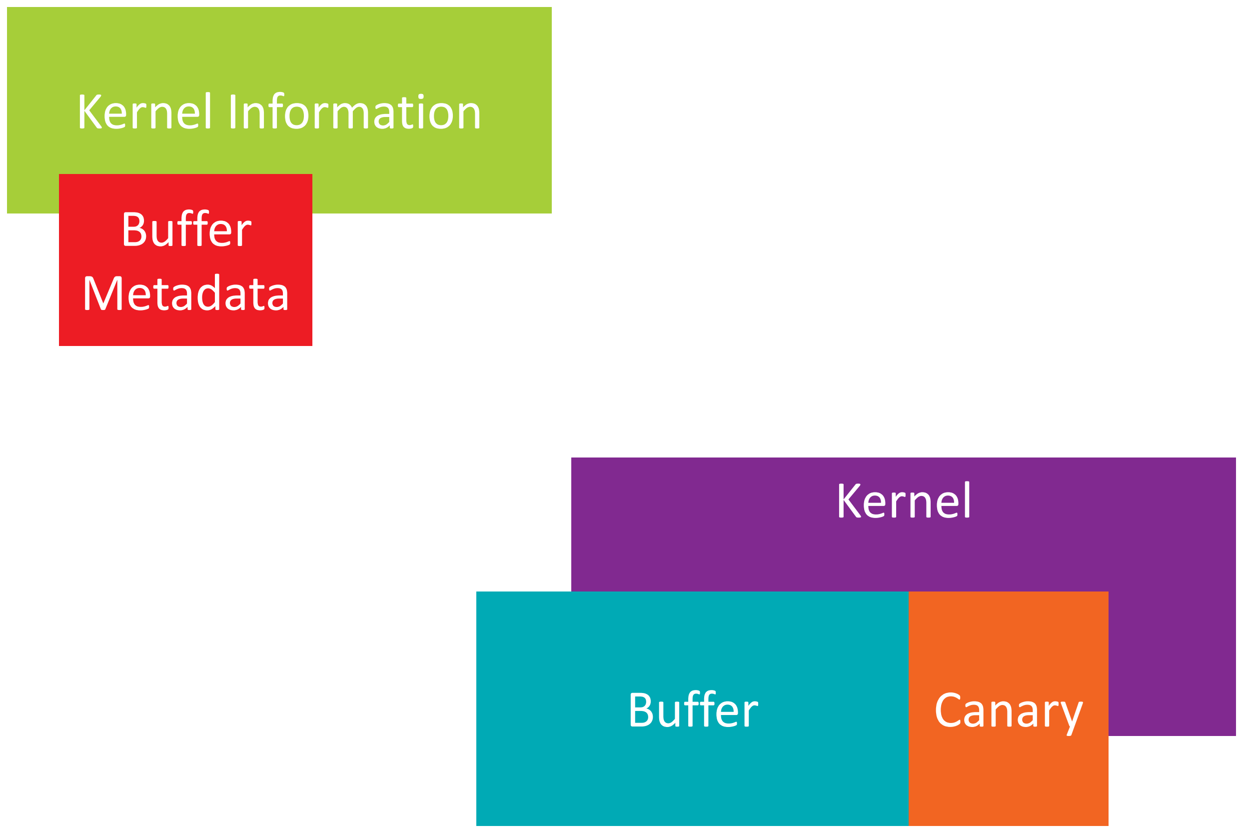

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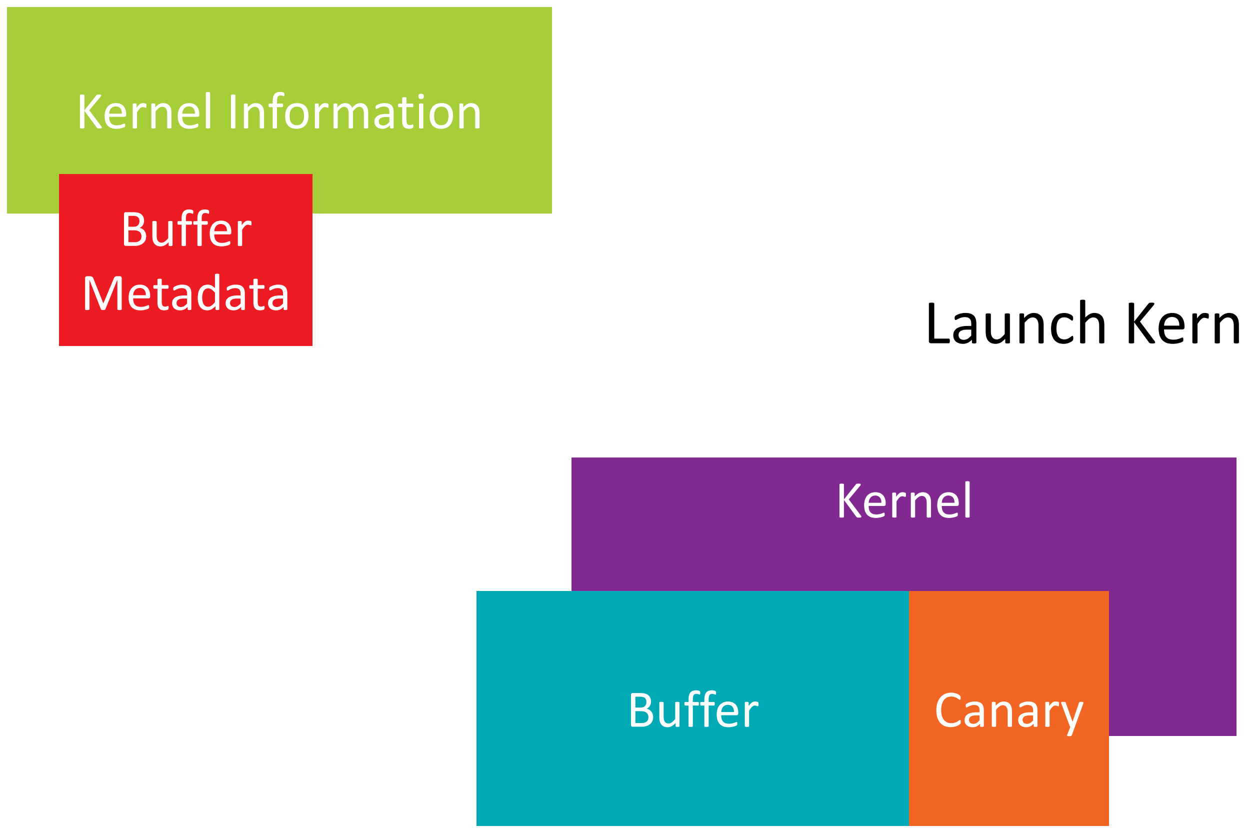

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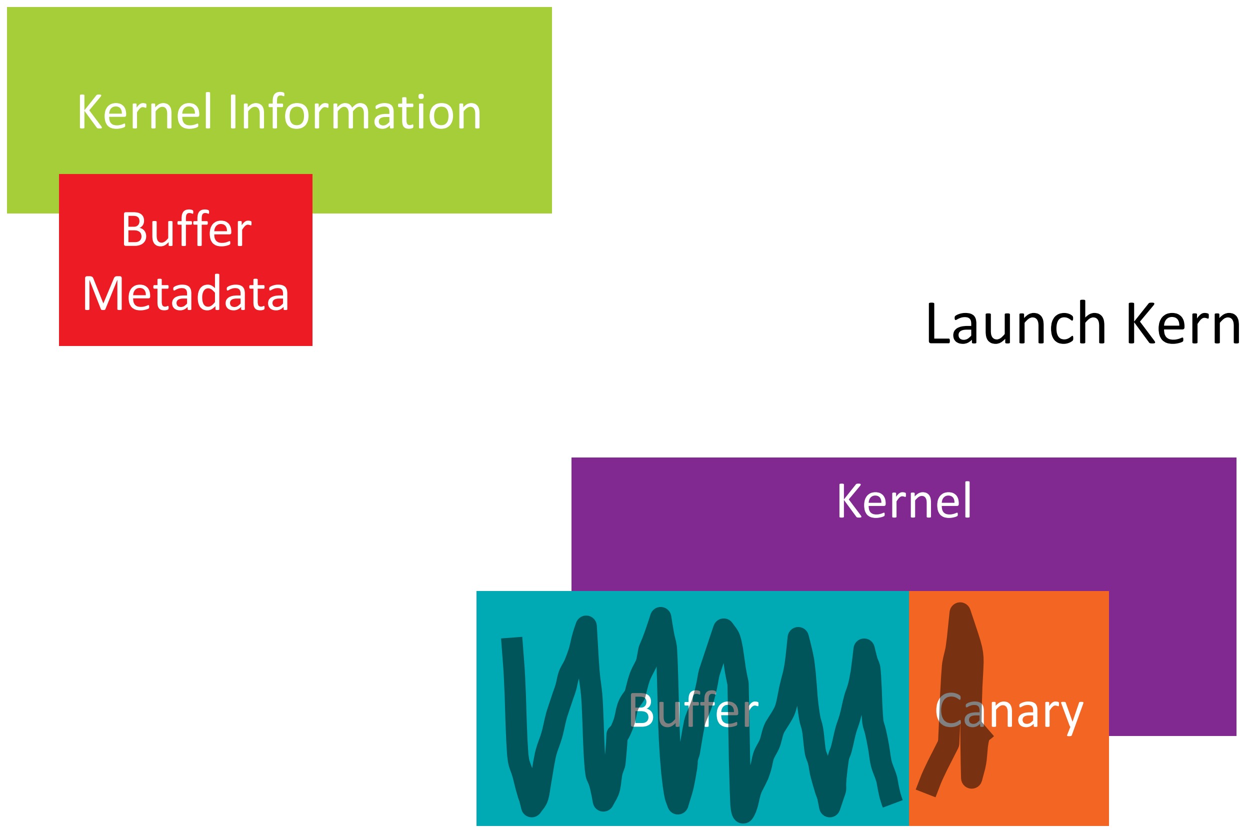

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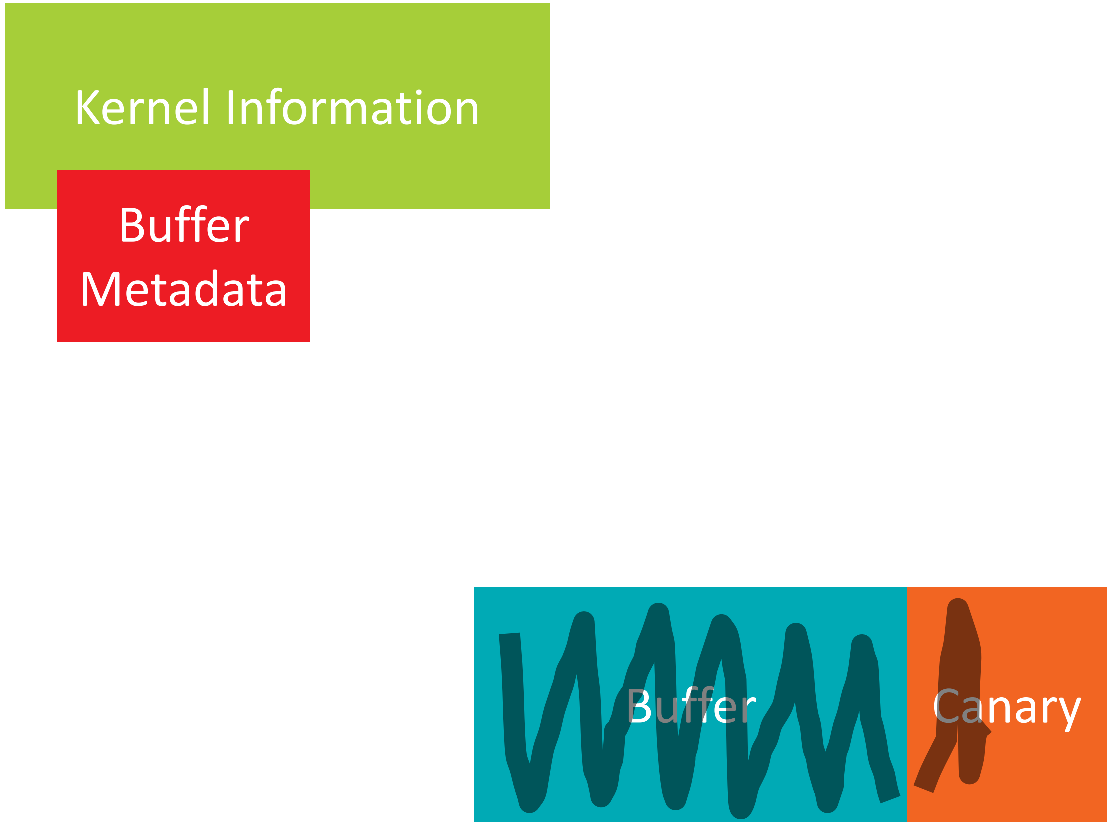

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Kernel Information

Buffer Metadata

Canary Verification

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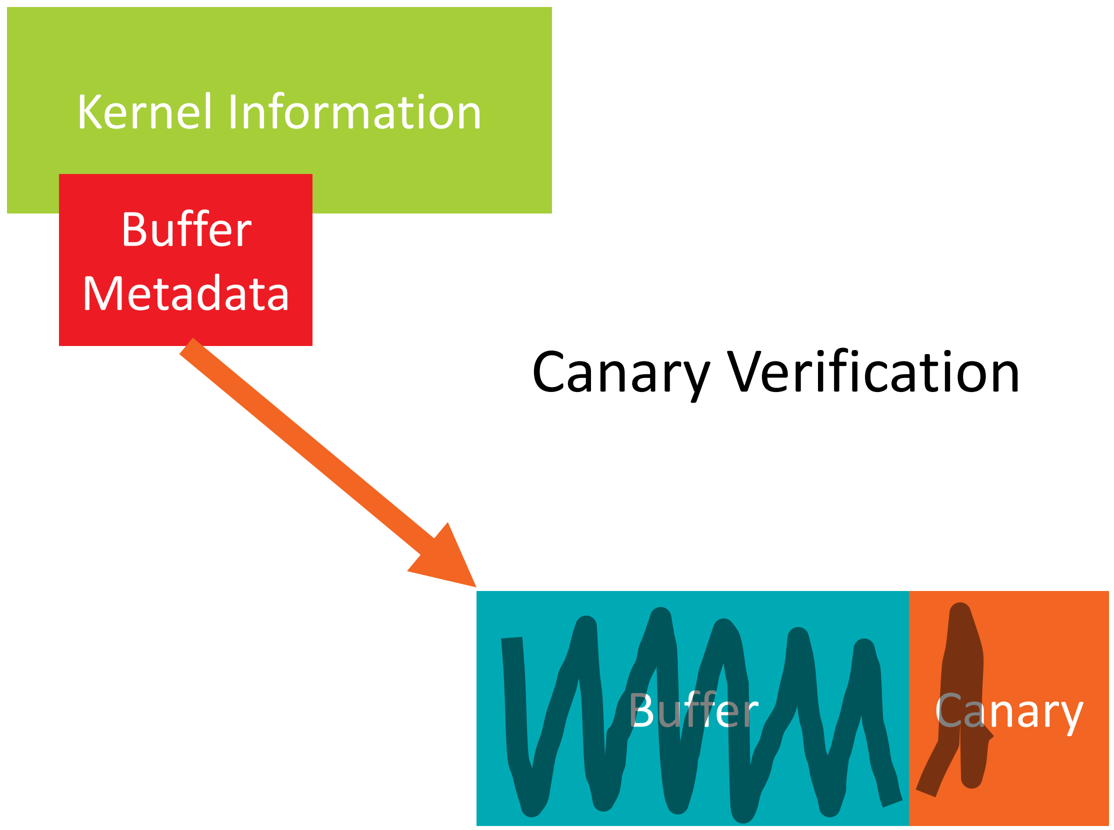

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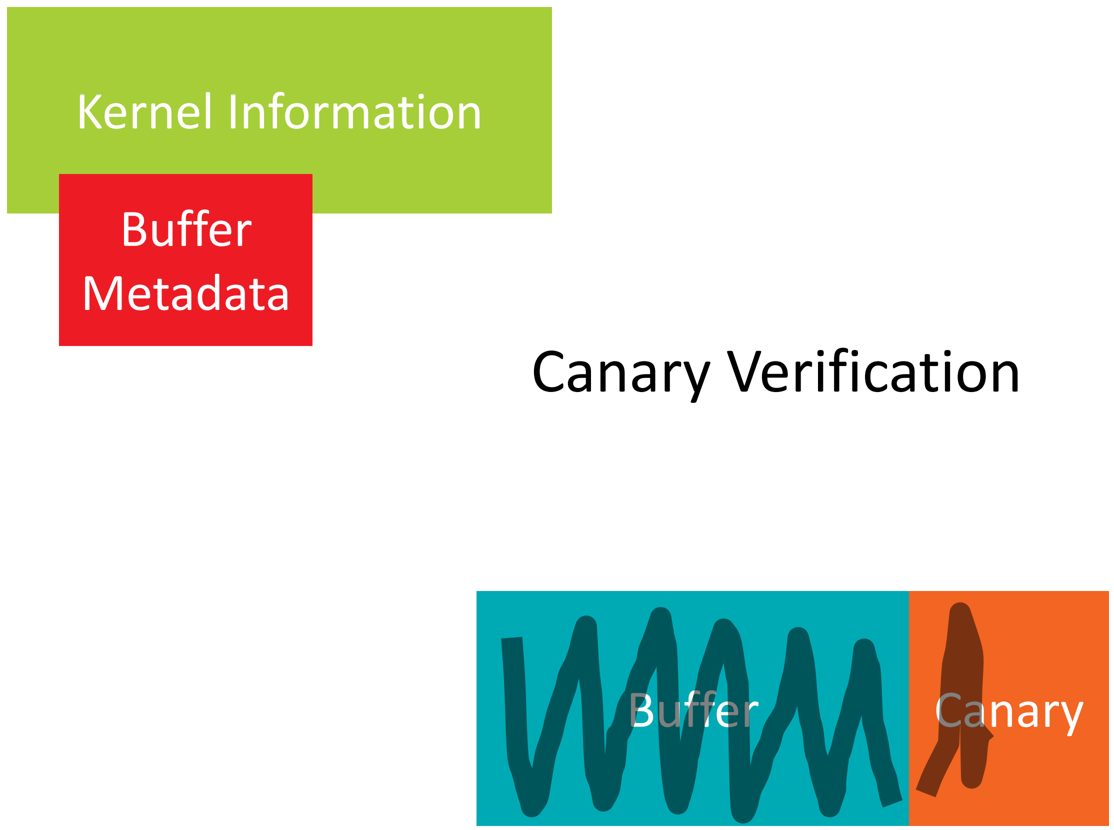

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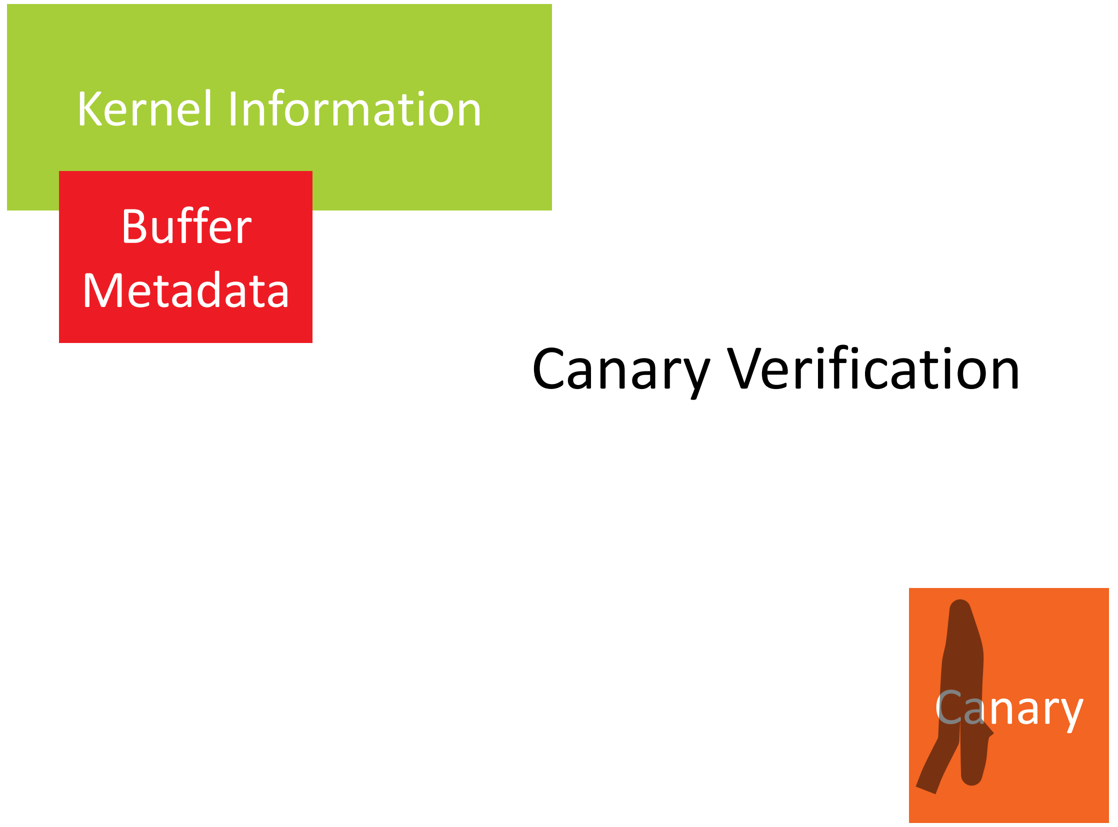

# LAUNCHING AN OPENCL™ WITH CLARMOR

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# WRAPPING OPENCL™

## CLARMOR BETWEEN YOUR APPLICATION AND OPENCL

- clARMOR is a Linux® library that uses LD_PRELOAD to wrap OpenCL™ library calls
- Call Wrapping
  - Buffer and Image creates
  - Argument setters
  - Kernel launches
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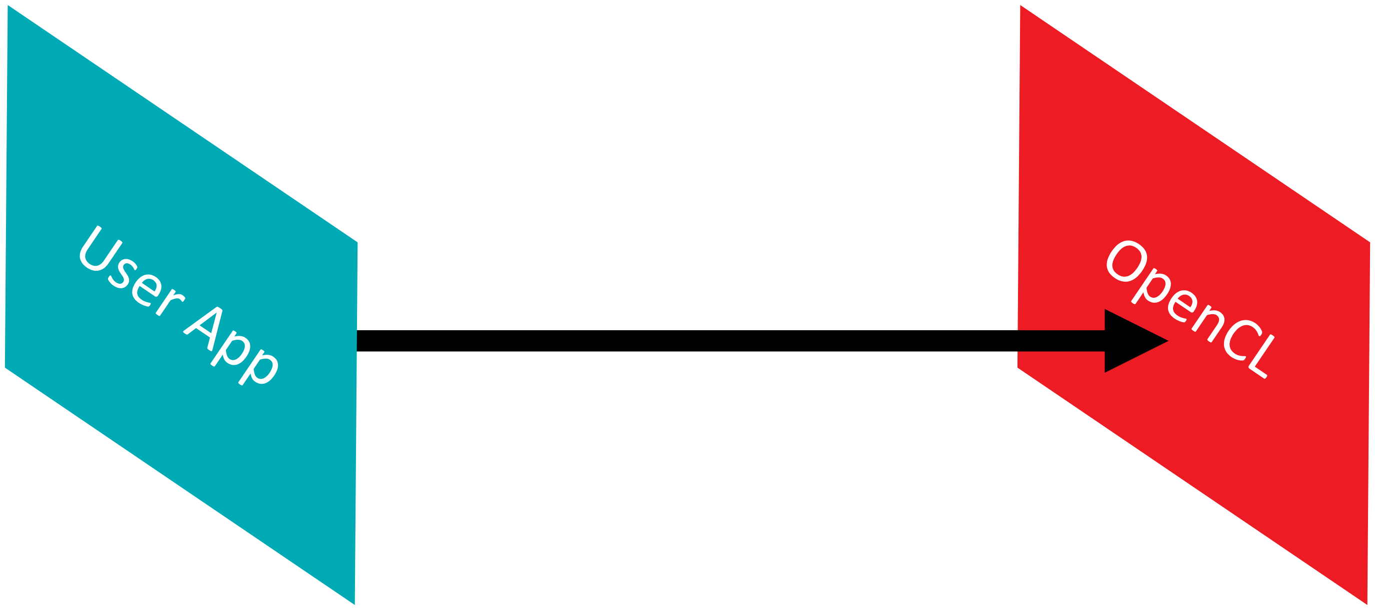

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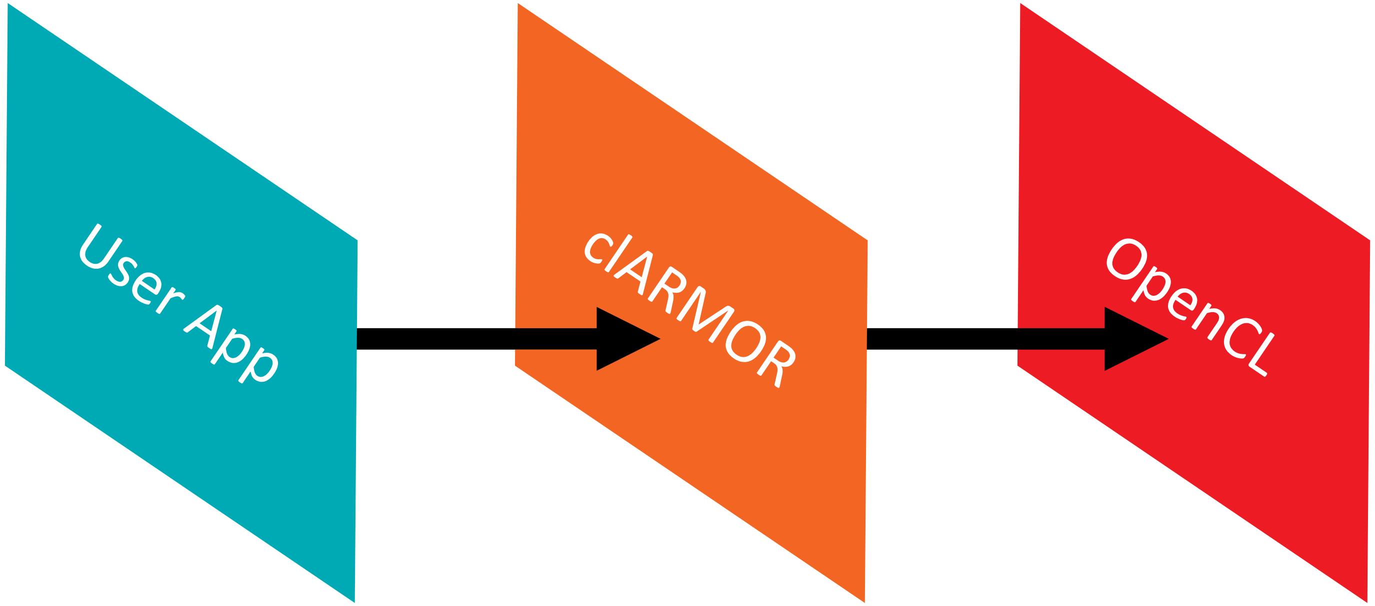

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## BUFFER AND IMAGE CREATION

- Attach canaries to memory objects

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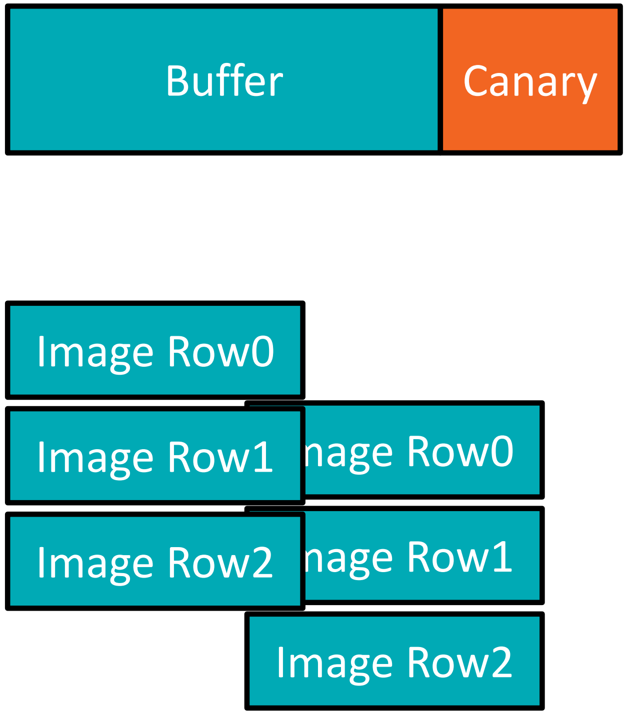

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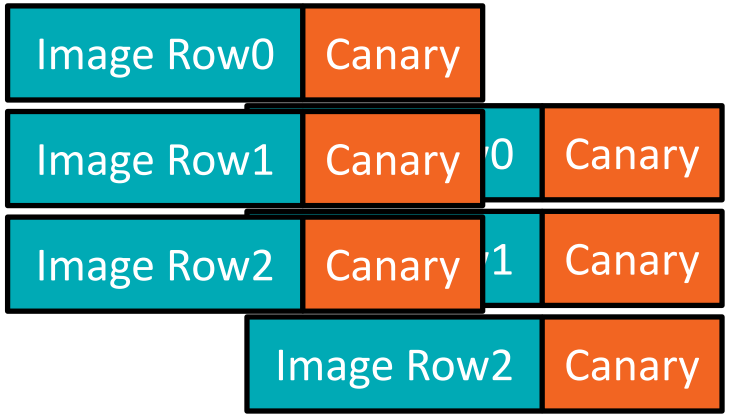

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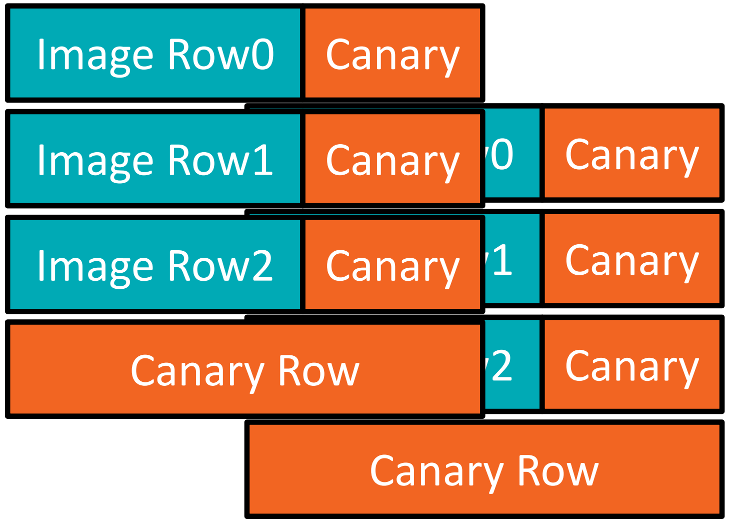

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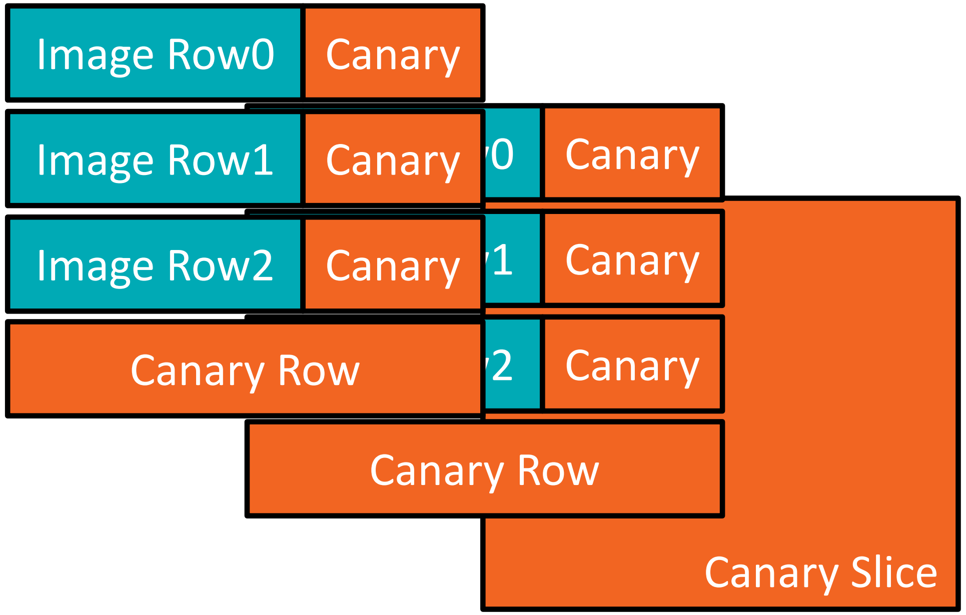

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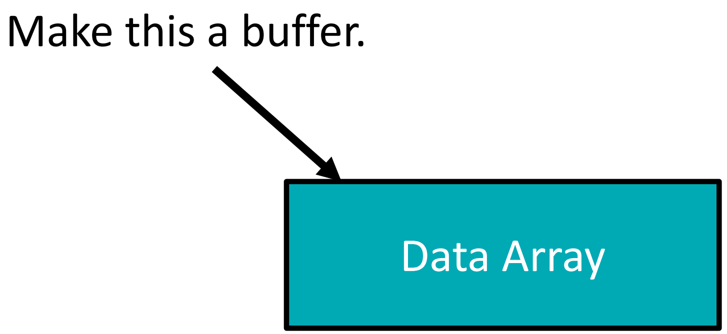

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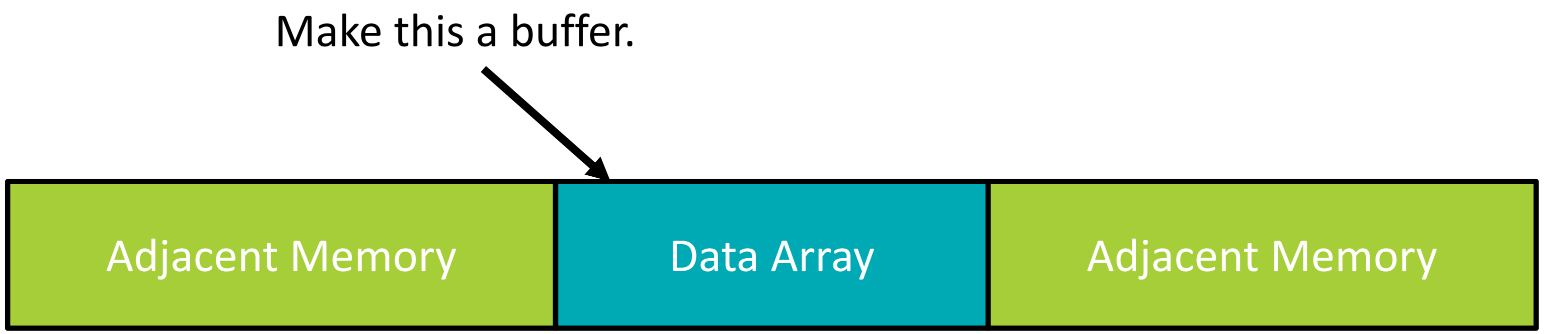

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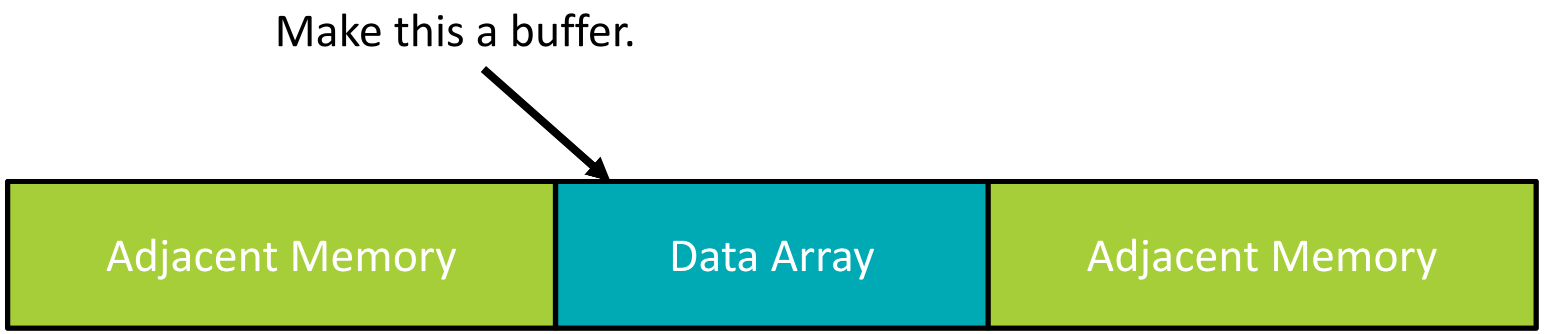

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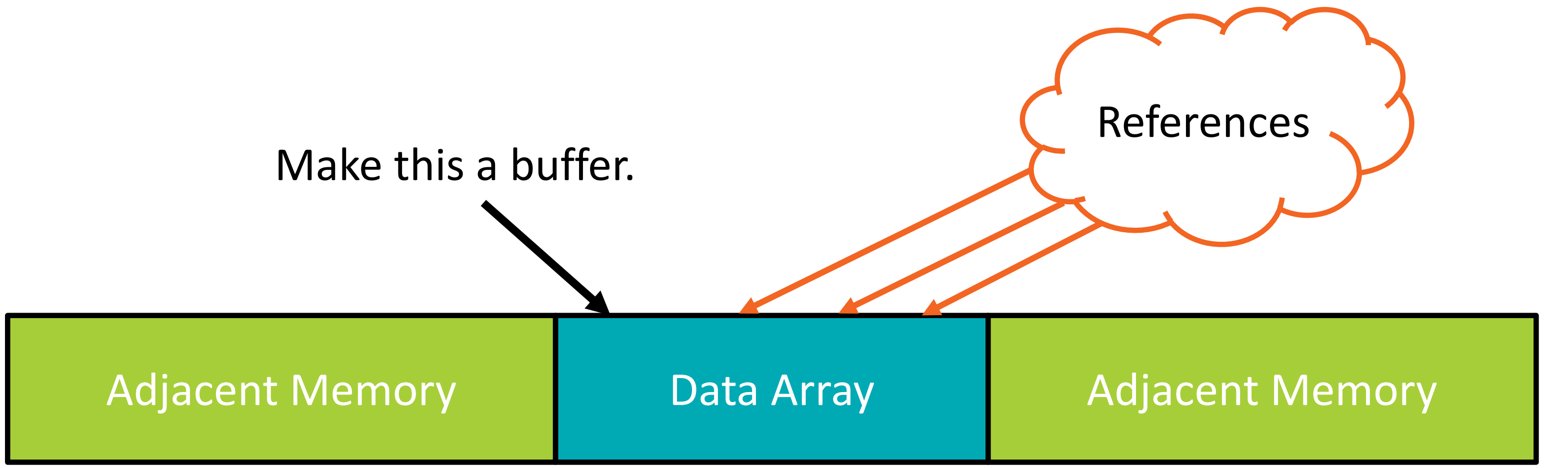

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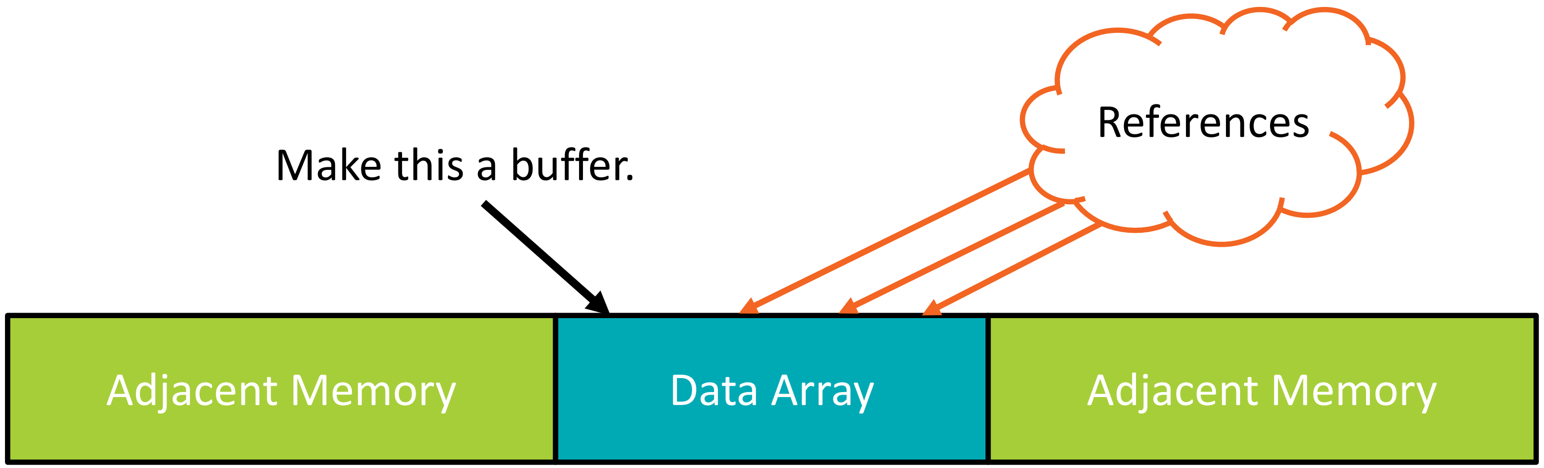

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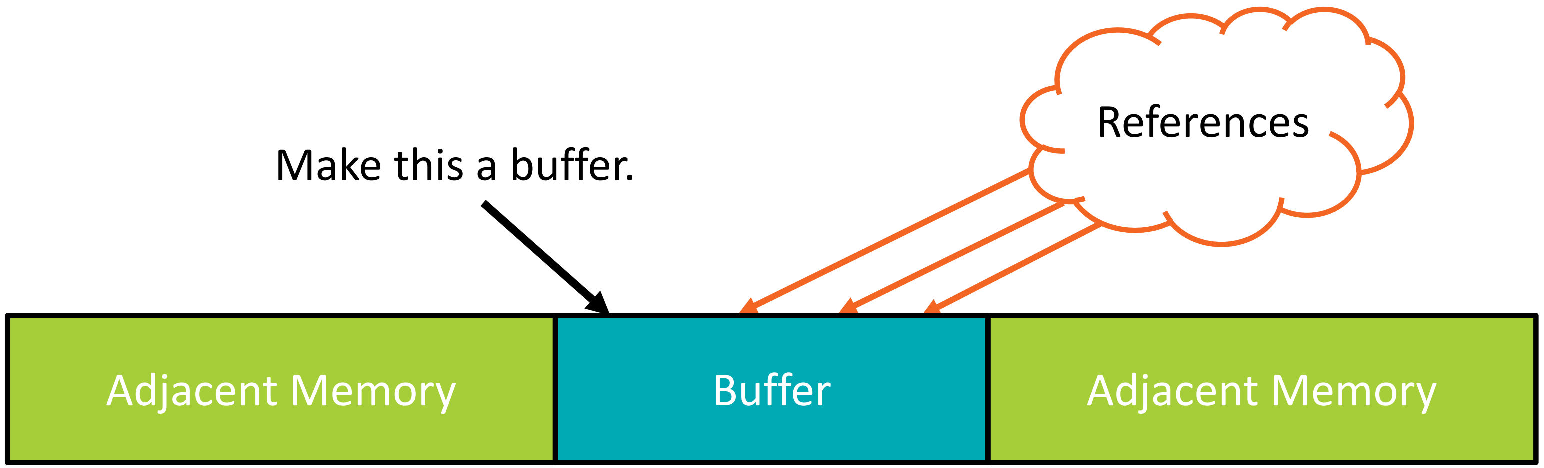

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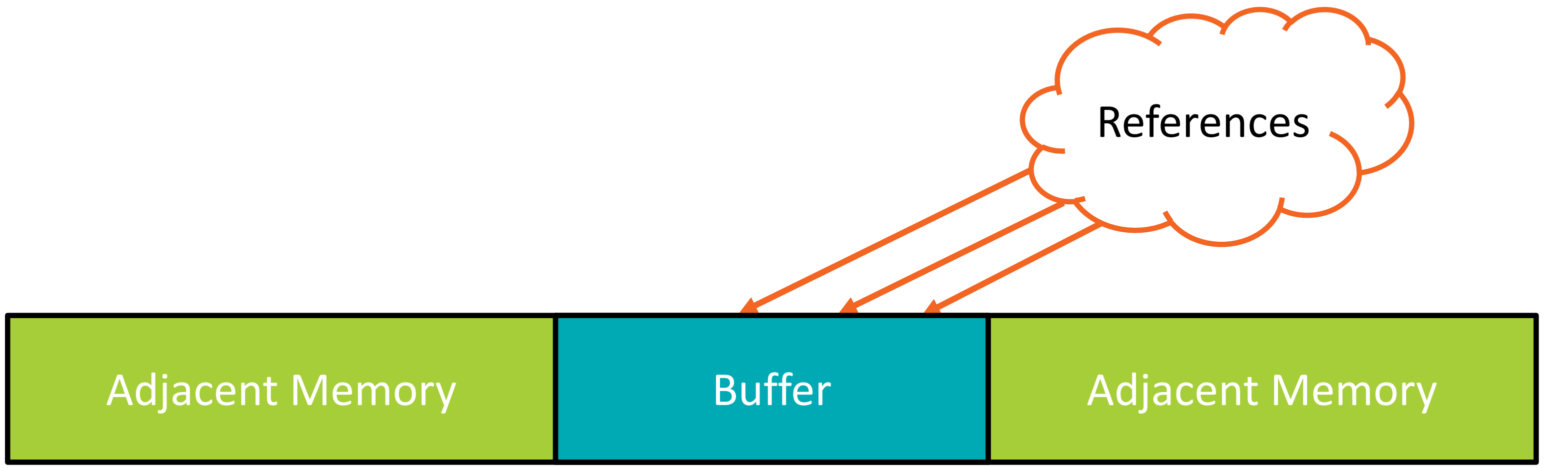

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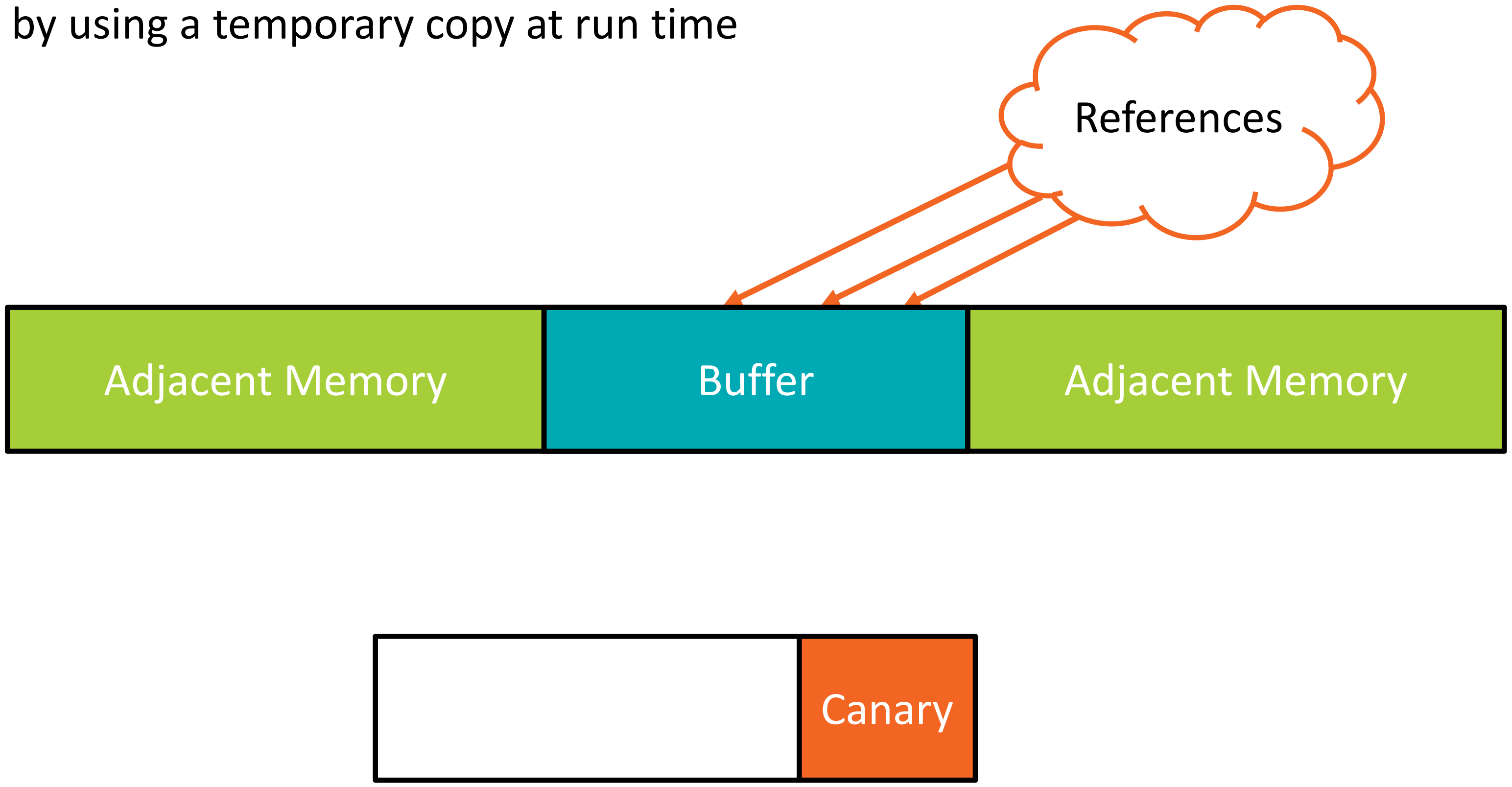

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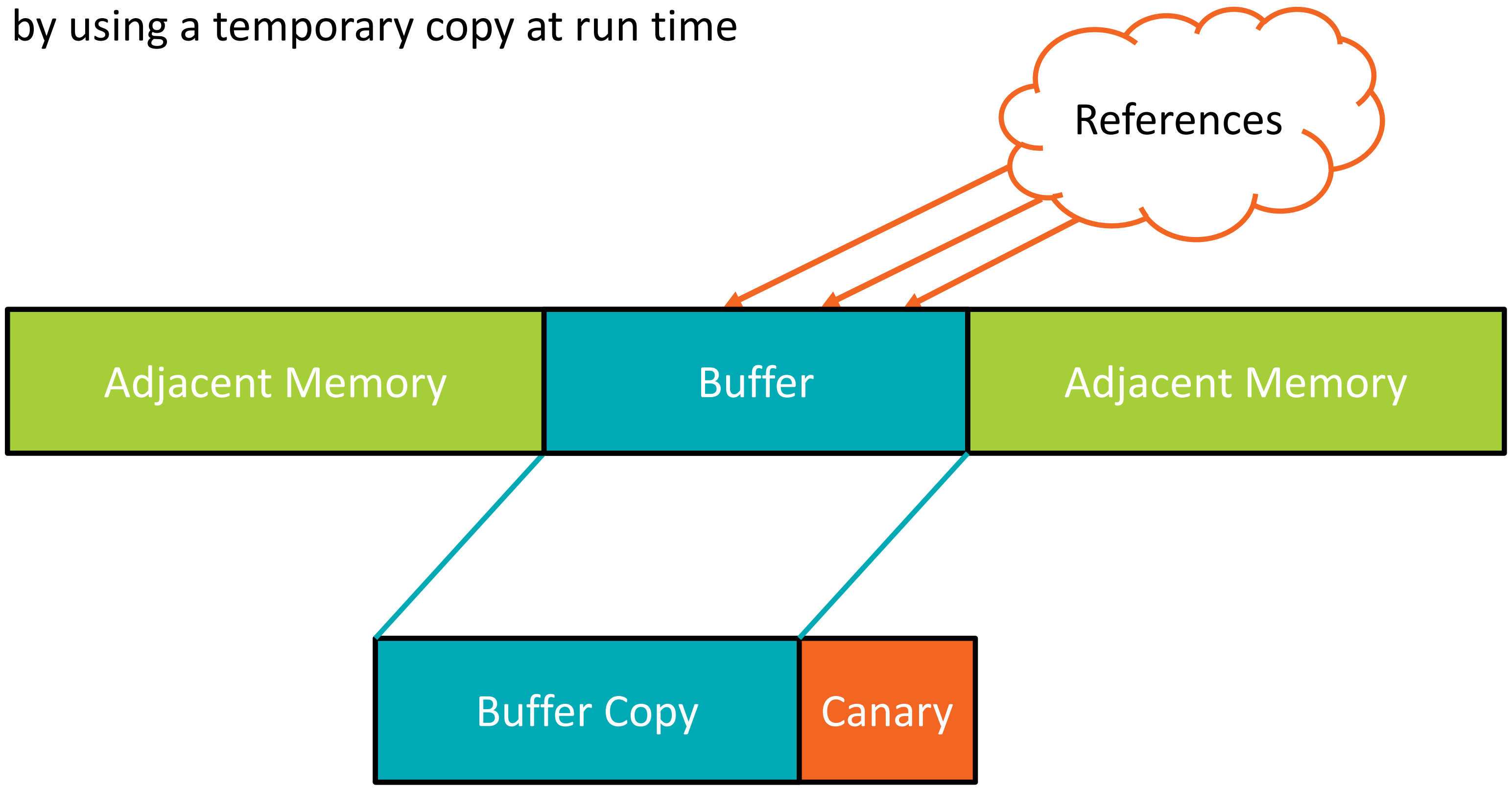

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- clARMOR needs to know which buffers/images to check for overflows
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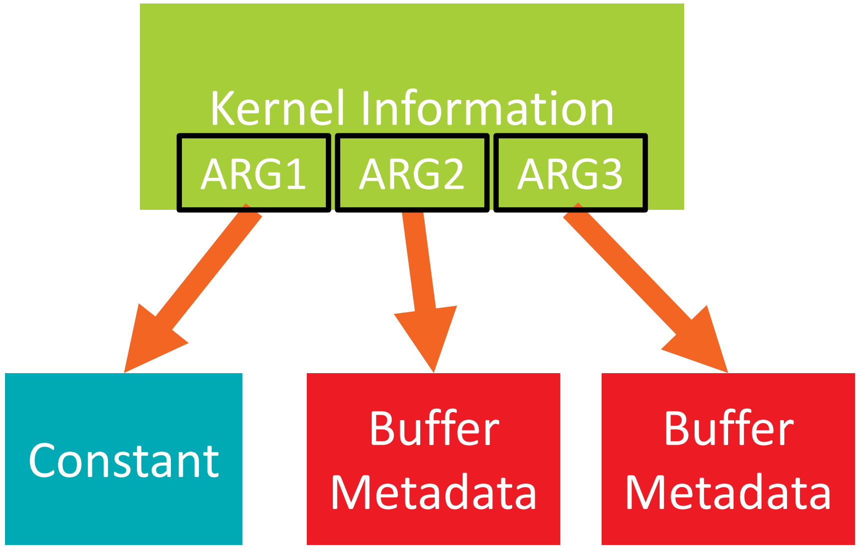

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## KERNEL LAUNCH

- Do the work of detecting buffer overflows
- On call to ***clEnqueueNDRangeKernel***
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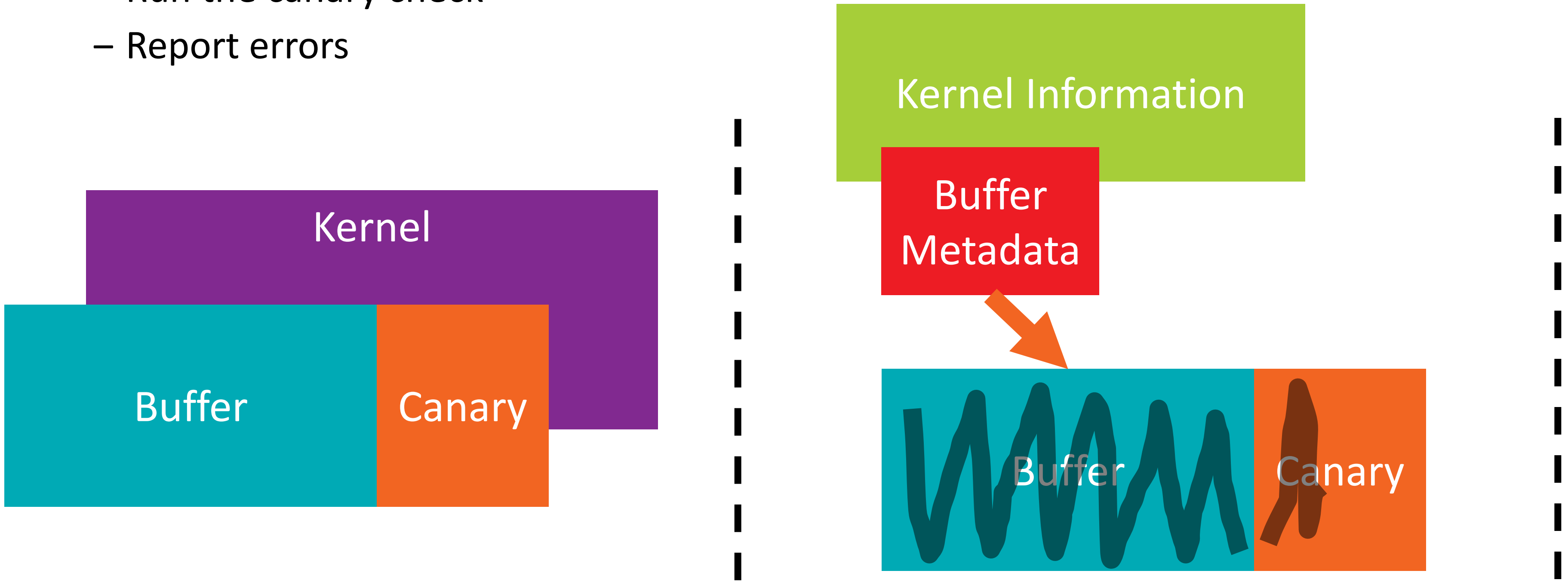
  - Report errors



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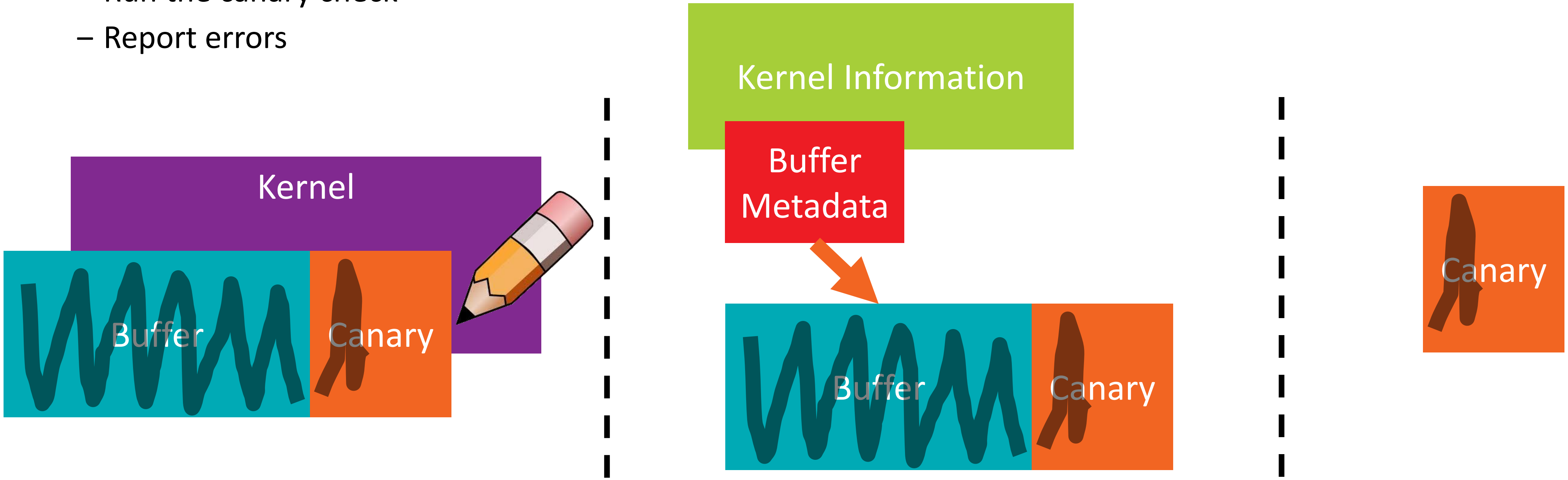

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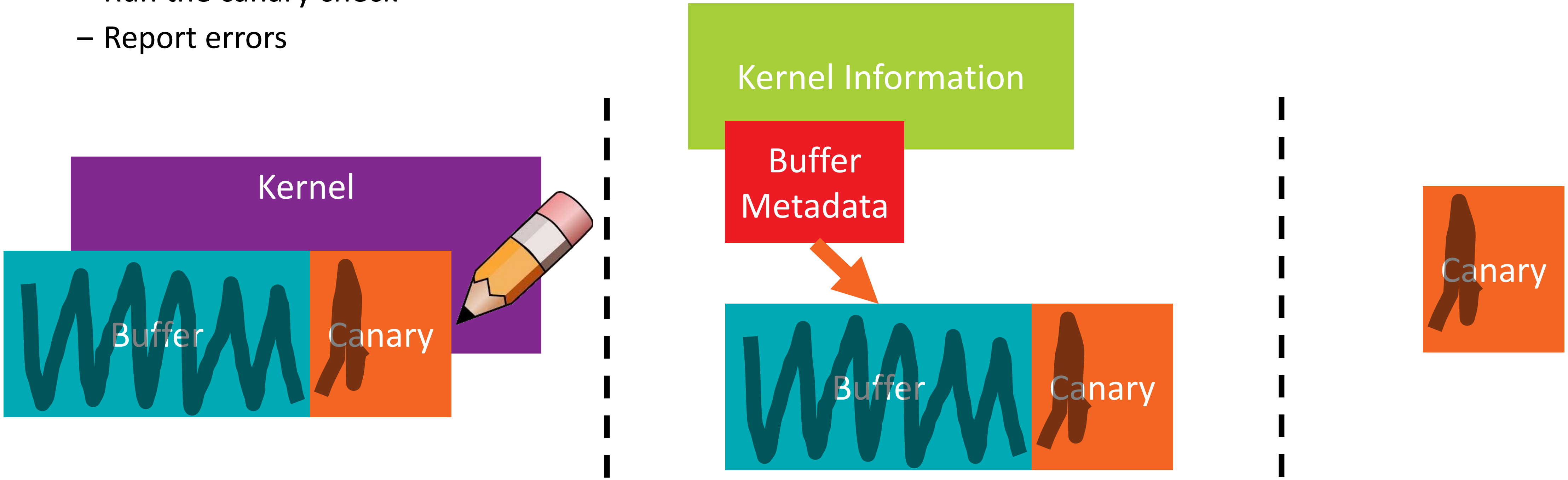

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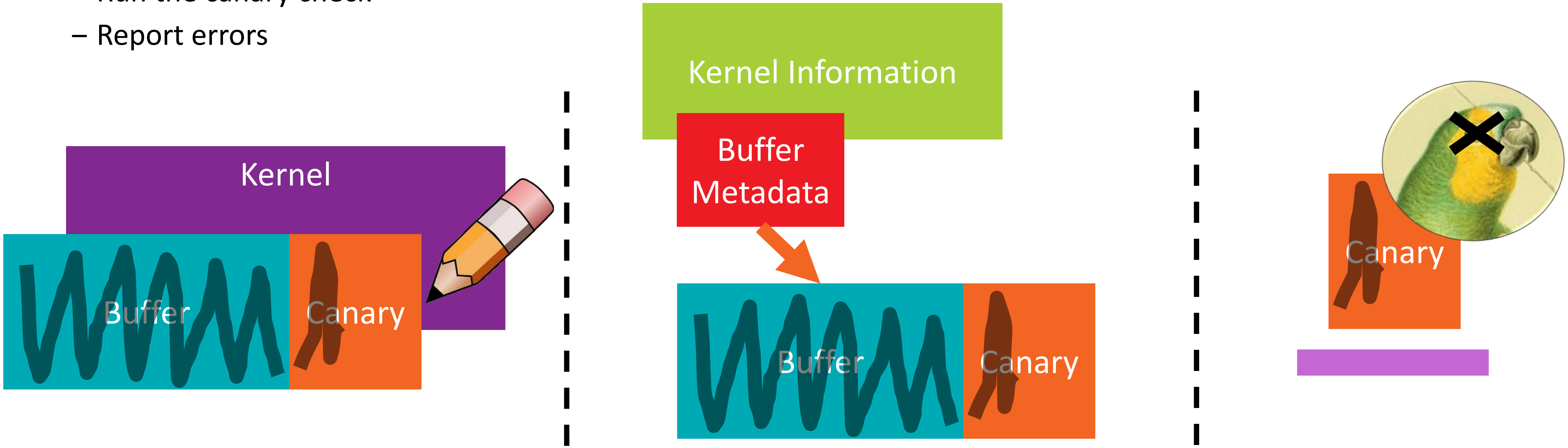


# GOALS

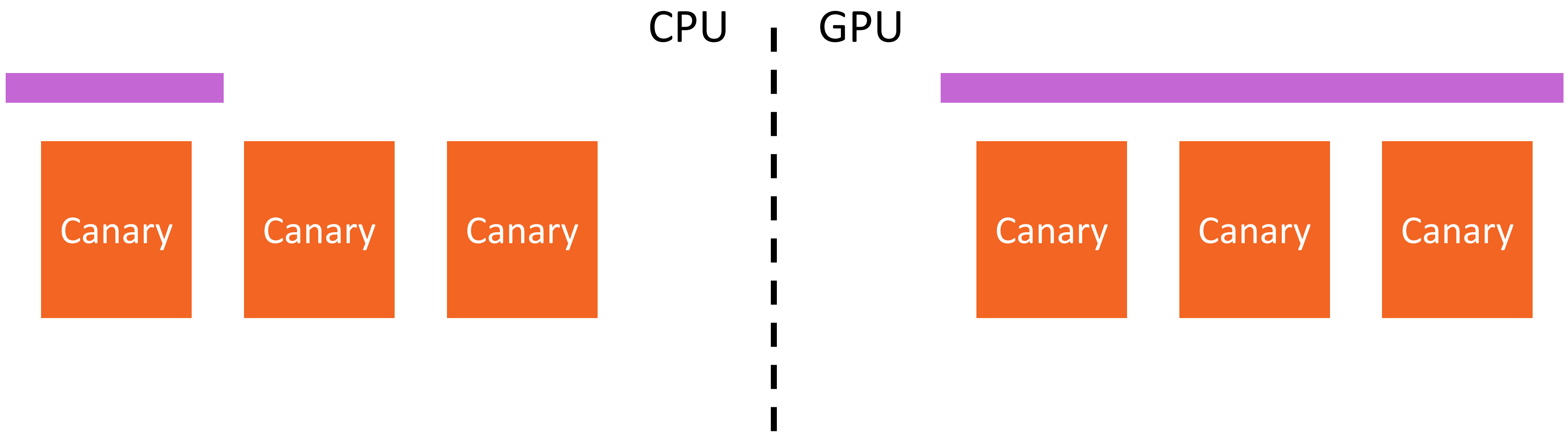
## BUILDING CLARMOR

- Software tool to detect buffer overflows caused by GPU
  - –clARMOR found 13 GPU buffer overflows in 7 programs
- Runnable with most OpenCL™ applications
  - –Tested for GPU and CPU device types from multiple vendors
- Low runtime overhead
  - –14% overhead across 175 applications in 16 GPU benchmark suites

# ACCELERATION

## SELECTING A DEVICE FOR PERFORMING CANARY VERIFICATION

- CPU is faster
  - small / few canary regions (latency advantage)
- GPU is faster
  - large / many canary regions (throughput advantage with embarrassingly parallel workload)
  - reduced transfers over PCIe® by keeping on GPU



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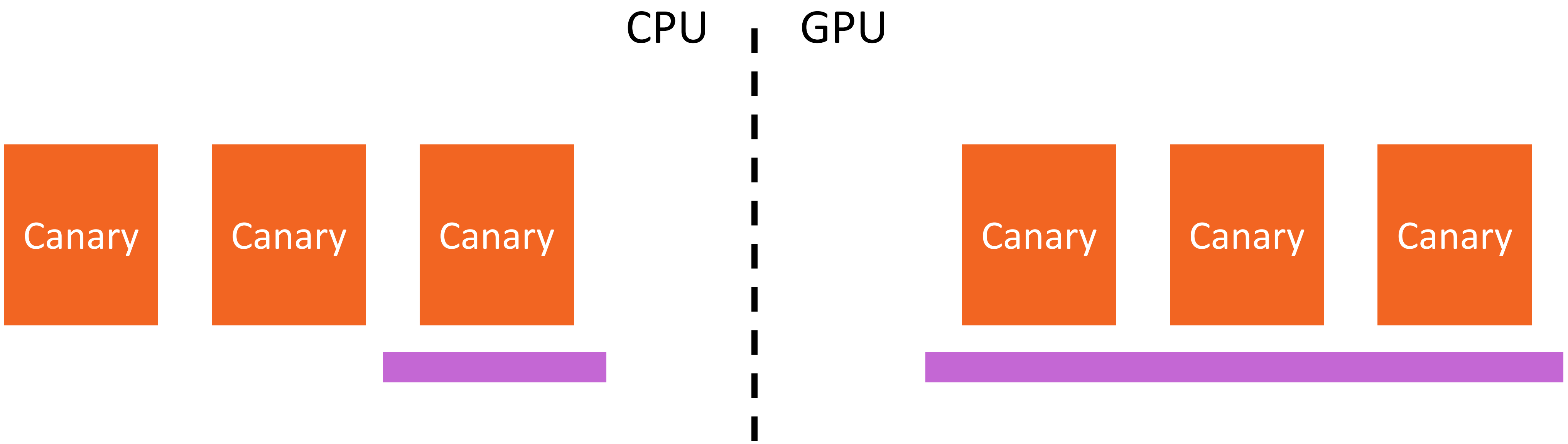

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- Maximizing asynchrony
  - Event-based programming wherever possible
  - GPU check kernels enqueue behind work kernels and wait on completion
  - Evaluation of check kernel results is done with call-backs

synchronous | asynchronous

CPU

GPU

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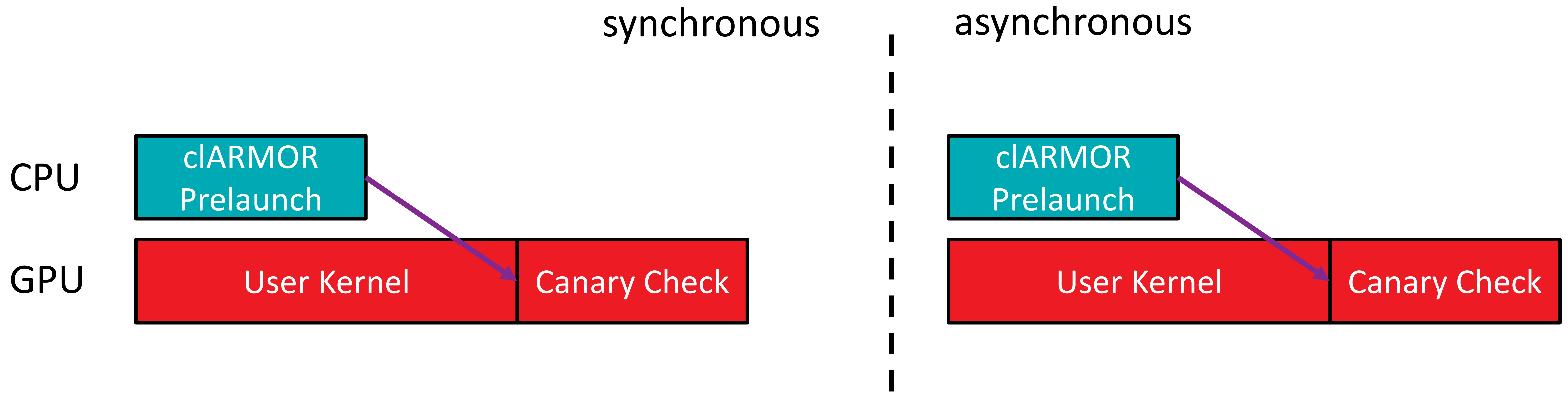

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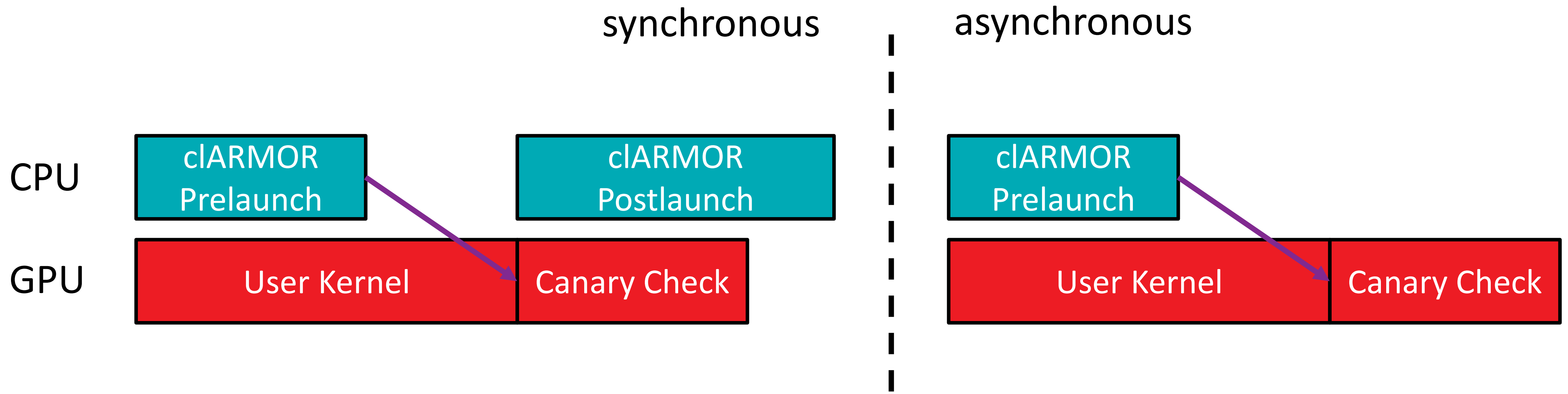

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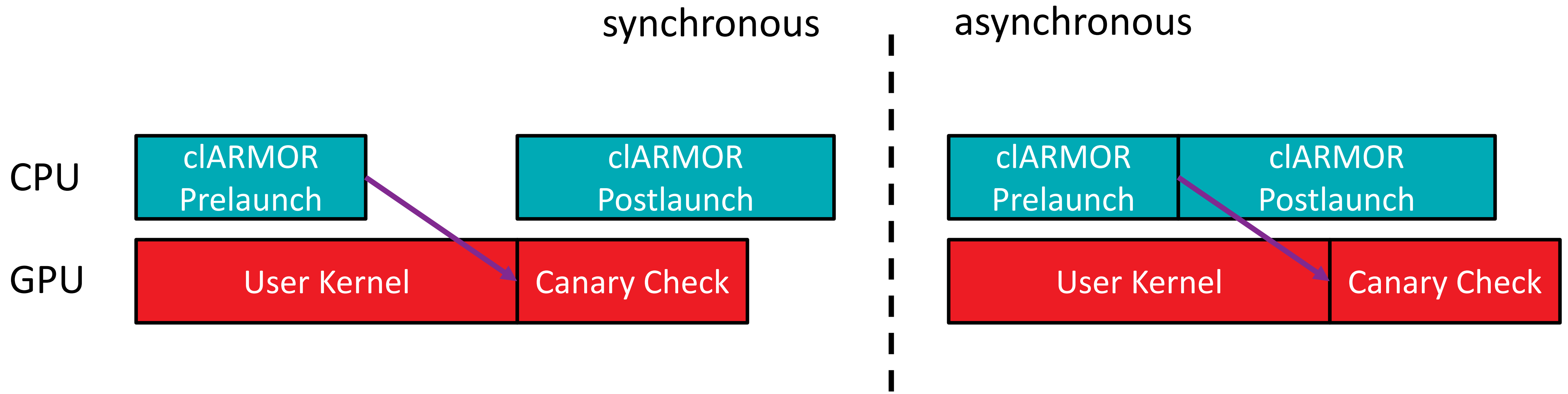

# TEST SETUP

## HARDWARE SPECIFICATIONS AND BENCHMARKS SUITES

- 3.7 GHz AMD A10-7850K CPU
  - 32 GB of DDR3-1866
- AMD FirePro™ W9100 discrete GPU
  - 930 MHz core frequency
  - 320 GB/s of memory bandwidth
  - 16 GB of GDDR5 memory
- 3rd Generation PCIe® x8 CPU–GPU connection
- 175 benchmarks in 16 benchmark suites

| Suite | Num Benchmarks |
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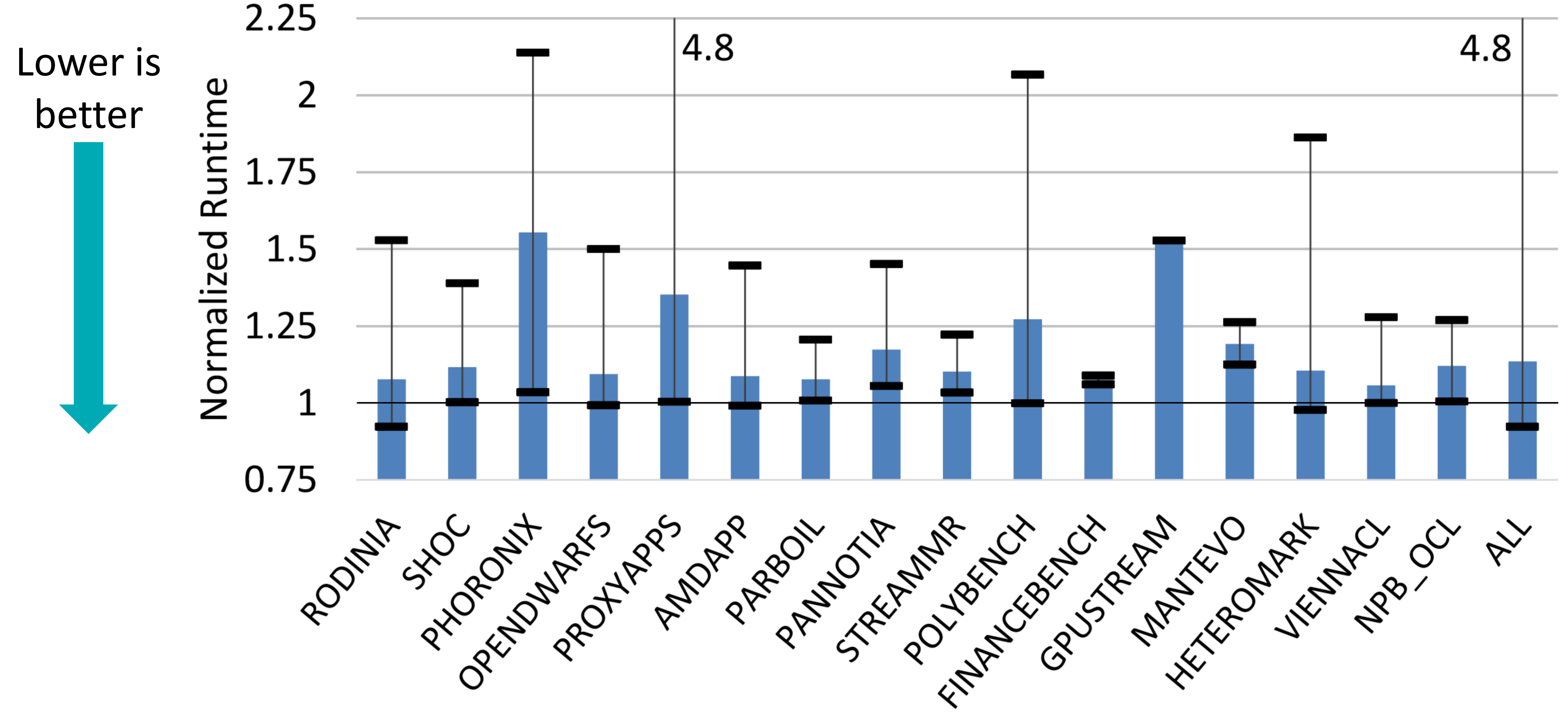

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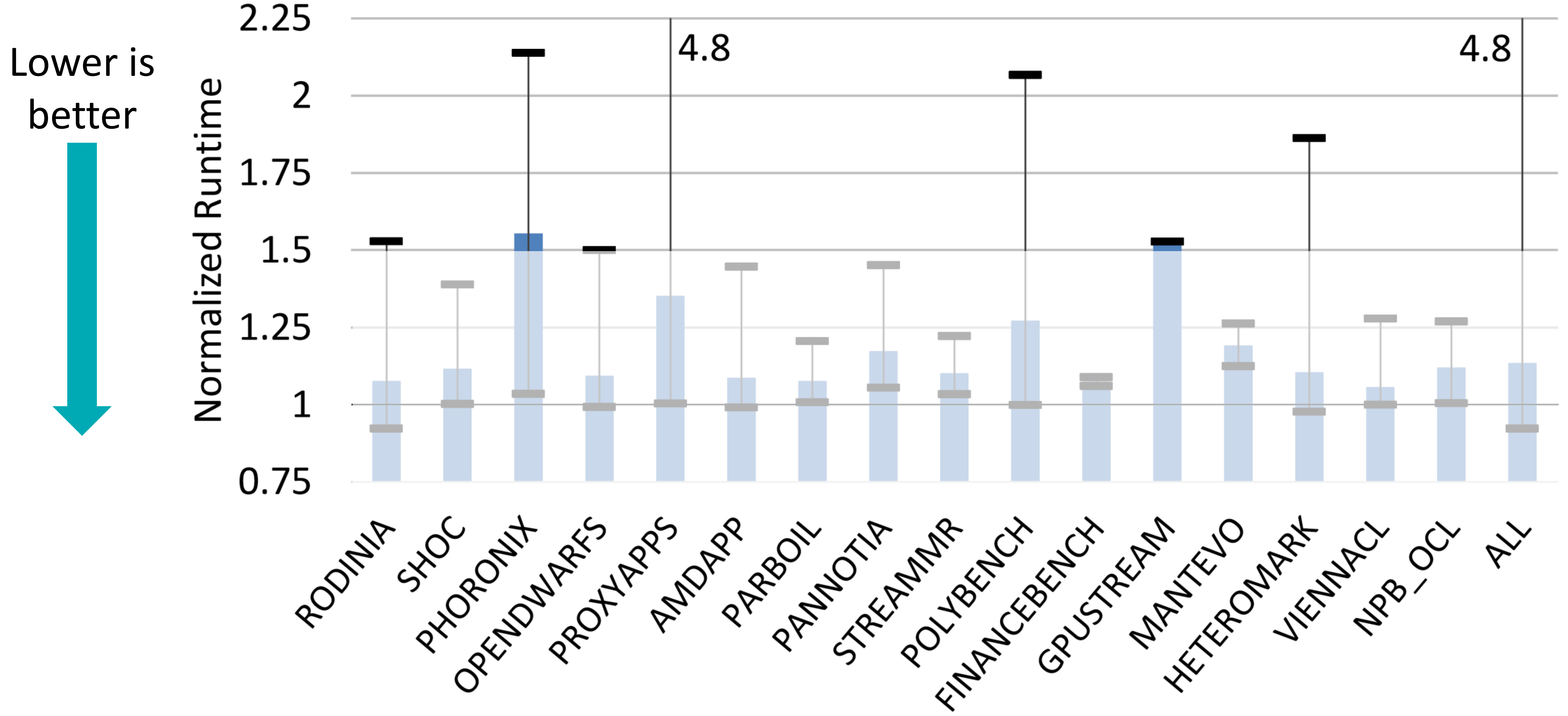

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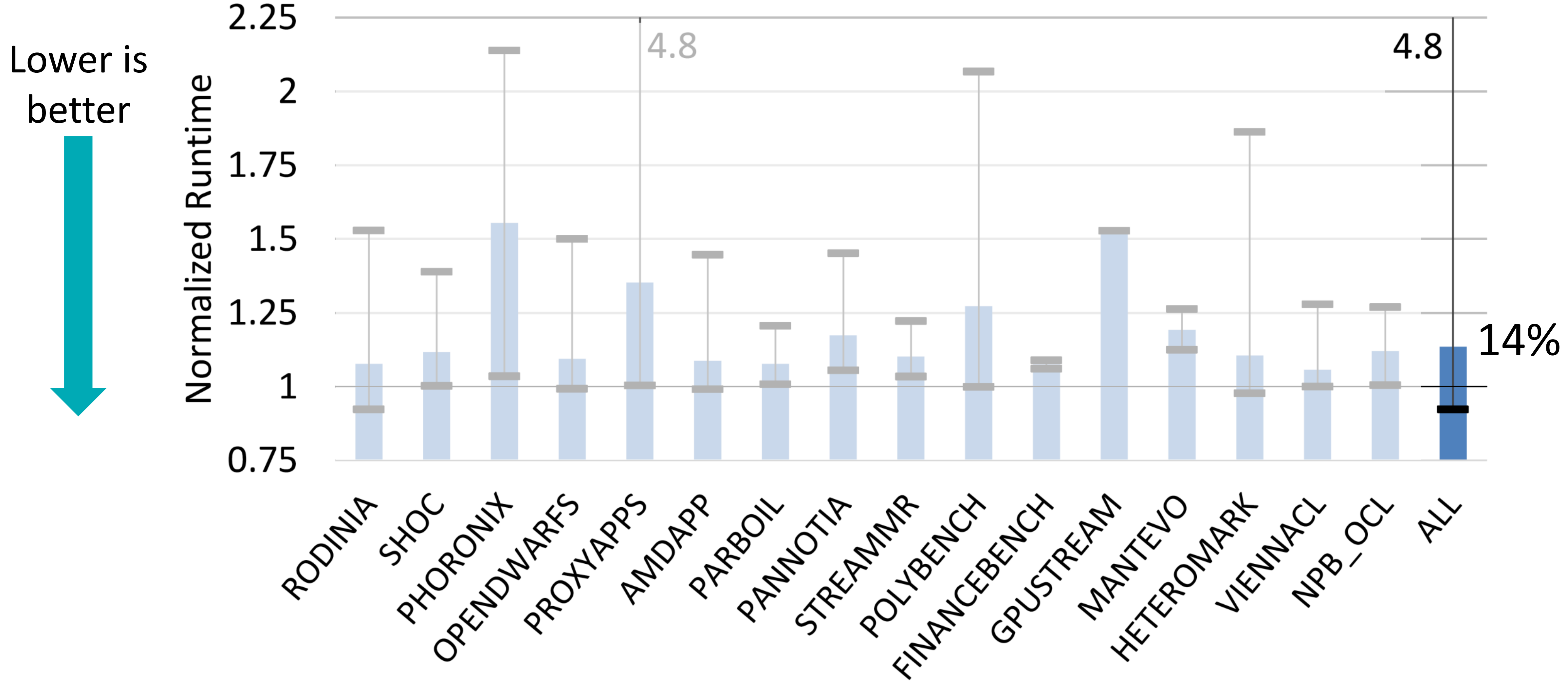

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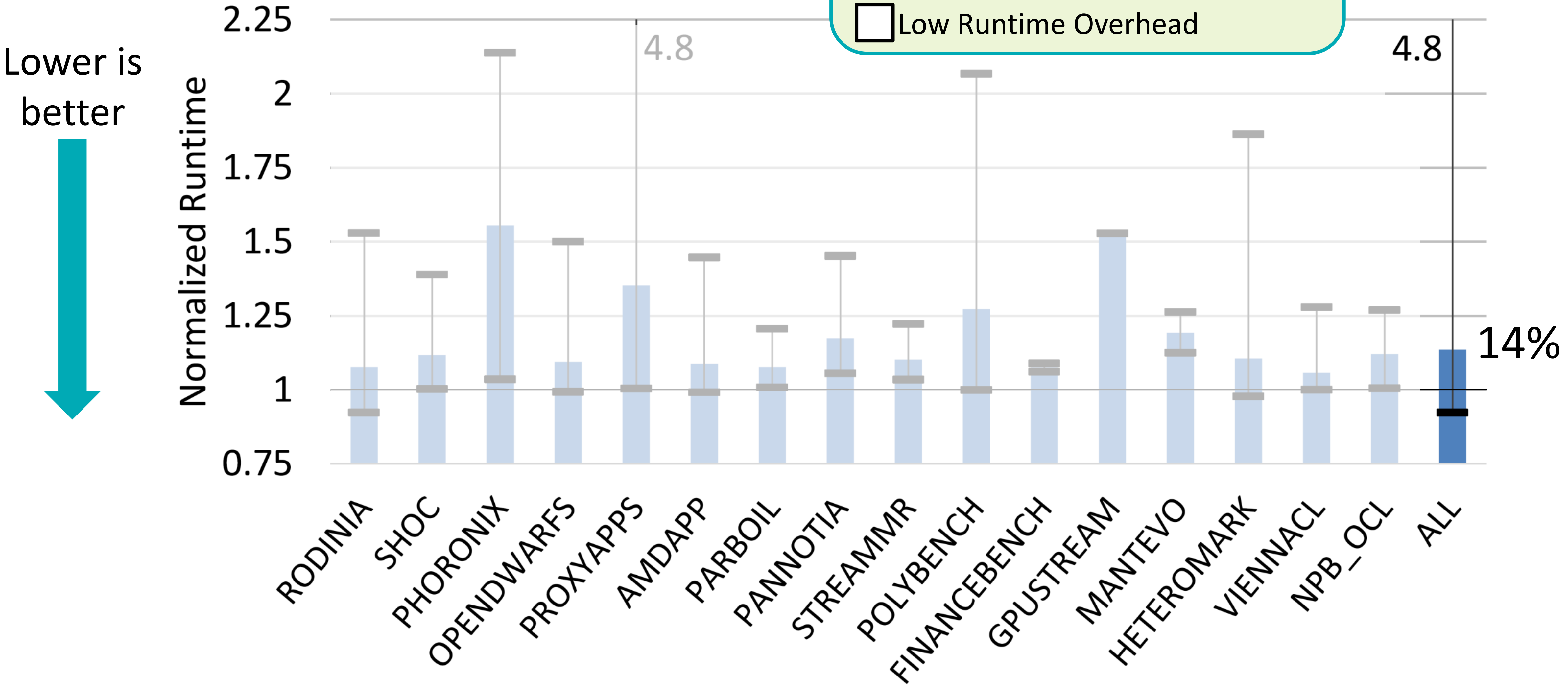

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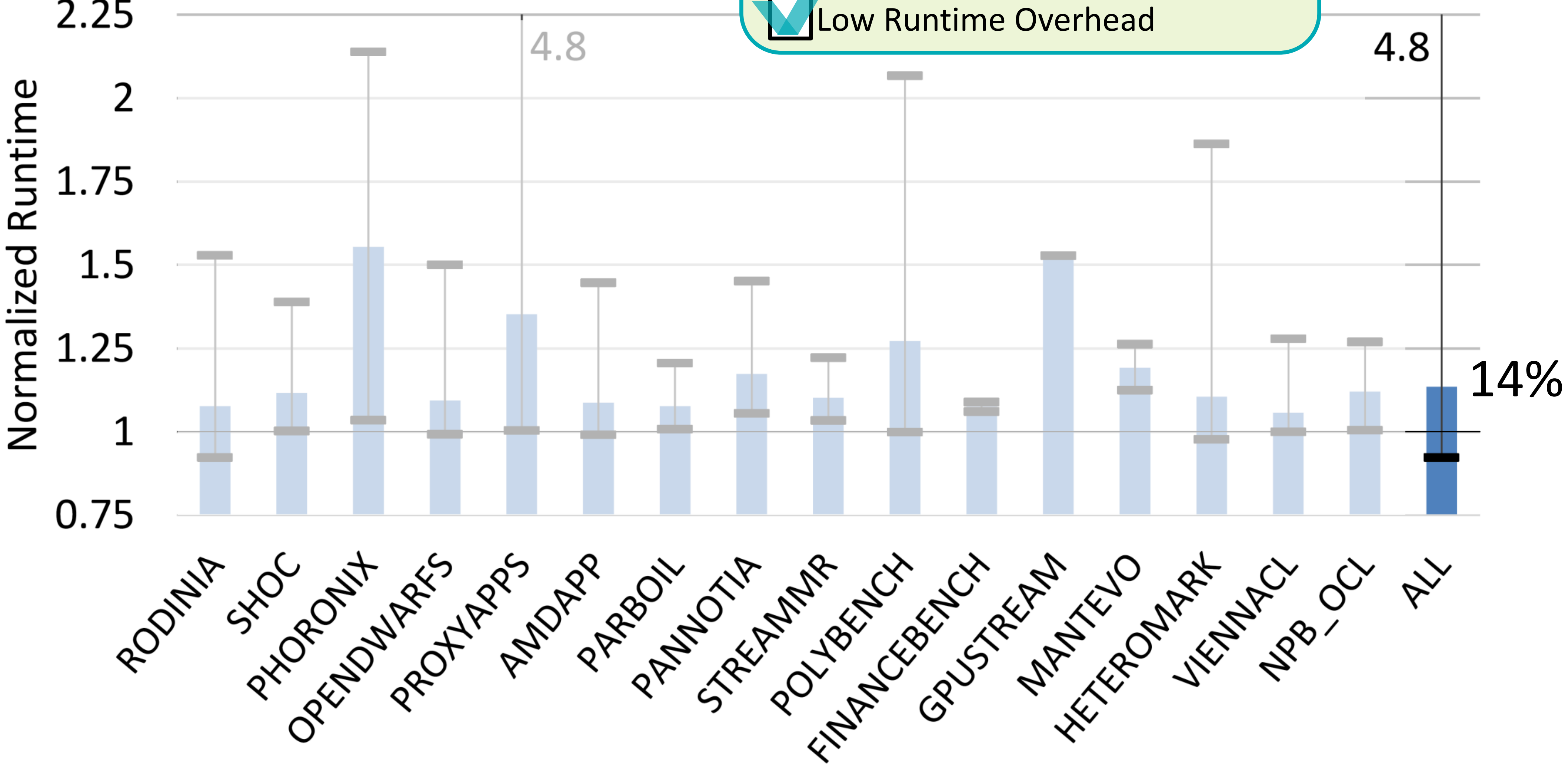
Lower is better



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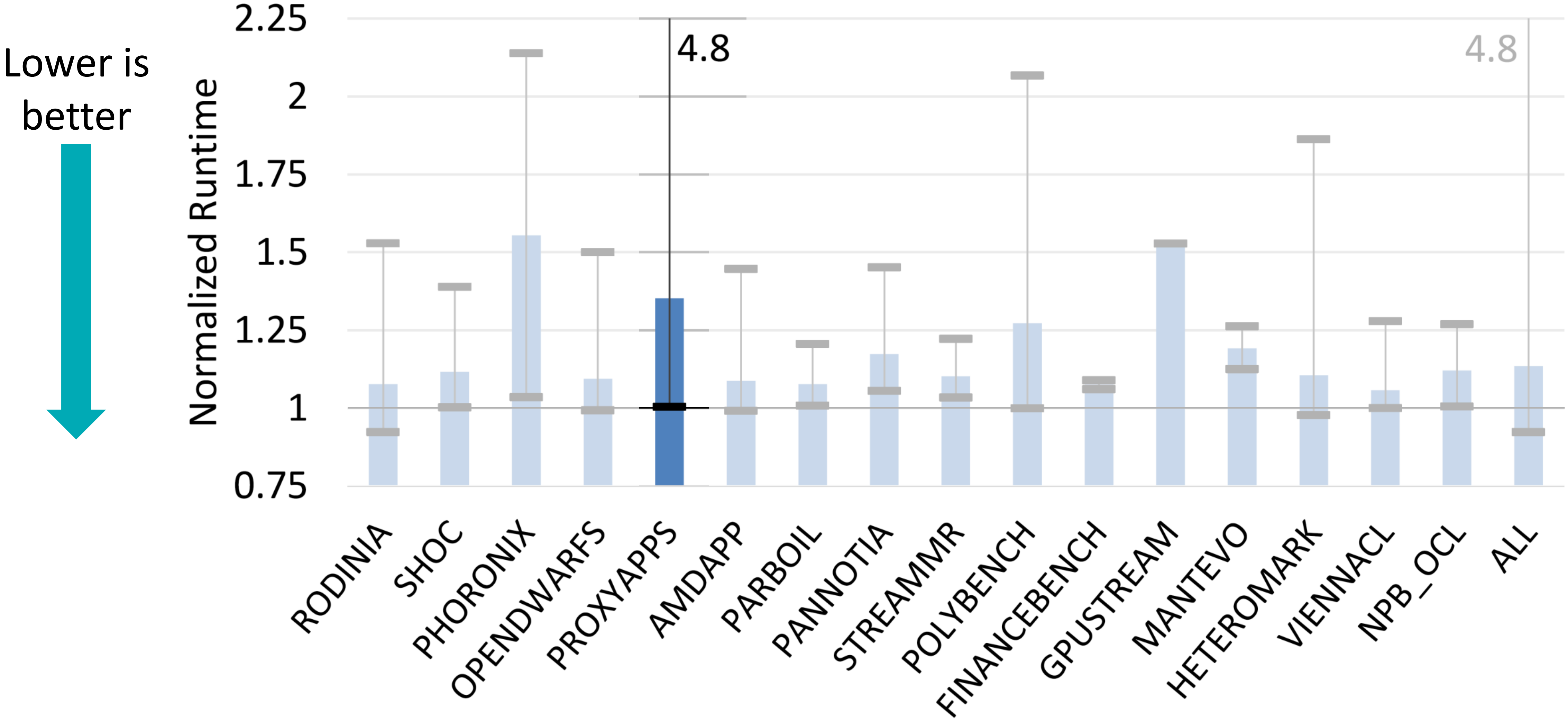

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Example SNAP_MPI kernel launch

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CPU

Application Prelaunch

GPU

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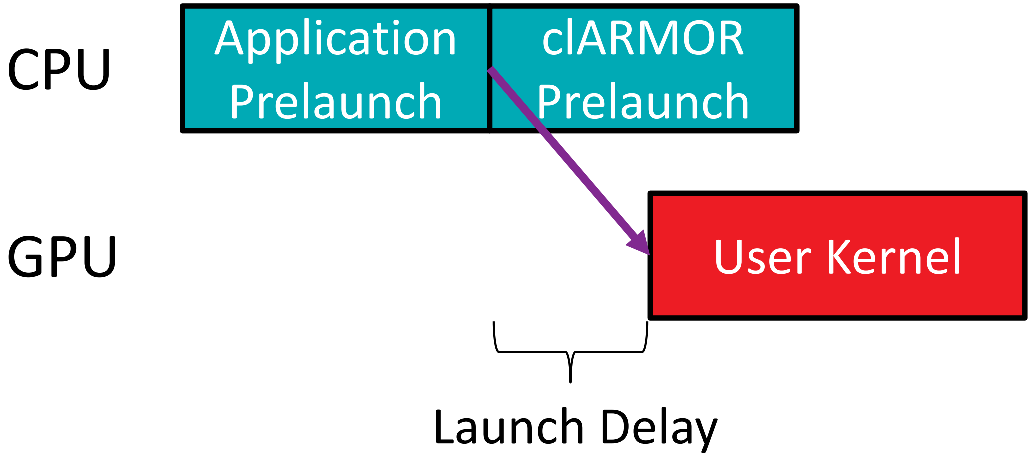

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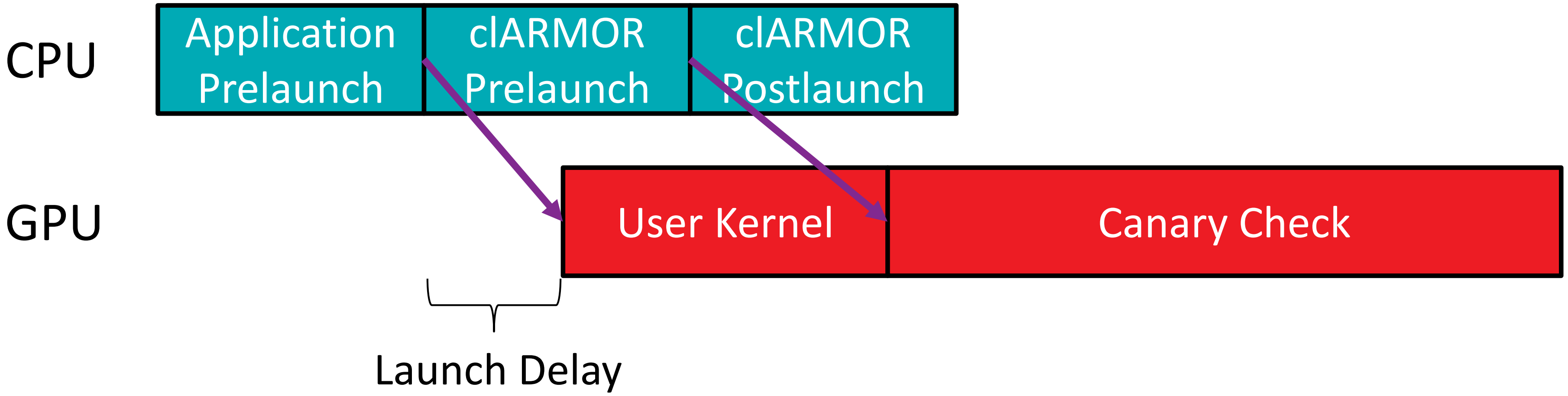

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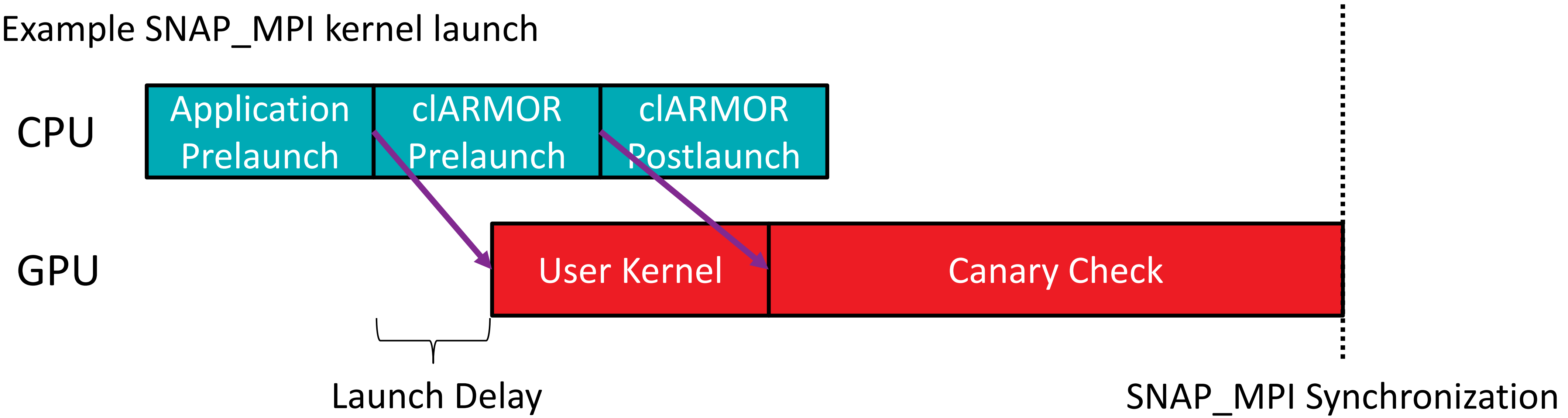

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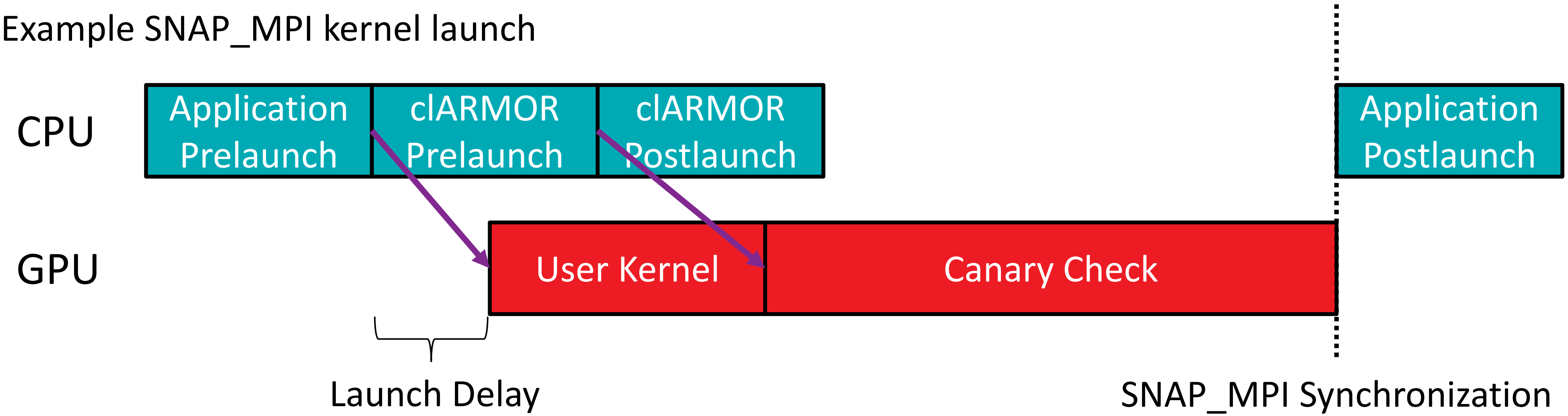

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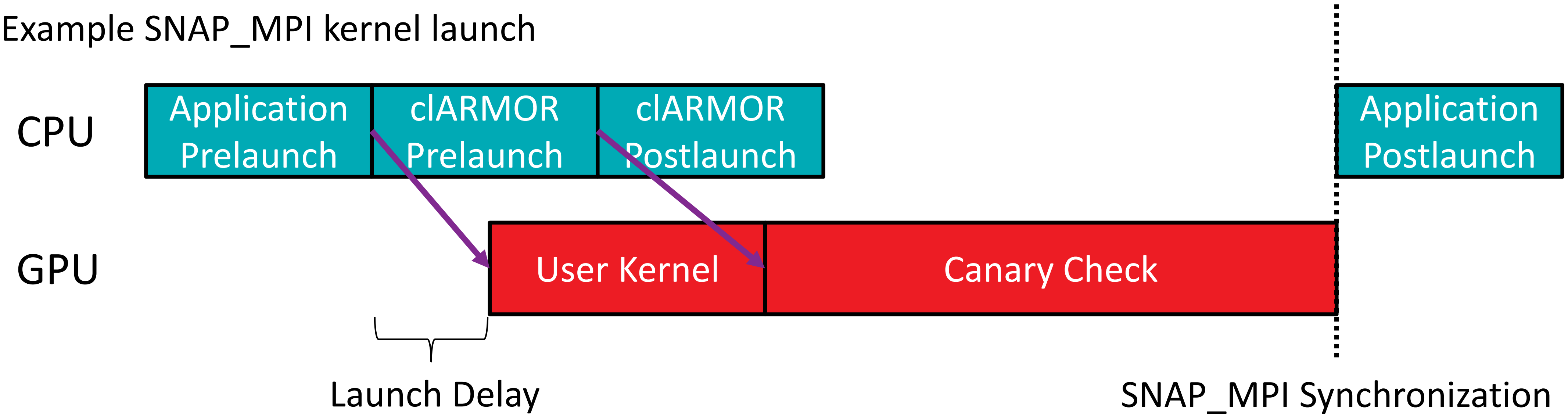


Possible improvement for SNAP_MPI kernel launch

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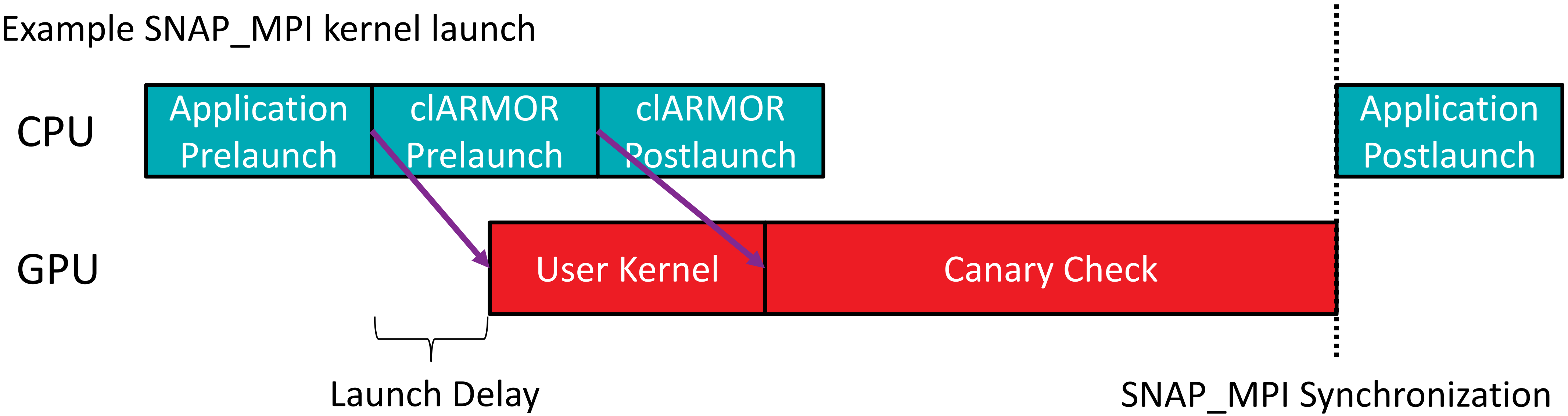


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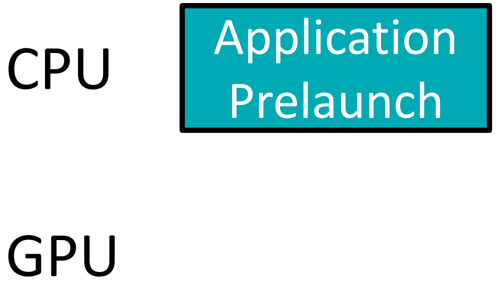

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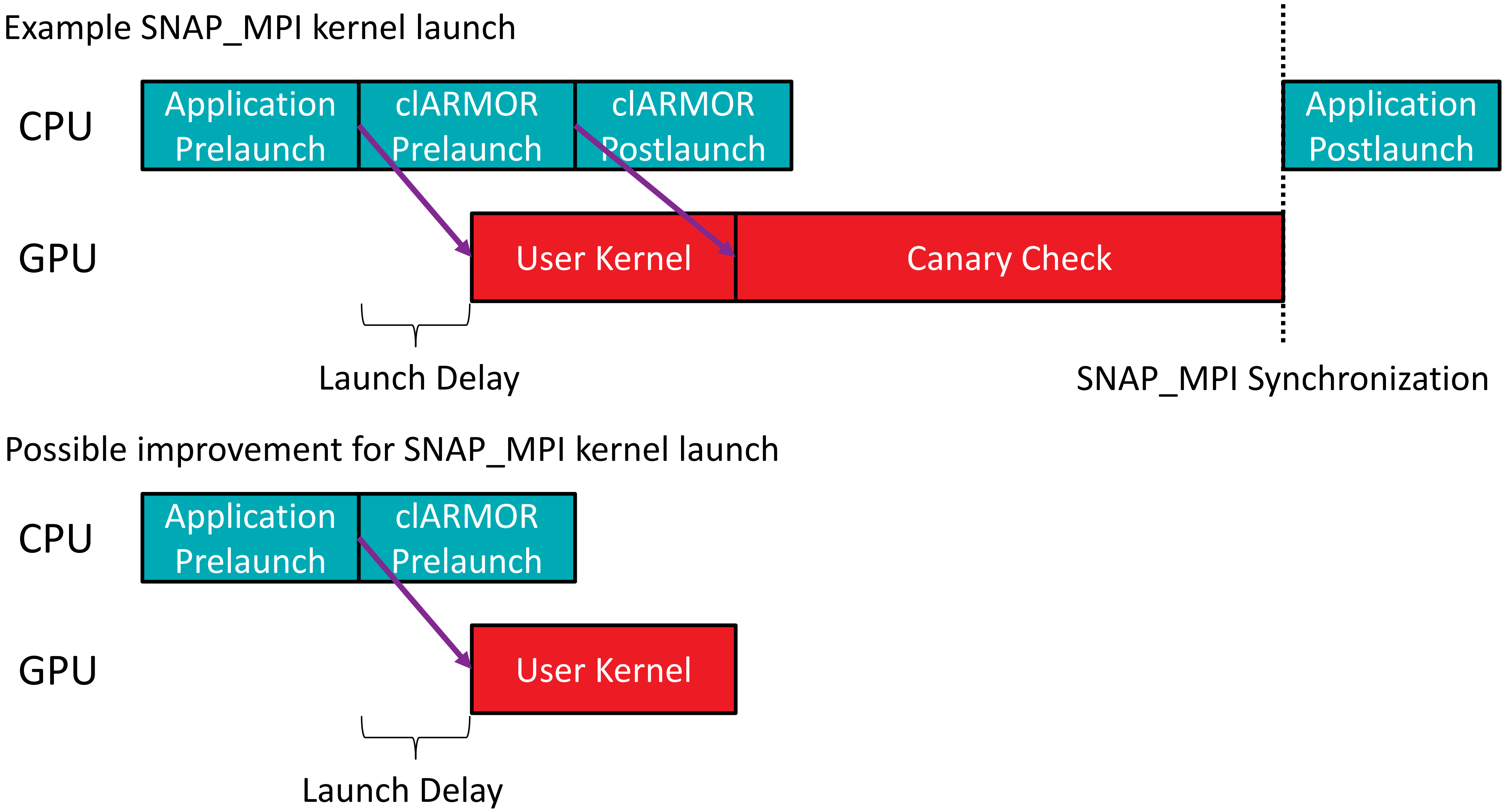

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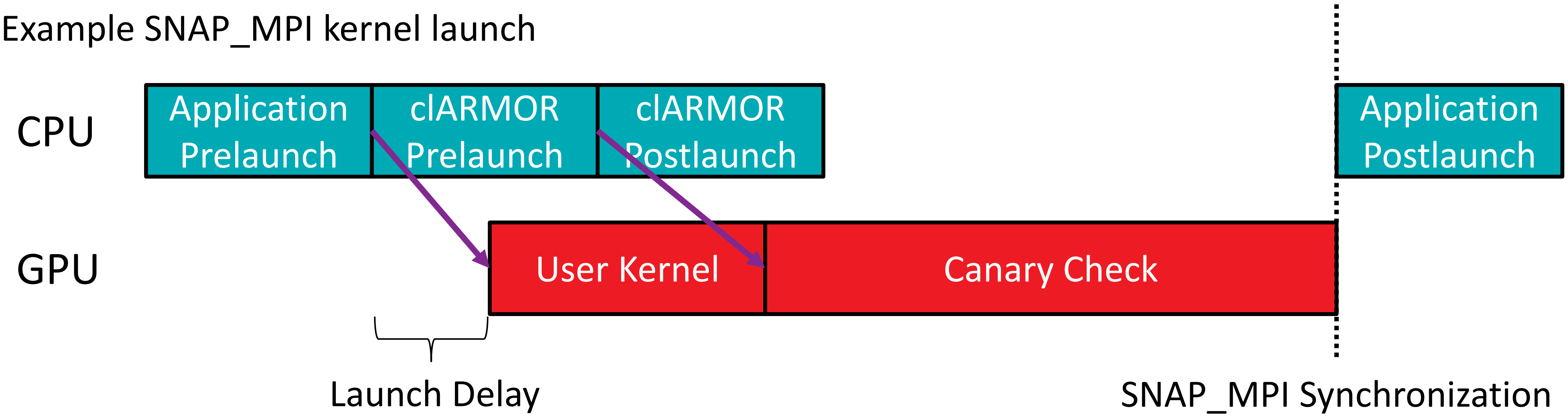


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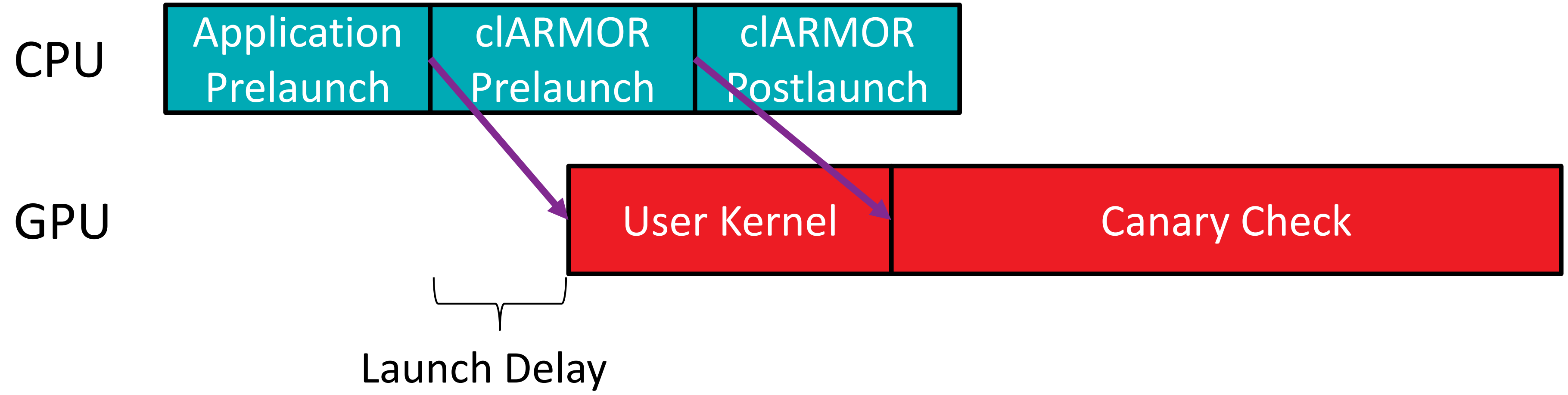

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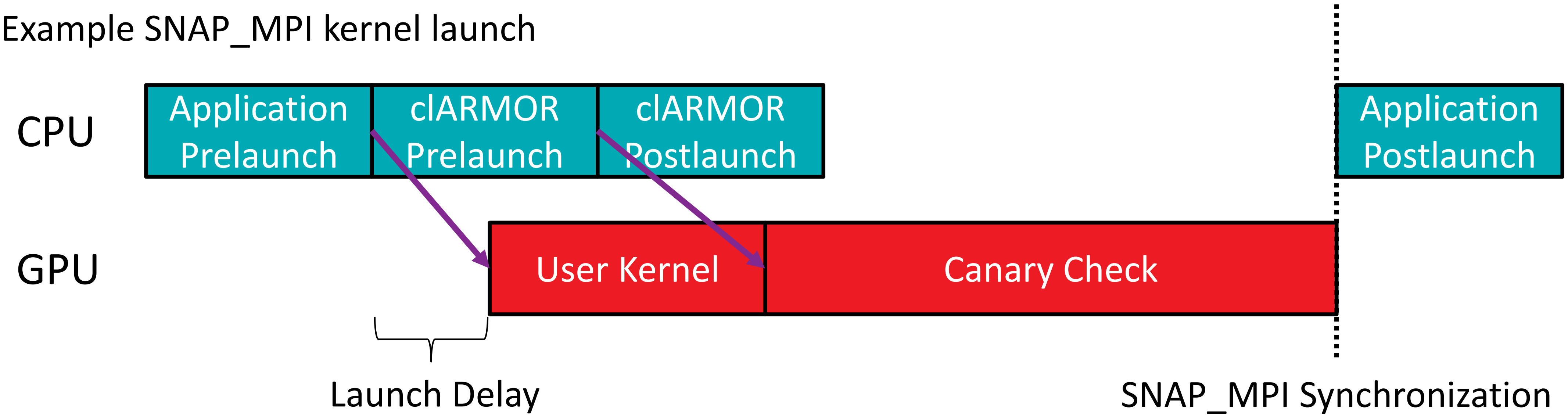


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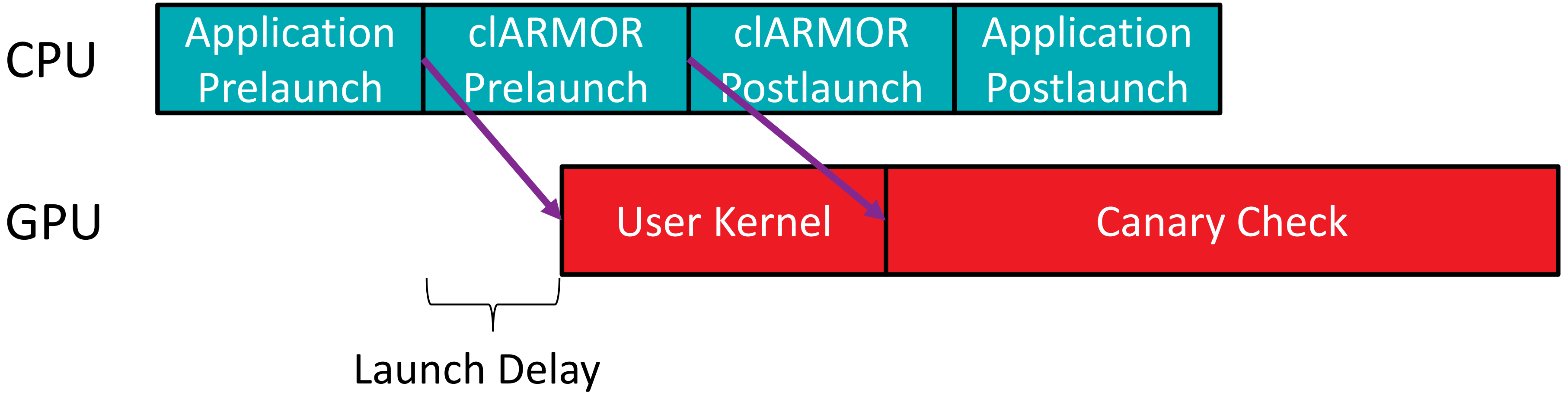

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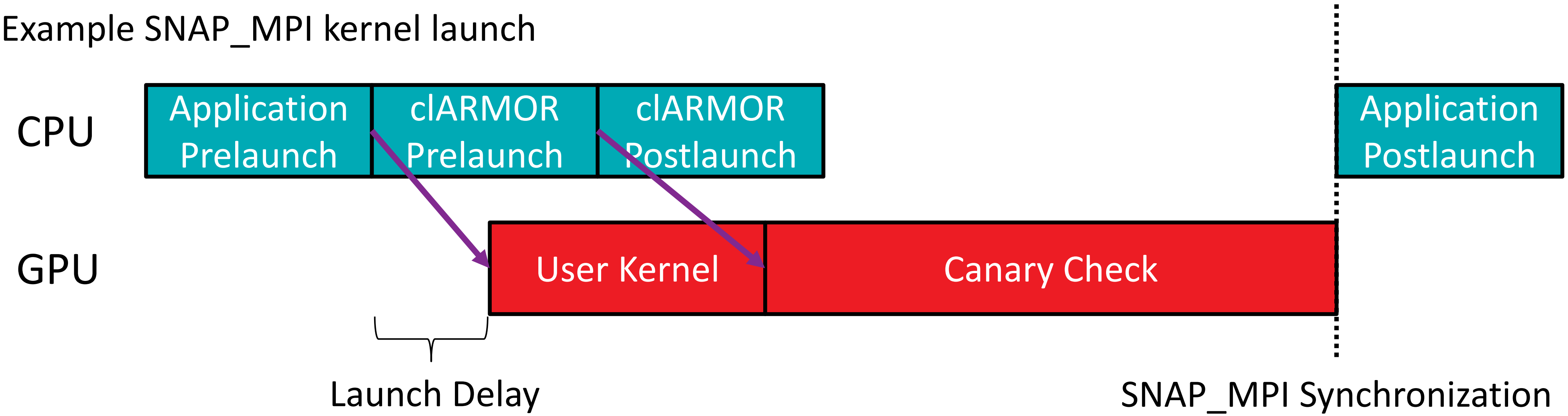


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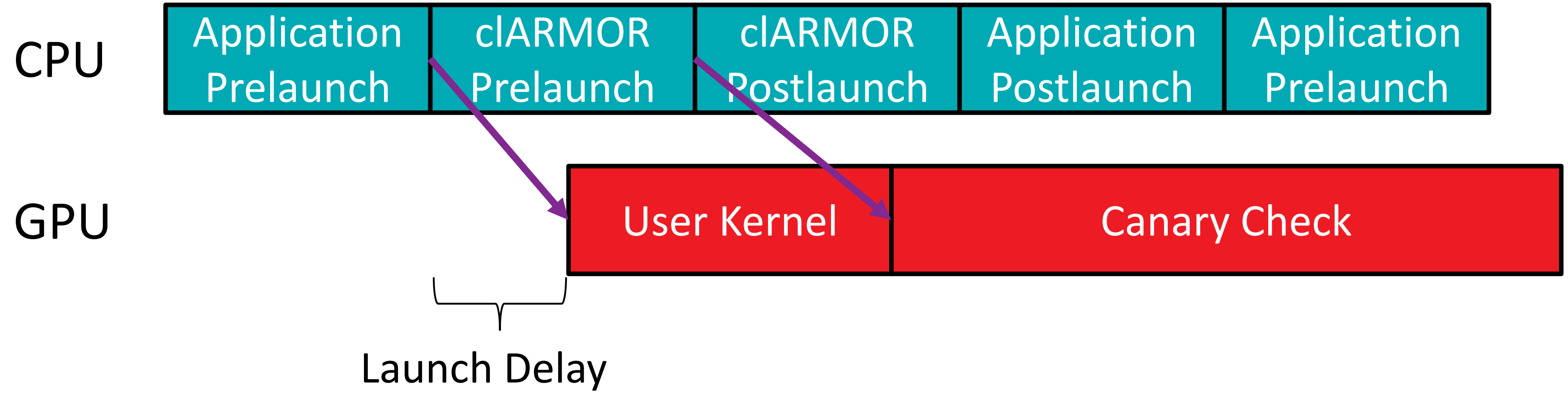

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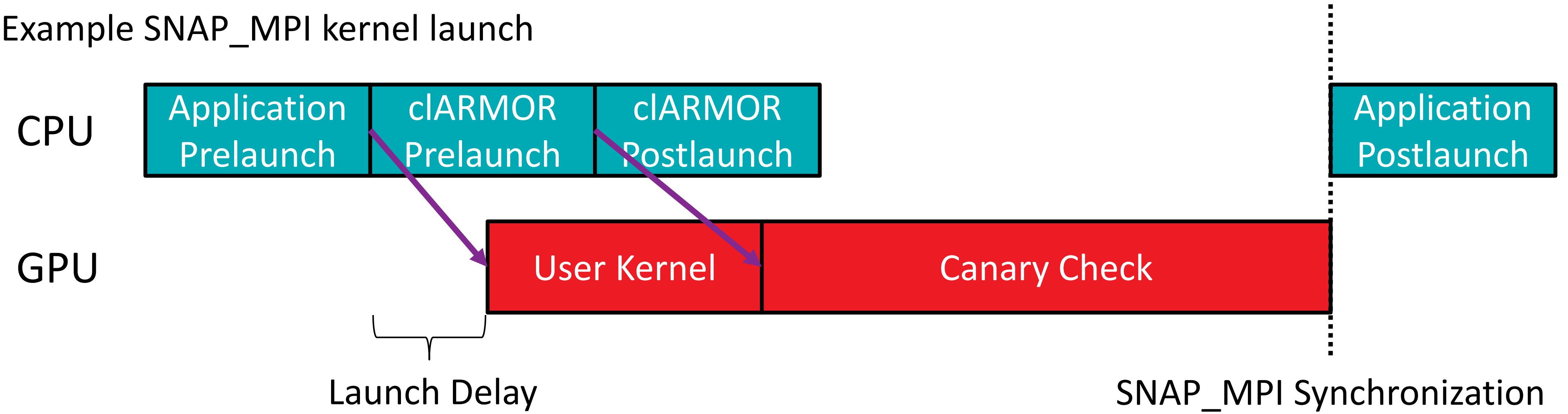


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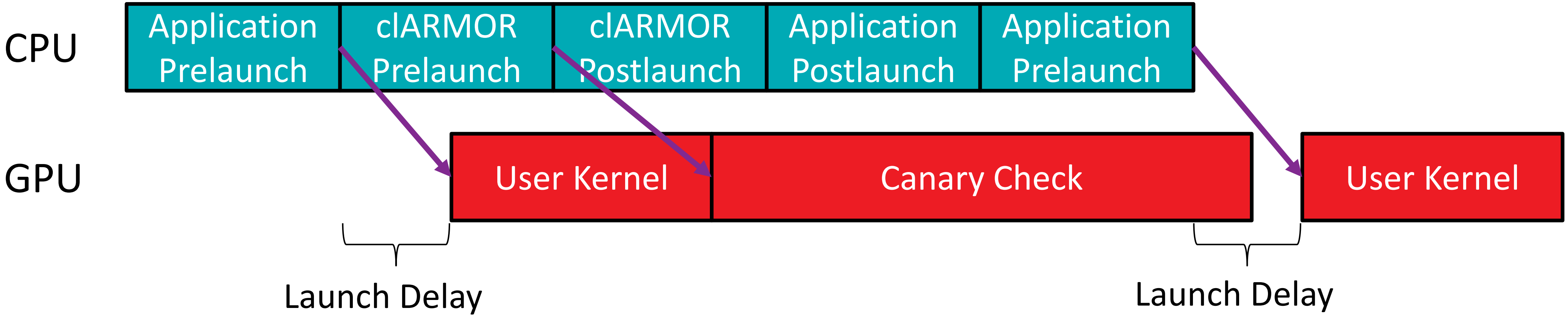

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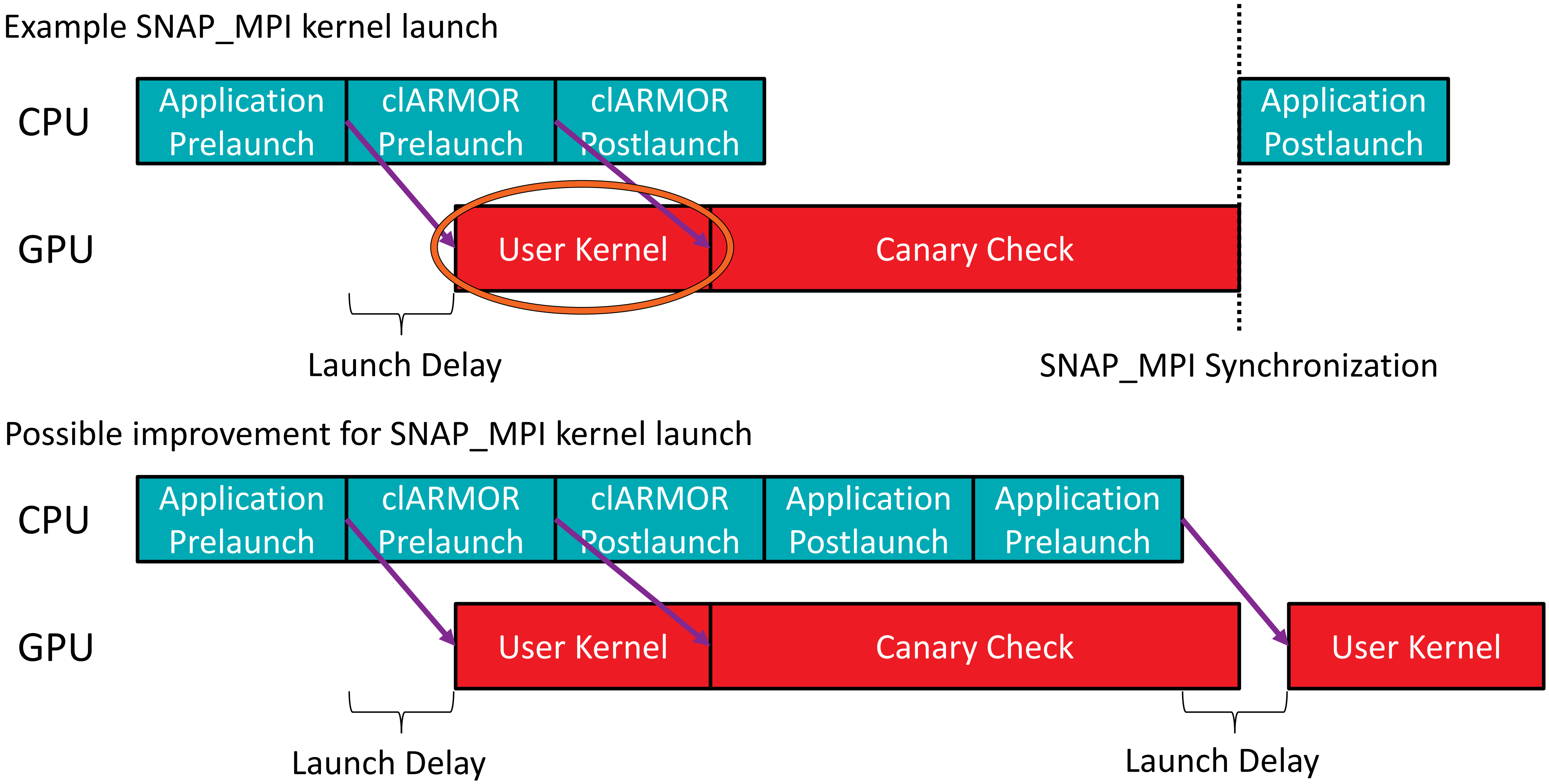

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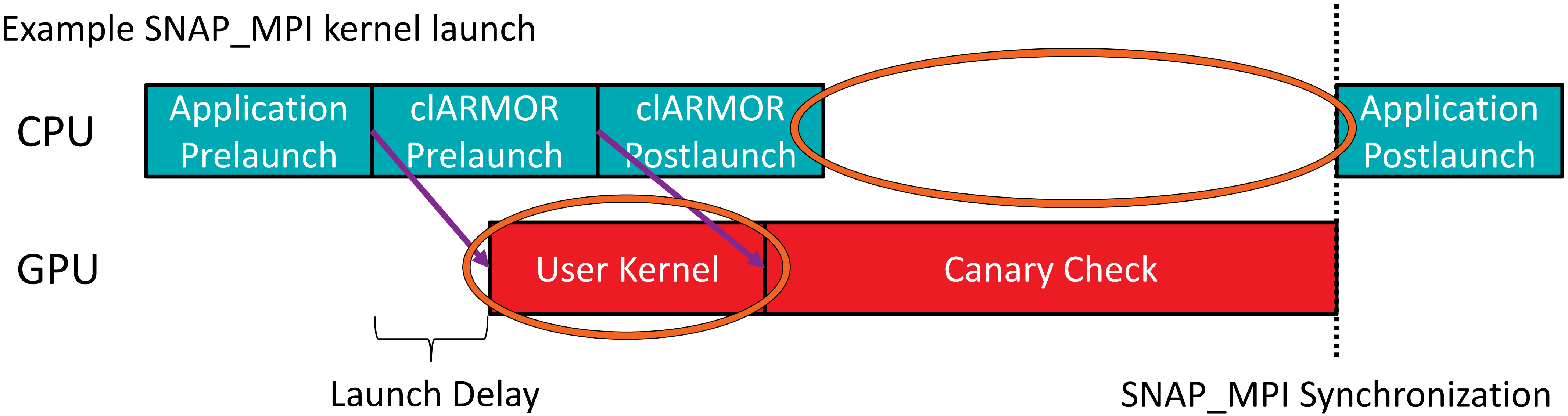


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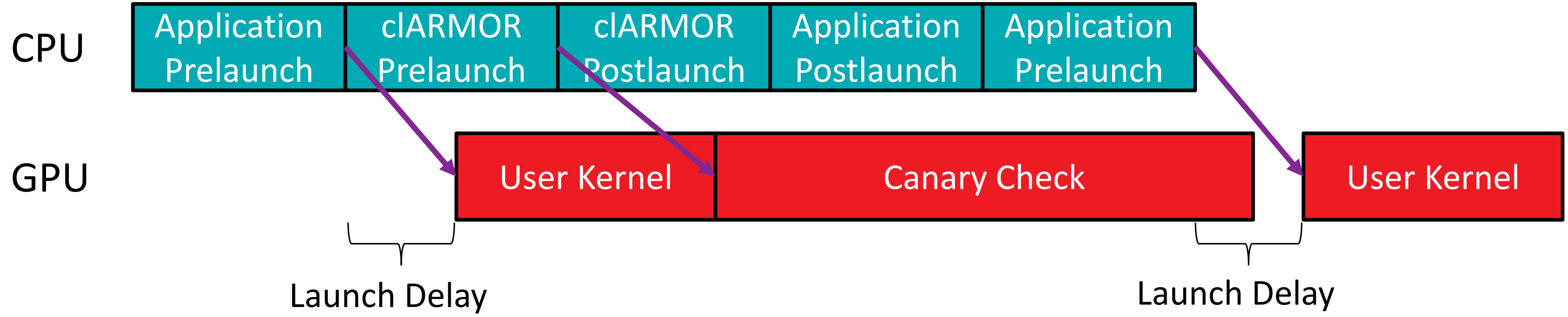

# CLARMOR DETECTION RESULTS

## LIST OF BENCHMARKS WITH BUFFER OVERFLOWS

- Parboil
  - mri-gridding
- StreamMR
  - kmeans
  - wordcount
- Hetero-Mark
  - OpenCL™ 1.2 kmeans
  - OpenCL 2.0 kmeans
  - OpenCL 1.2 sw, 4 errors
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- ☐ Detect GPU Buffer Overflows
- ☑ Compatible With Most OpenCL™
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

Kernel

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__kernel void sw_compute0(…
        const unsigned M_LEN,
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        … ) {
  int x = get_global_id(0);
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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
        sizeInBytes, NULL, &err);
…
const size_t globalSize[2] = {m_len_, n_len_};
…
err |= clSetKernelArg(kernel_sw_compute0_, 6,
        sizeof(cl_mem),
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err = clEnqueueNDRangeKernel(cmdQueue_,
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AMD

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x = m - 1

y = n - 1

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(y + 1) * M_LEN + x
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        …
}
```

```
(y + 1) * M_LEN + x
```

x = m - 1

y = n - 1

m == M_LEN

Host

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size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
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        …
        __global double *cu,
        … ) {
  int x = get_global_id(0);
  int y = get_global_id(1);
  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
```

x = m - 1

y = n - 1

m == M_LEN

Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
        sizeInBytes, NULL, &err);
…
const size_t globalSize[2] = {m_len_, n_len_};
…
err |= clSetKernelArg(kernel_sw_compute0_, 6,
        sizeof(cl_mem),
        reinterpret_cast<void *>(&cu_));
…
err = clEnqueueNDRangeKernel(cmdQueue_,
        kernel_sw_compute0_, 2, NULL, globalSize,
        localSize, 0, NULL, NULL);
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

Kernel

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__kernel void sw_compute0(…
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  cu[(y + 1) * M_LEN + x] = <input_equation>
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}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
```

x = m - 1

y = n - 1

m == M_LEN

Host

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        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
```

x = m - 1

y = n - 1

m == M_LEN

Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
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        …
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```

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(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
```

x = m - 1

y = n - 1

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Host

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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

## Kernel

```
__kernel void sw_compute0(…
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        __global double *cu,
        … ) {
  int x = get_global_id(0);
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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
n * m + m - 1
```

x = m - 1

y = n - 1

m == M_LEN

## Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
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        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
n * m + m - 1
```

x = m - 1

y = n - 1

m == M_LEN

## Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
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        sizeInBytes, NULL, &err);
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

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  int y = get_global_id(1);
  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
n * m + m - 1
m*n – 1 + m > m*n - 1
```

x = m - 1

y = n - 1

m == M_LEN

Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
        sizeInBytes, NULL, &err);
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…
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

### Kernel

```
__kernel void sw_compute0(…
        const unsigned M_LEN,
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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

$(y + 1) * M\_LEN + x$

$(y + 1) * m + x$

$(n) * m + x$

$n * m + m - 1$

$\cancel{m*n - 1} + m > \cancel{m*n - 1}$

$x = m - 1$

$y = n - 1$

$m == M\_LEN$

### Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
        sizeInBytes, NULL, &err);
…
const size_t globalSize[2] = {m_len_, n_len_};
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err |= clSetKernelArg(kernel_sw_compute0_, 6,
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

### Kernel

```
__kernel void sw_compute0(…
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  int x = get_global_id(0);
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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

```
(y + 1) * M_LEN + x
(y + 1) * m + x
(n) * m + x
n * m + m - 1
~~m*n - 1~~ + m > ~~m*n - 1~~
m > 0
```

x = m - 1

y = n - 1

m == M_LEN

### Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
        sizeInBytes, NULL, &err);
…
const size_t globalSize[2] = {m_len_, n_len_};
…
err |= clSetKernelArg(kernel_sw_compute0_, 6,
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# Hetero-Mark OpenCL™ 1.2 SW Overflow Error

## Kernel

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__kernel void sw_compute0(…
        const unsigned M_LEN,
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  int x = get_global_id(0);
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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
}
```

(y + 1) * M_LEN + x

(y + 1) * m + x

(n) * m + x

n * m + m - 1

~~m*n - 1~~ + m > ~~m*n - 1~~

m > 0

x = m - 1

y = n - 1

m == M_LEN

## Host

```
size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
…
cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
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…
err = clEnqueueNDRangeKernel(cmdQueue_,
        kernel_sw_compute0_, 2, NULL, globalSize,
        localSize, 0, NULL, NULL);
```

# CONCLUSION

## CLARMOR IS READY FOR YOU TO USE

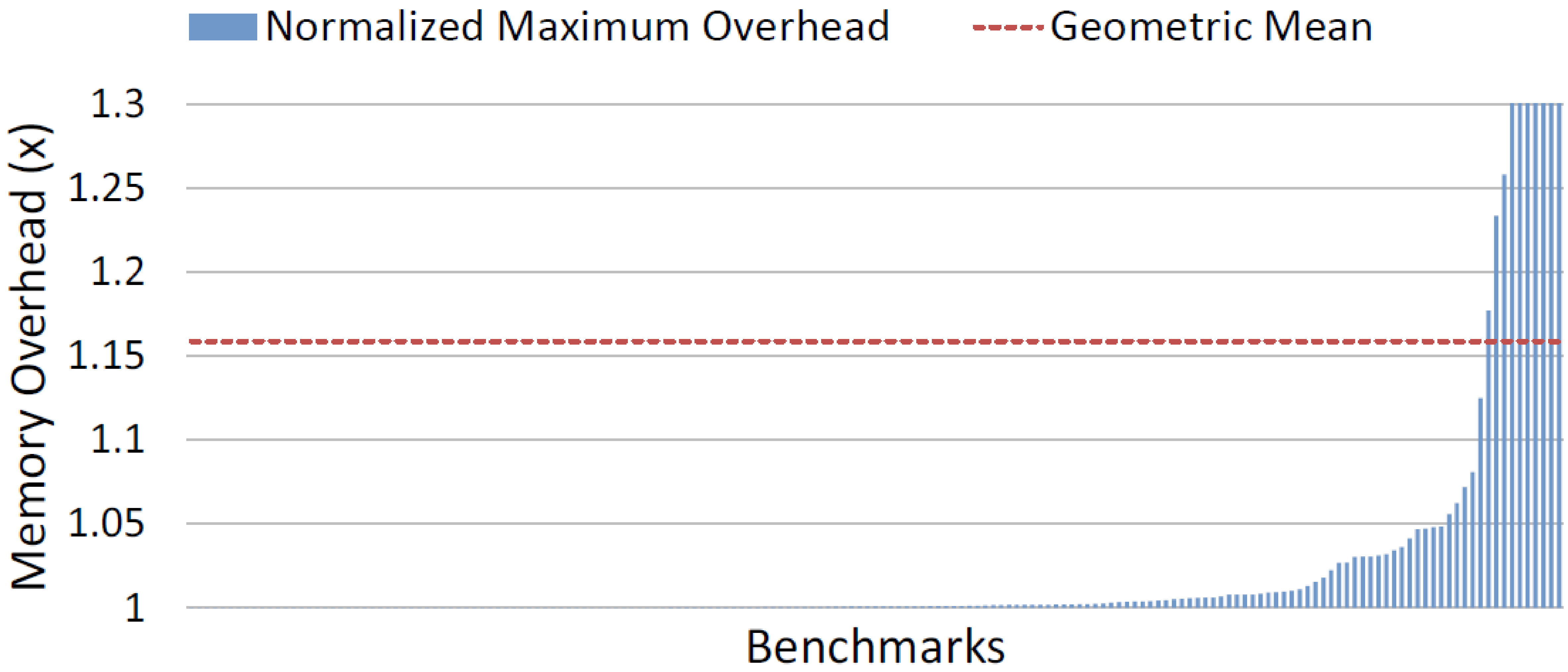
- Canary-based detection scheme finds GPU write overflows
  - 13 GPU buffer overflows in 7 programs
- Works for most OpenCL™ applications
  - Running on GPU or CPU, not vendor specific
- Near real time detection
  - 14% overhead across 175 applications in 16 GPU benchmark suites

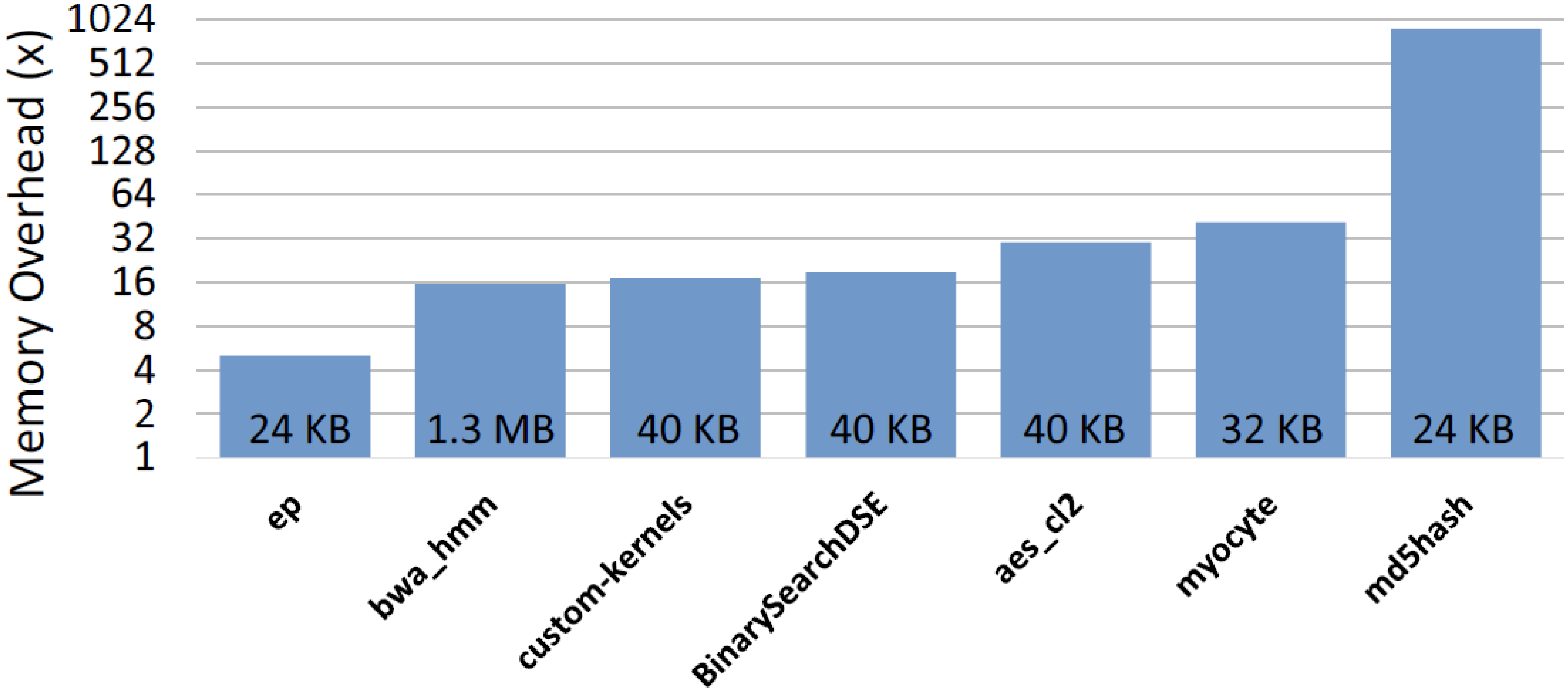
- Open Sourced
  - https://github.com/GPUOpen-ProfessionalCompute-Tools/clARMOR
  - Branch available for reproducing paper measurements

# DISCLAIMER & ATTRIBUTION

AMD

# MEMORY OVERHEAD




Memory Overhead (x)
1024
512
256
128
64
32
16
8
4
2
1
24 KB
1.3 MB
40 KB
40 KB
40 KB
32 KB
24 KB
ep
bwa_hmm
custom-kernels
BinarySearchDSE
aes_cl2
myocyte
md5hash

# EXAMPLE ERROR

```
clARMOR: Loaded CL_WRAPPER
clARMOR:
clARMOR: ATTENTION:
clARMOR: ************* Buffer overflow detected ***********
clARMOR: Kernel: sw_compute0, Buffer: cu
clARMOR:    First observed writing 1 byte(s) past the end.
clARMOR:
clARMOR: Exiting application because of buffer overflow.
```