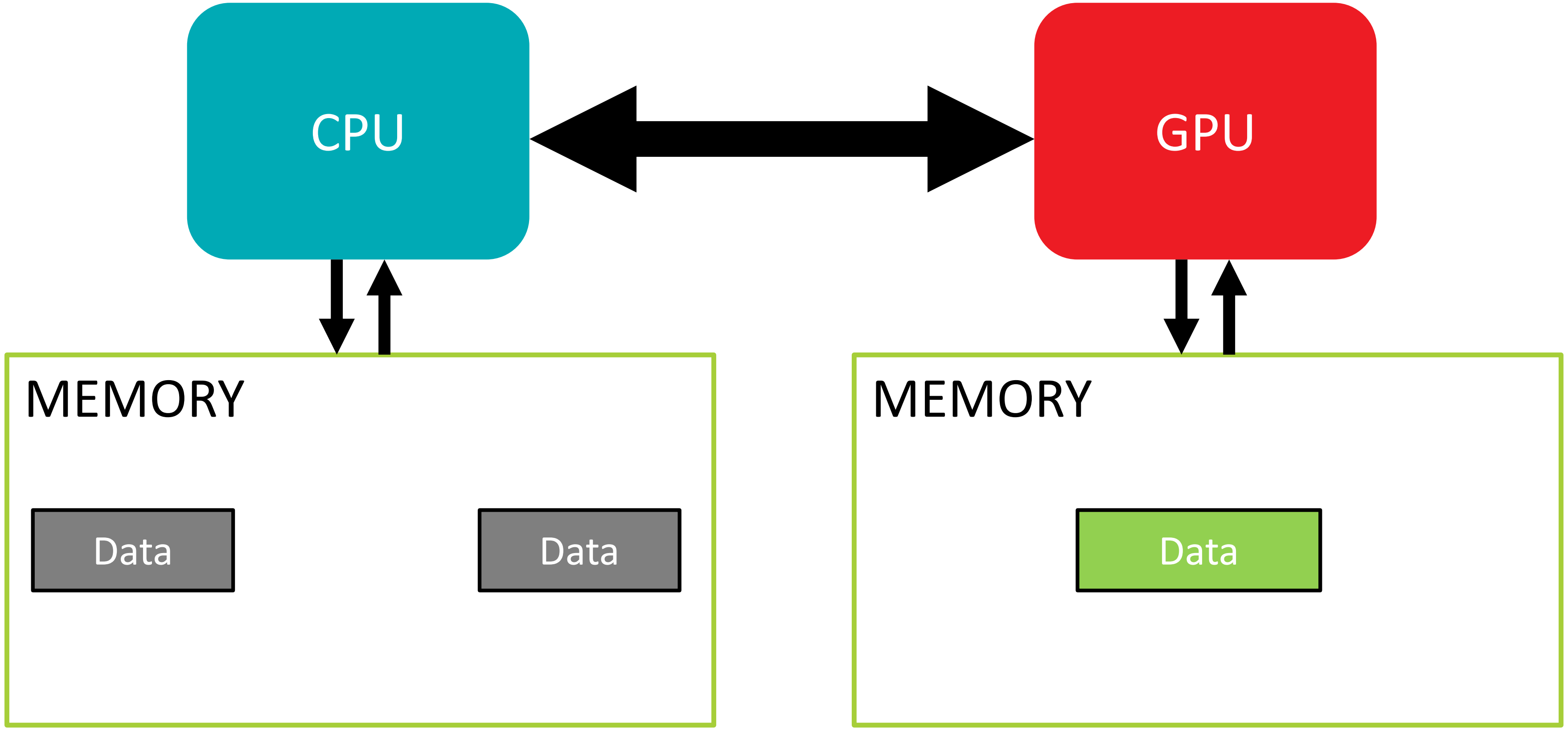
clARMOR: A DYNAMIC BUFFER OVERFLOW DETECTOR FOR OPENCL KERNELS

CHRIS ERB, JOE GREATHOUSE,
MAY 16, 2018

ANECDOTE

DISCOVERING A BUFFER OVERFLOW



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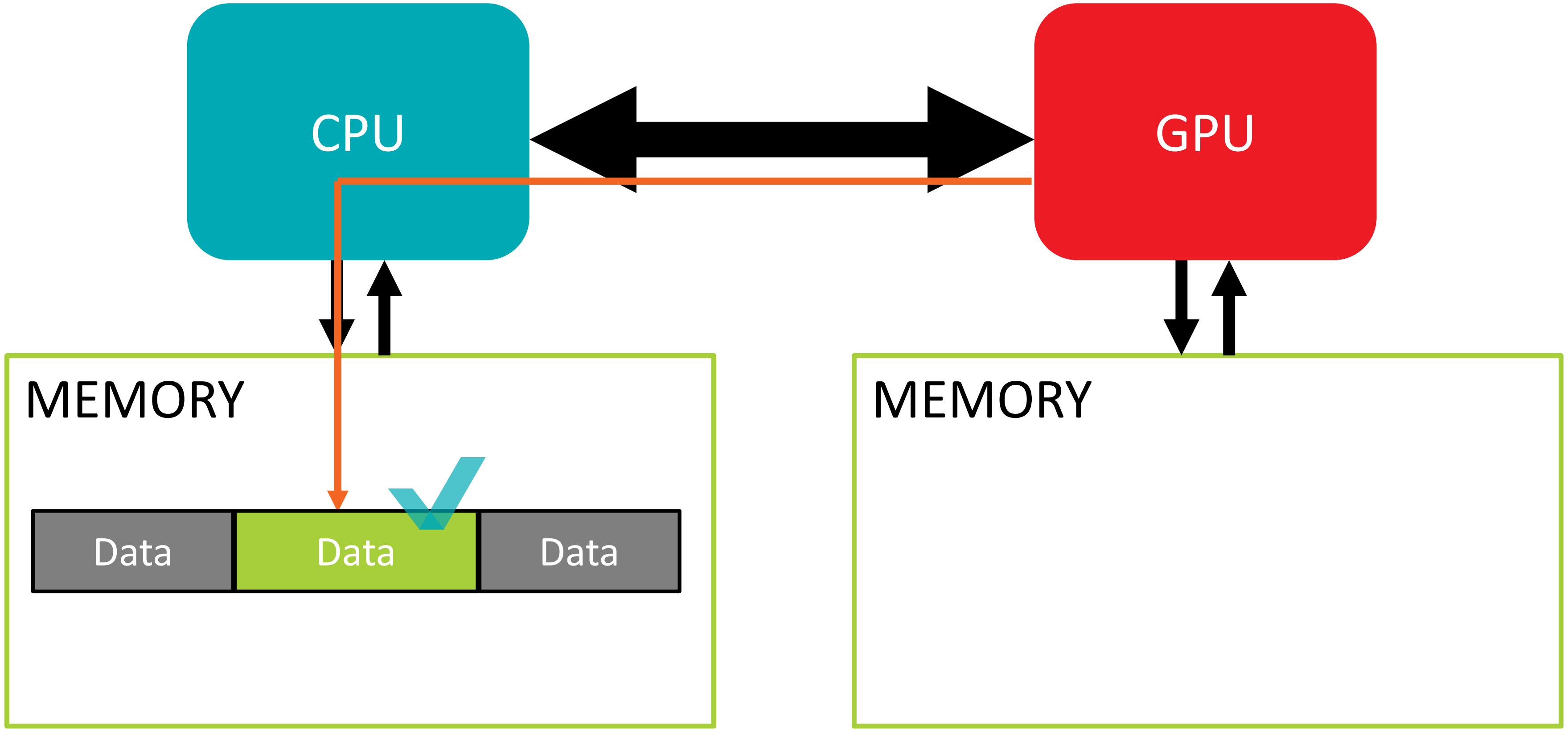

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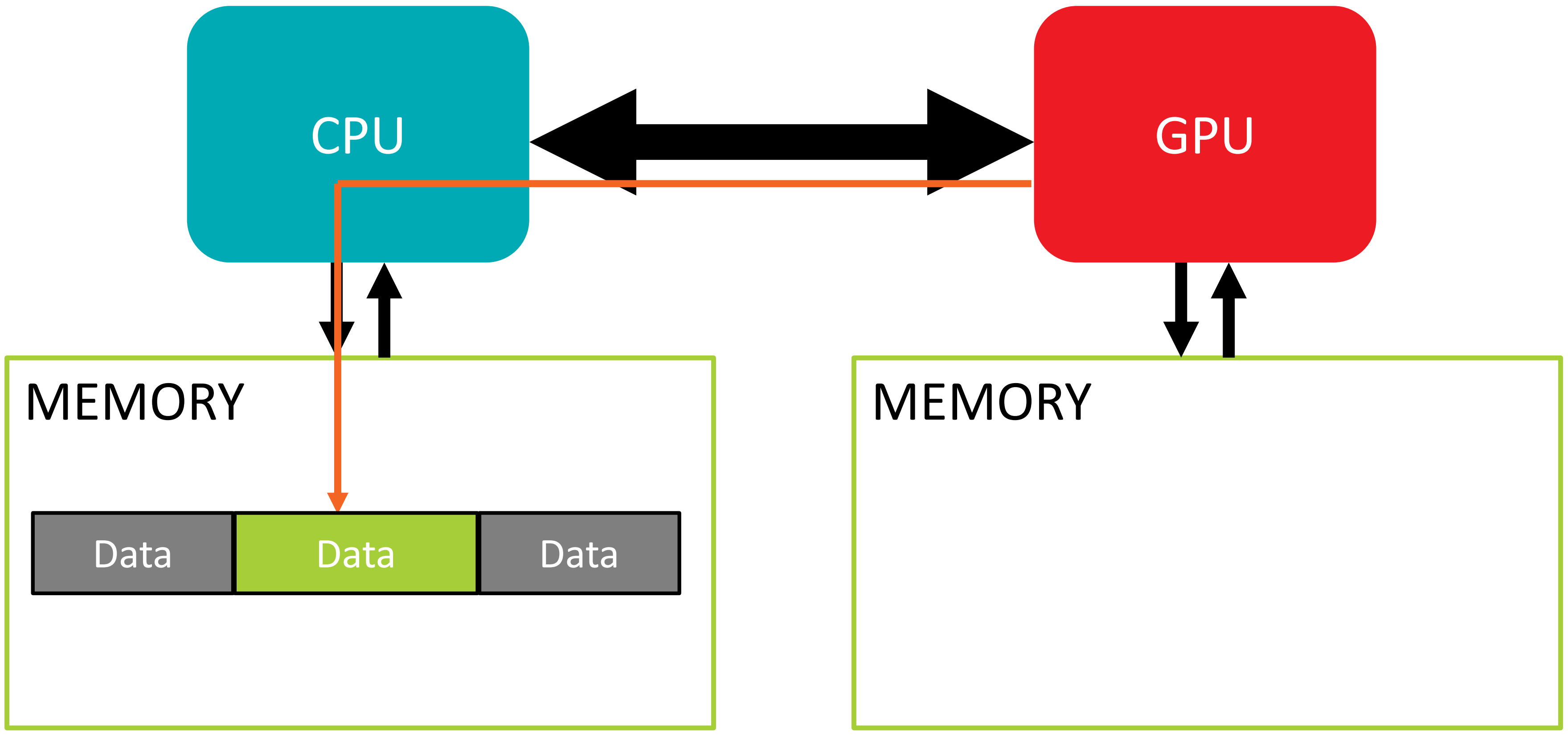

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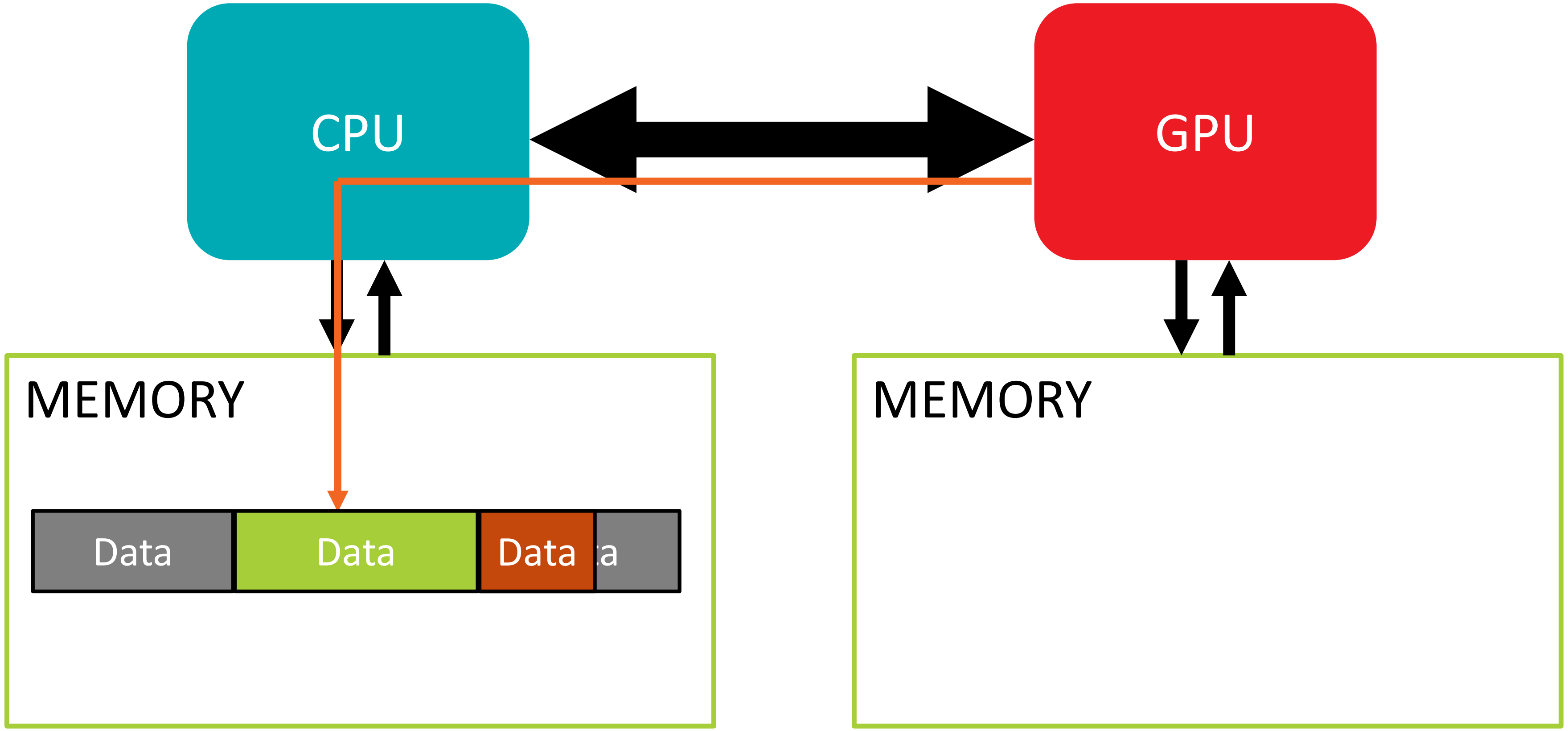

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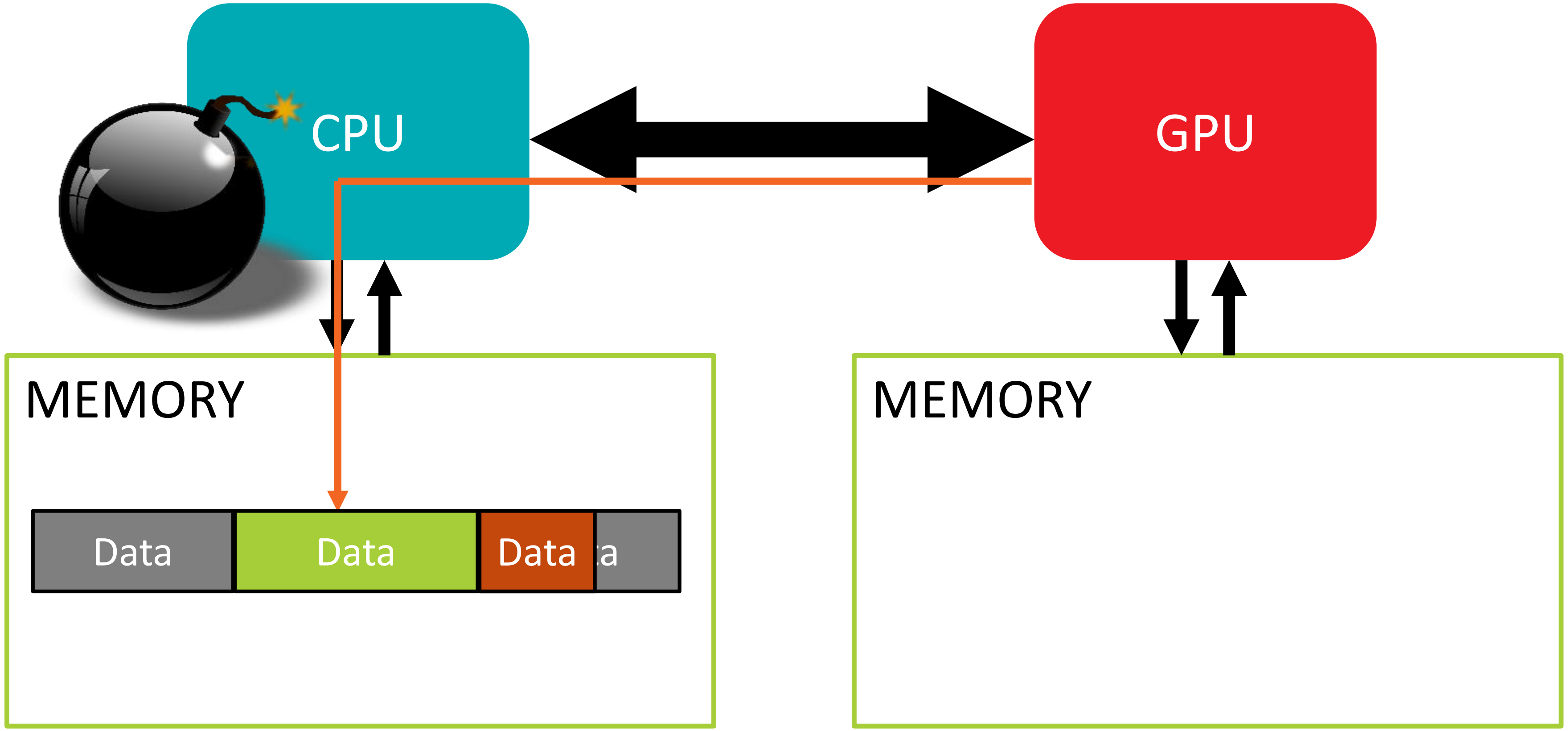

BACKGROUND: NORMAL BUFFER FILL

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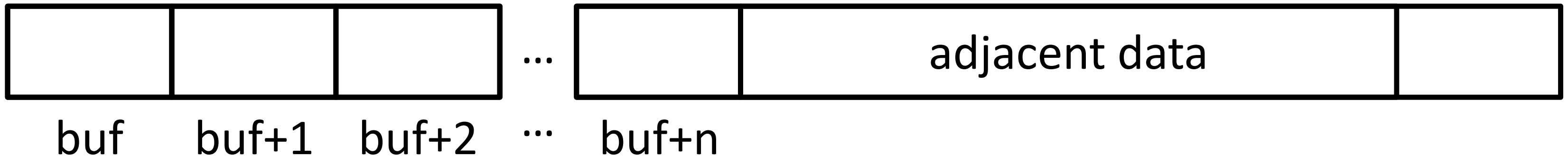

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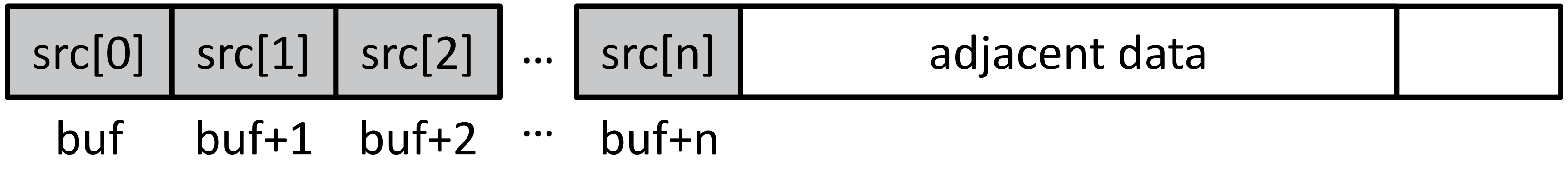

BACKGROUND: BUFFER OVERFLOW

- buf[n+1]
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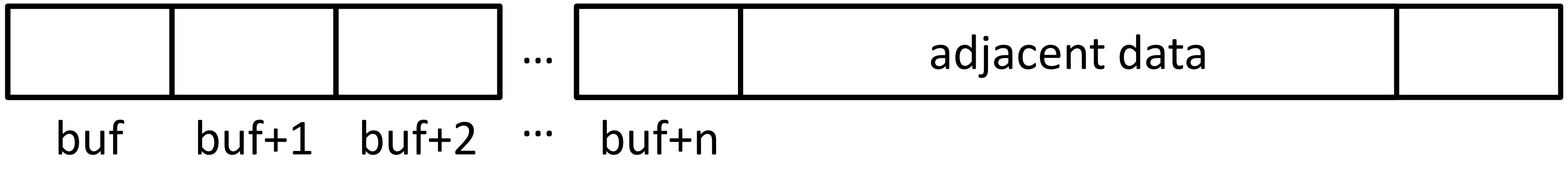

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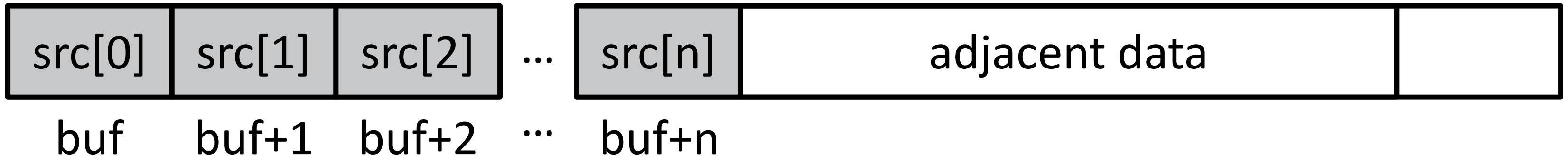

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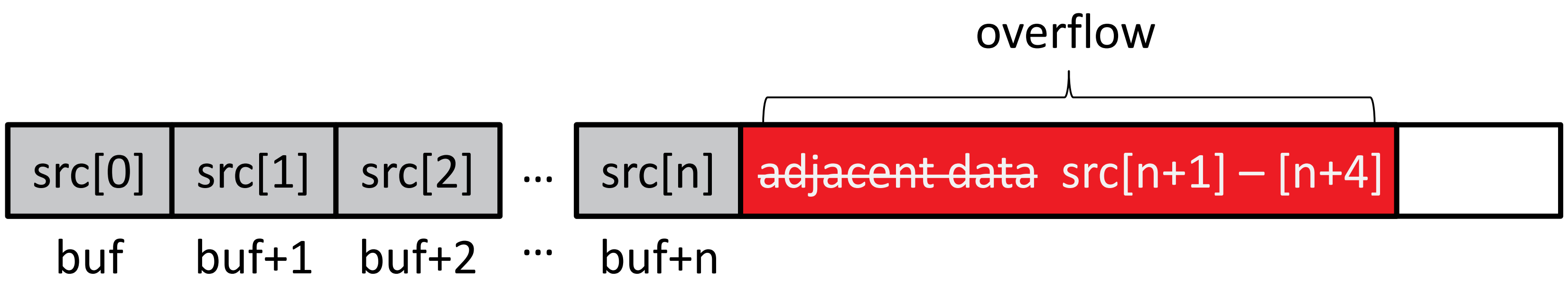
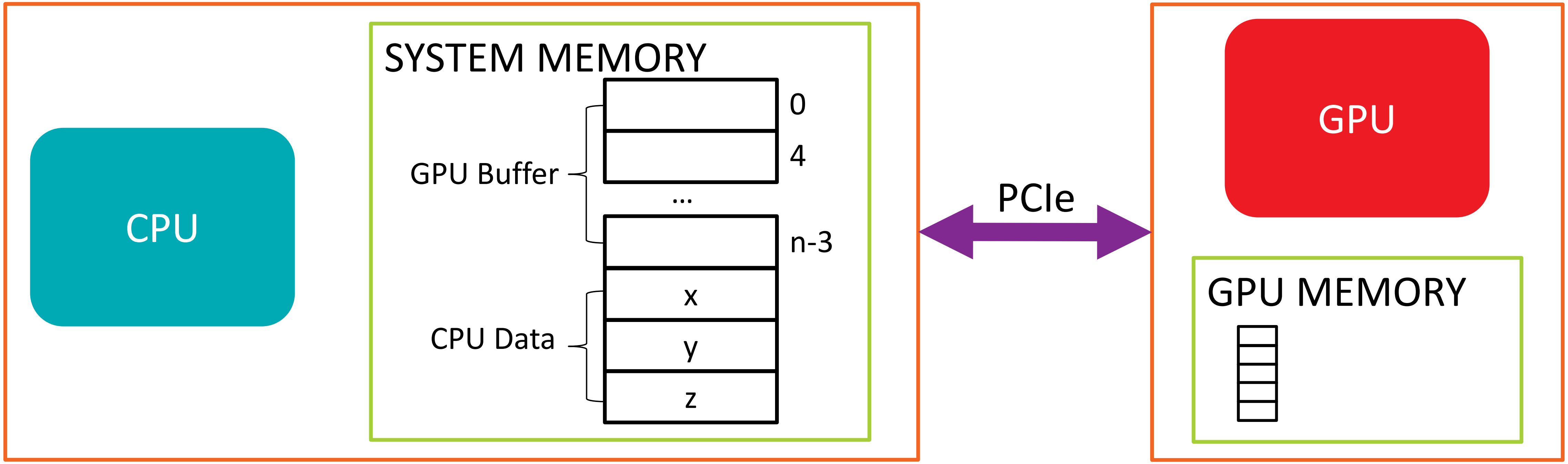


GPU INDUCED OVERFLOW

SHARED MEMORY CORRUPTION

- GPU can overflow buffers in system memory
  - Over Interconnects like PCIe®



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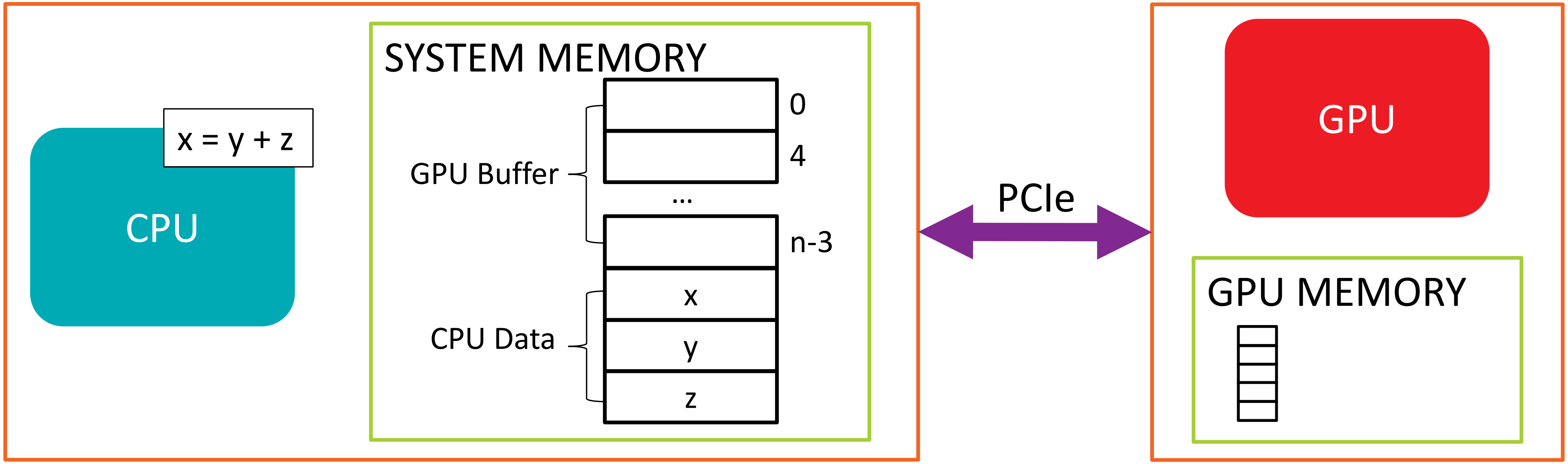

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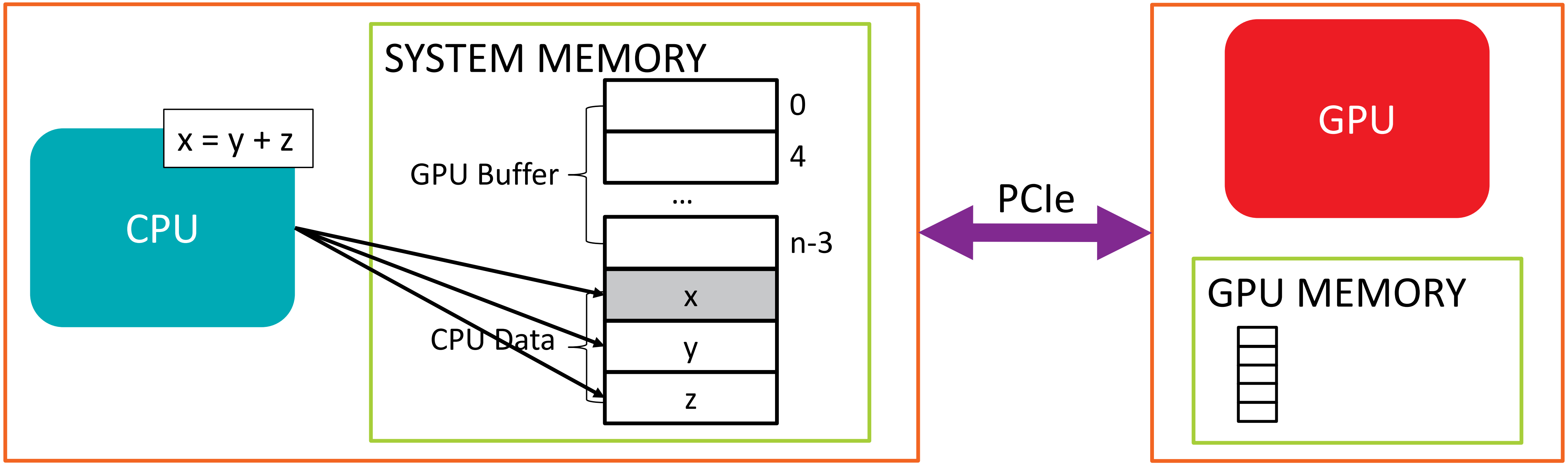

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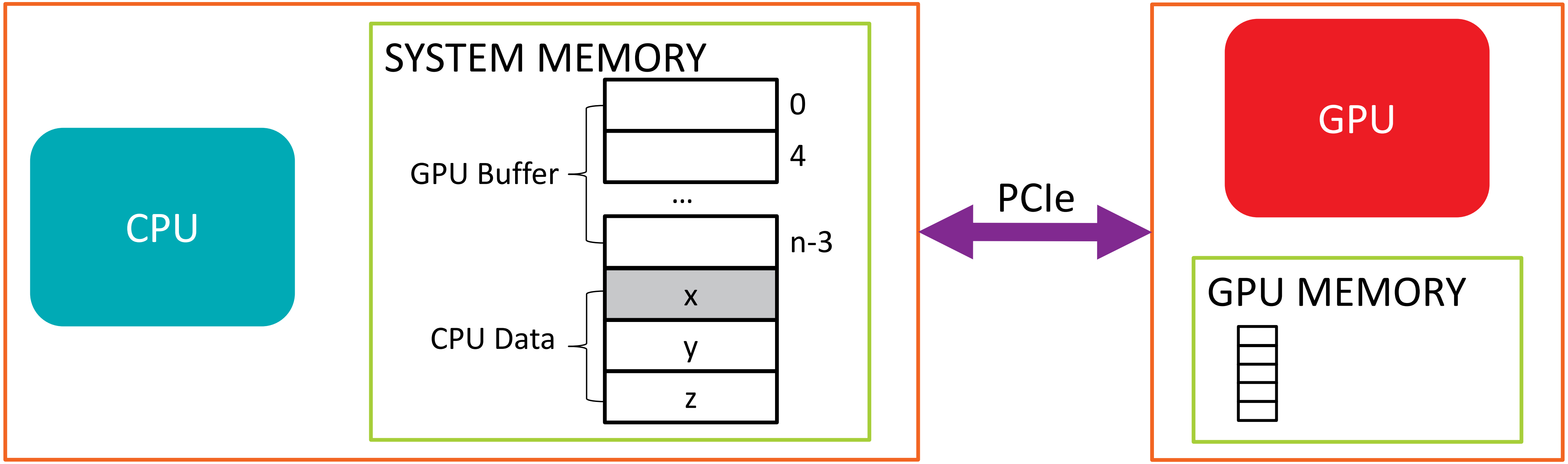

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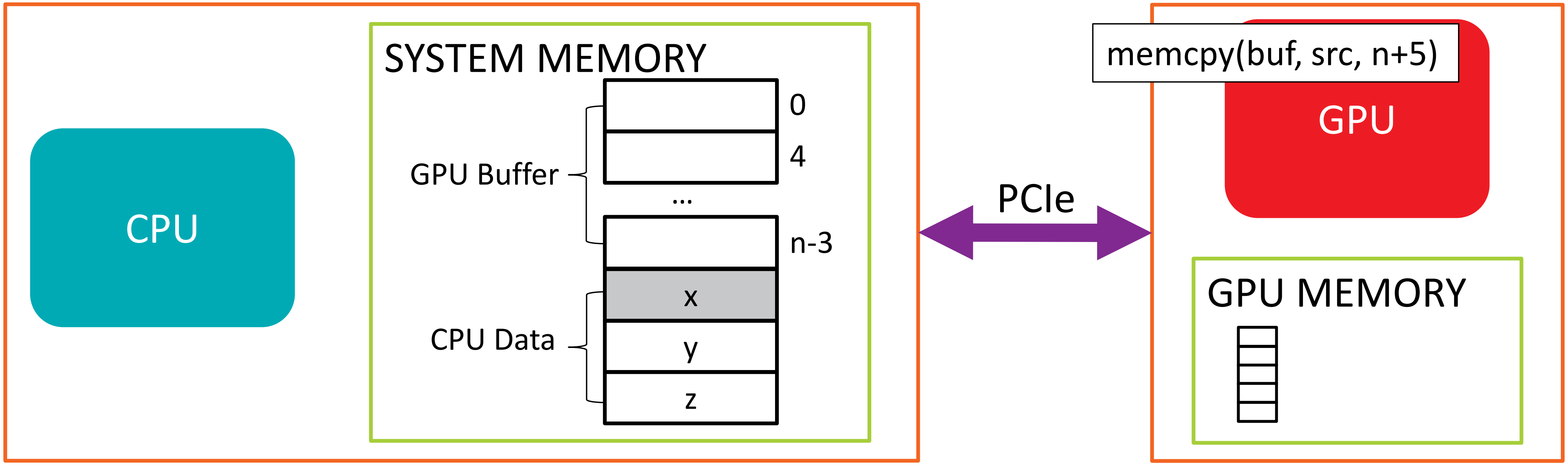

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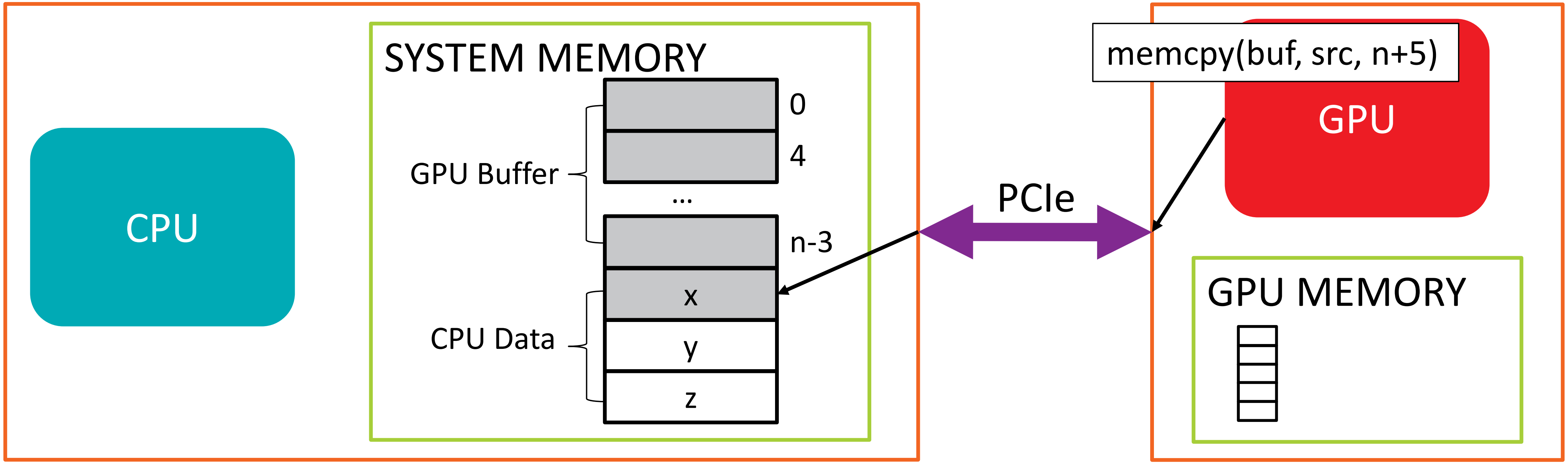

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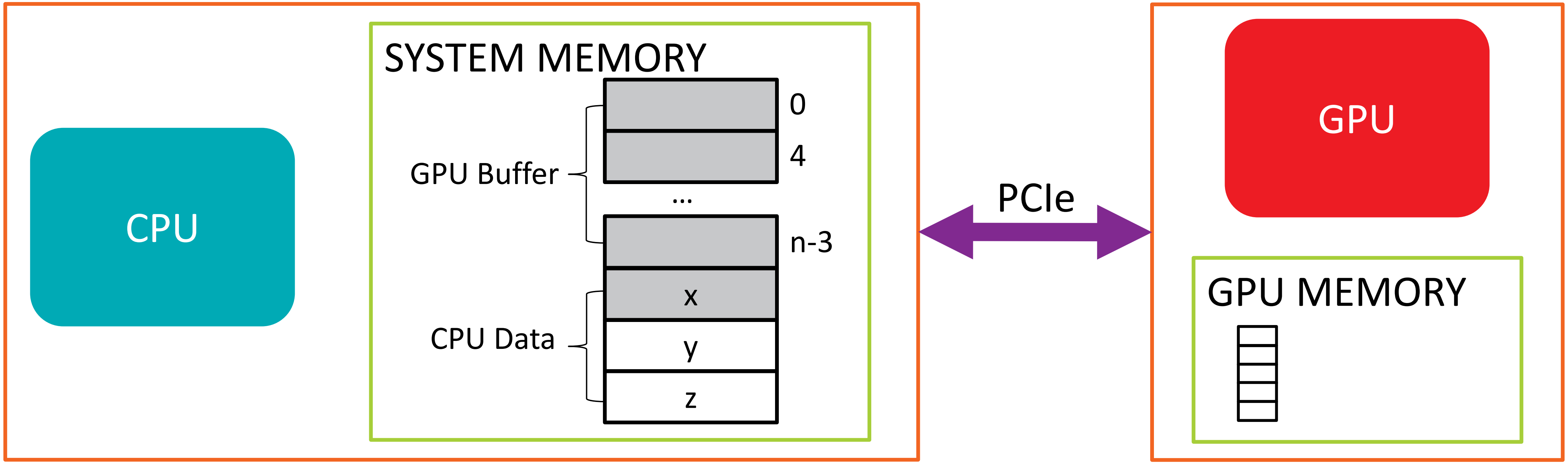

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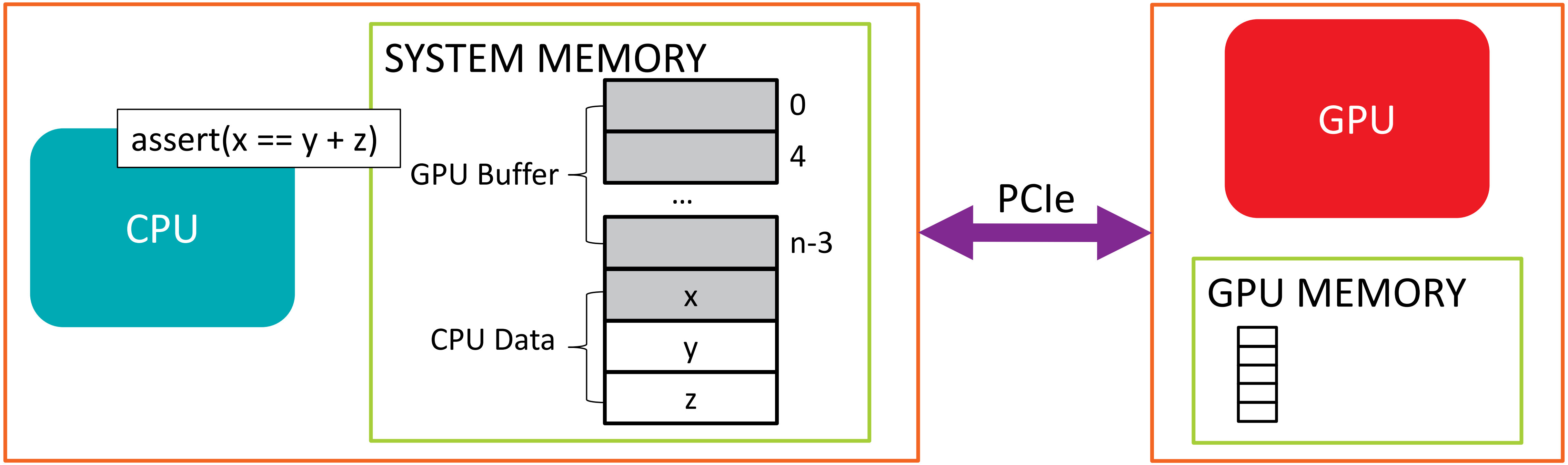

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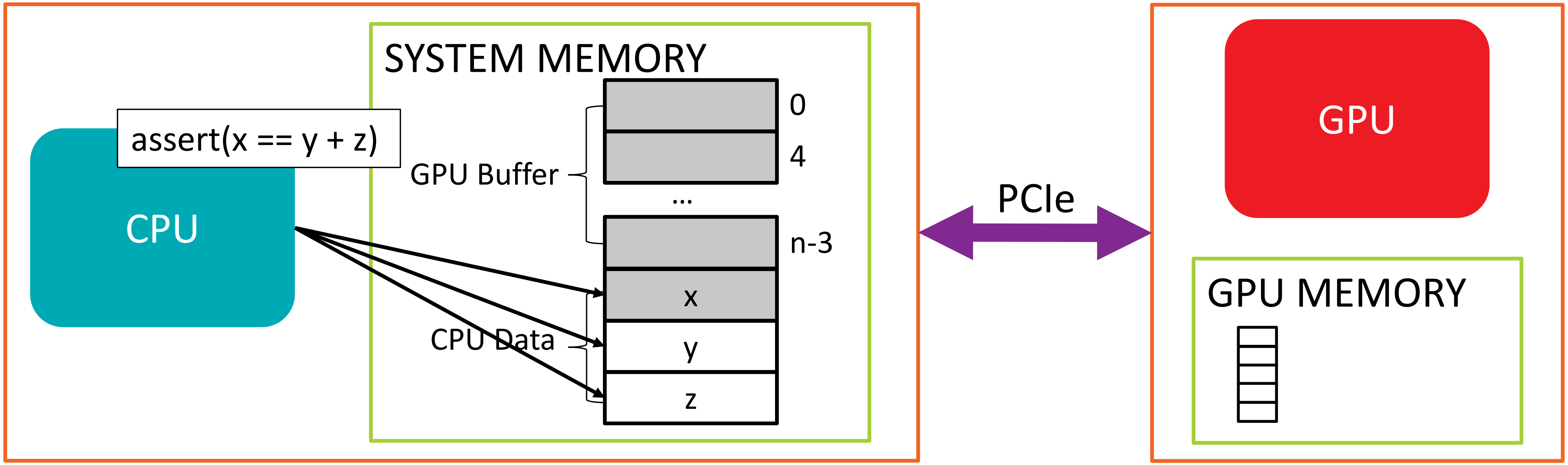

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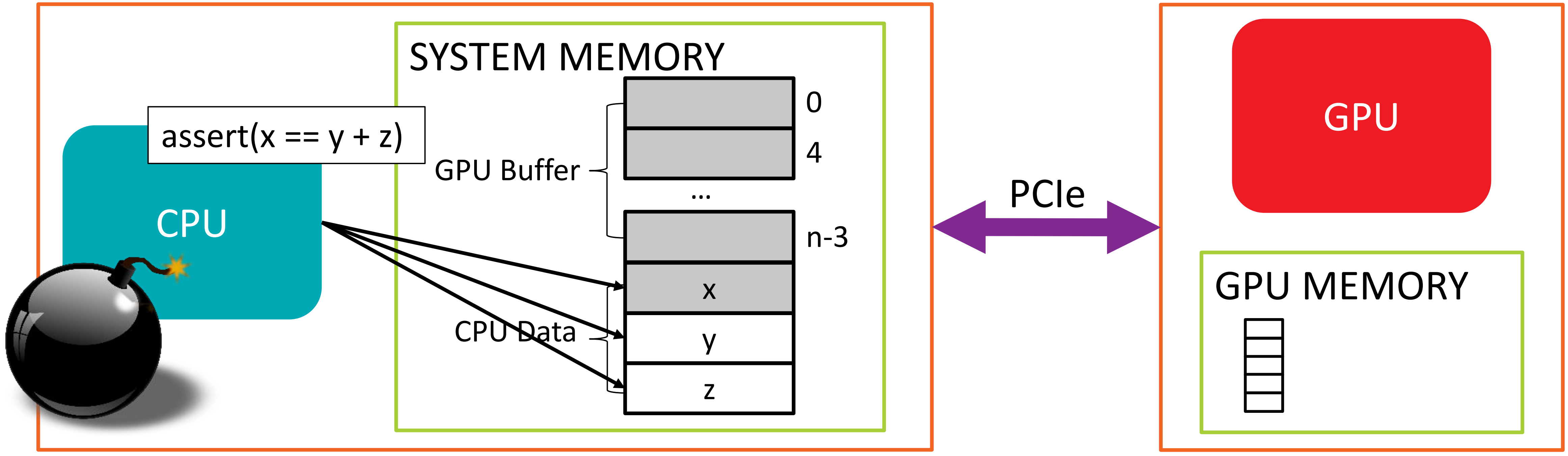

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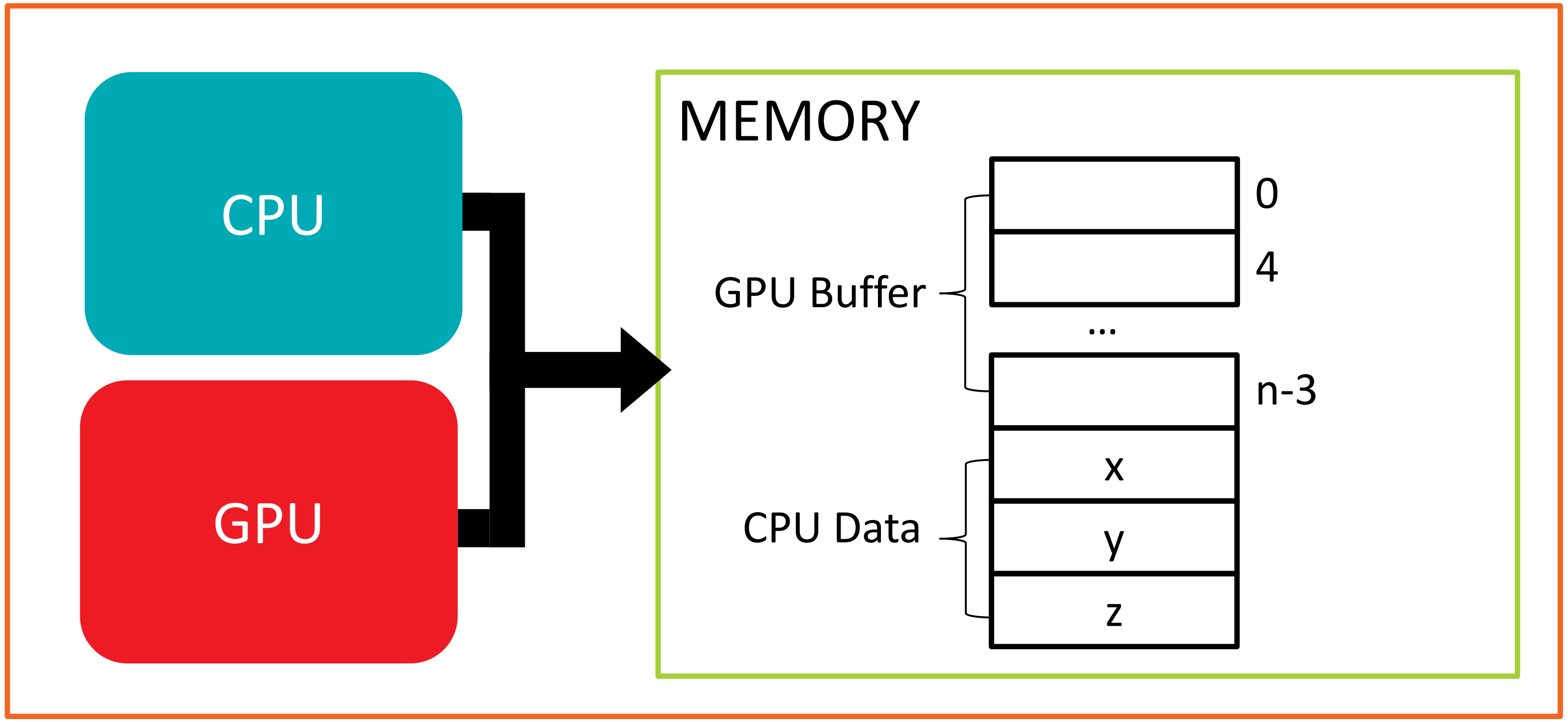
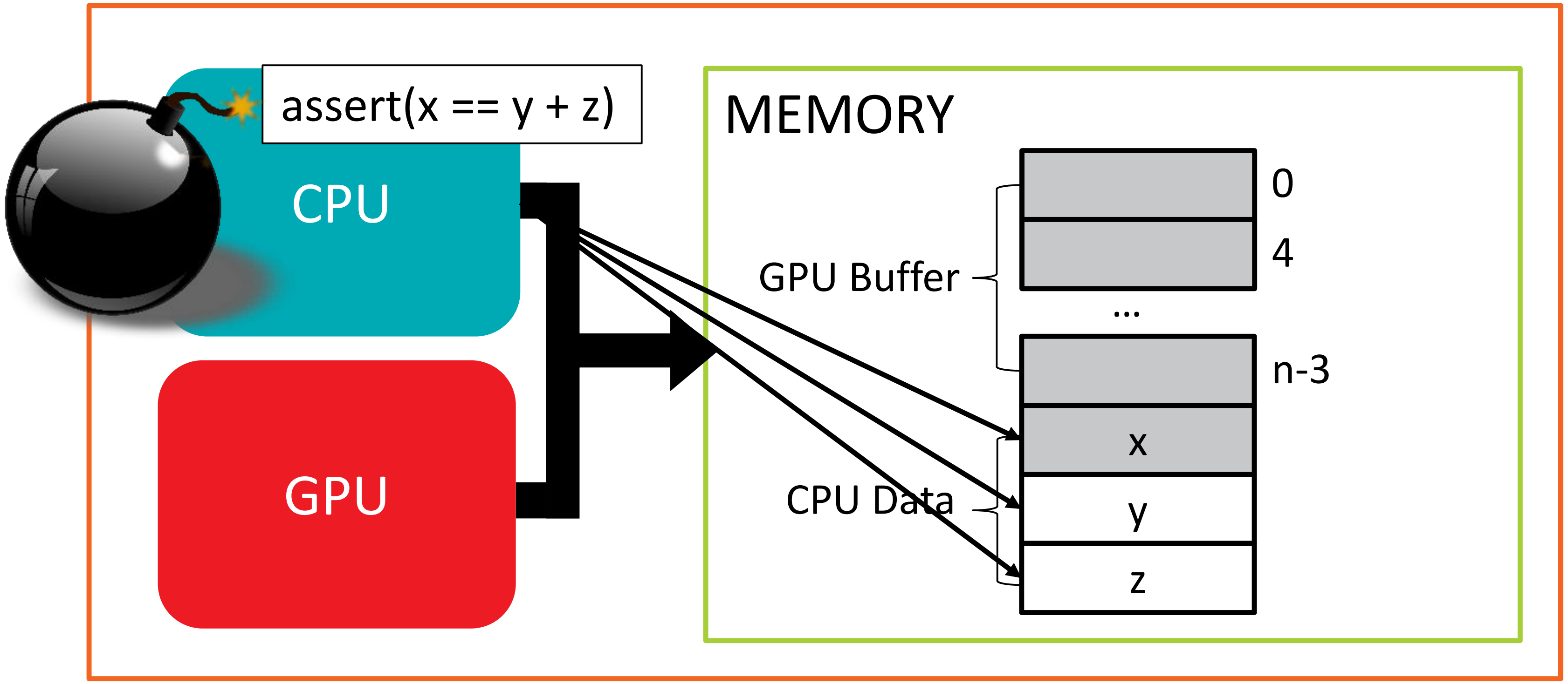


GPU INDUCED OVERFLOW

SHARED MEMORY CORRUPTION

- CPU and GPU as part of the same package
  - Every GPU buffer overflow may affect CPU data



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REMOTE CODE EXECUTION

- Overflows on GPU can cause remote GPU code execution
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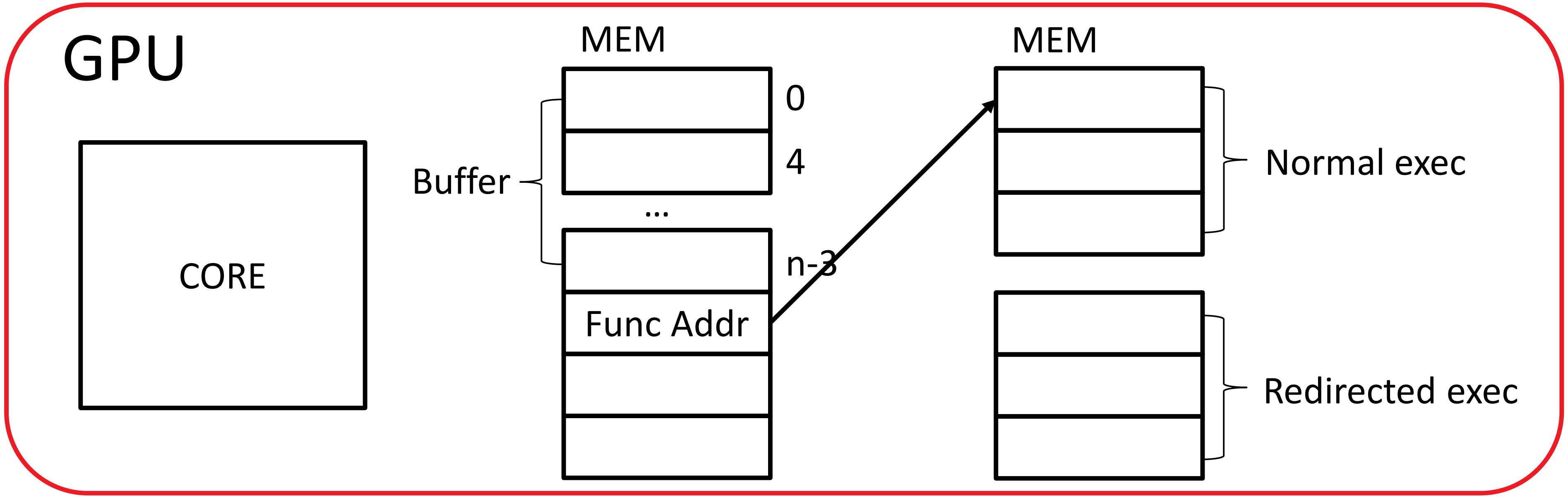

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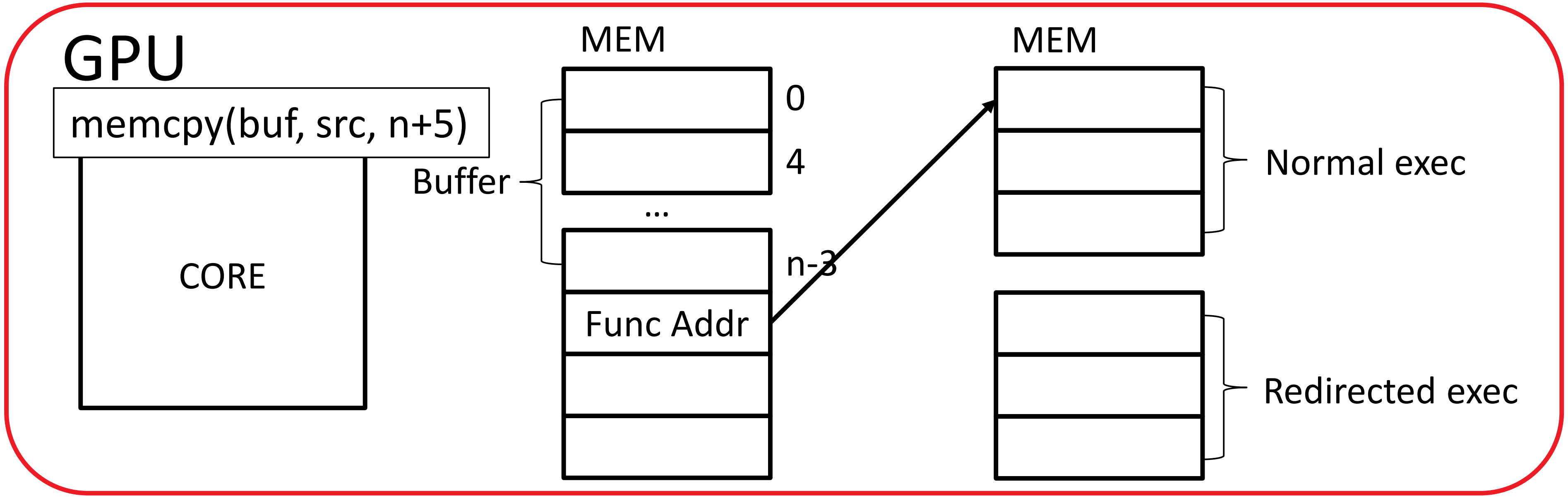

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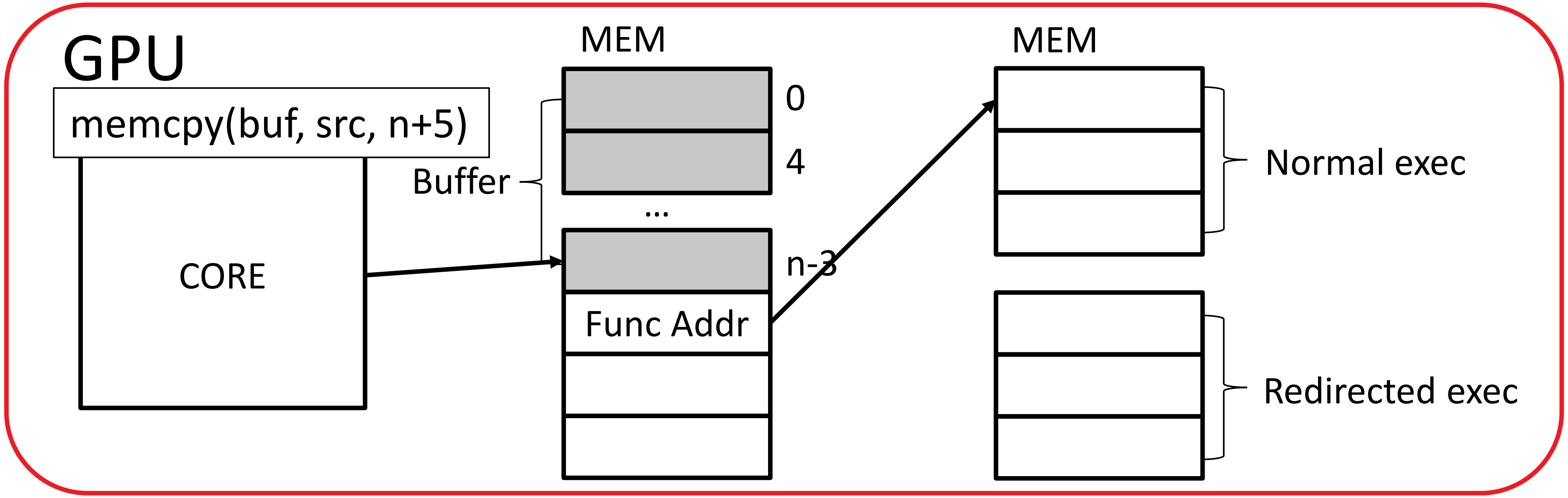

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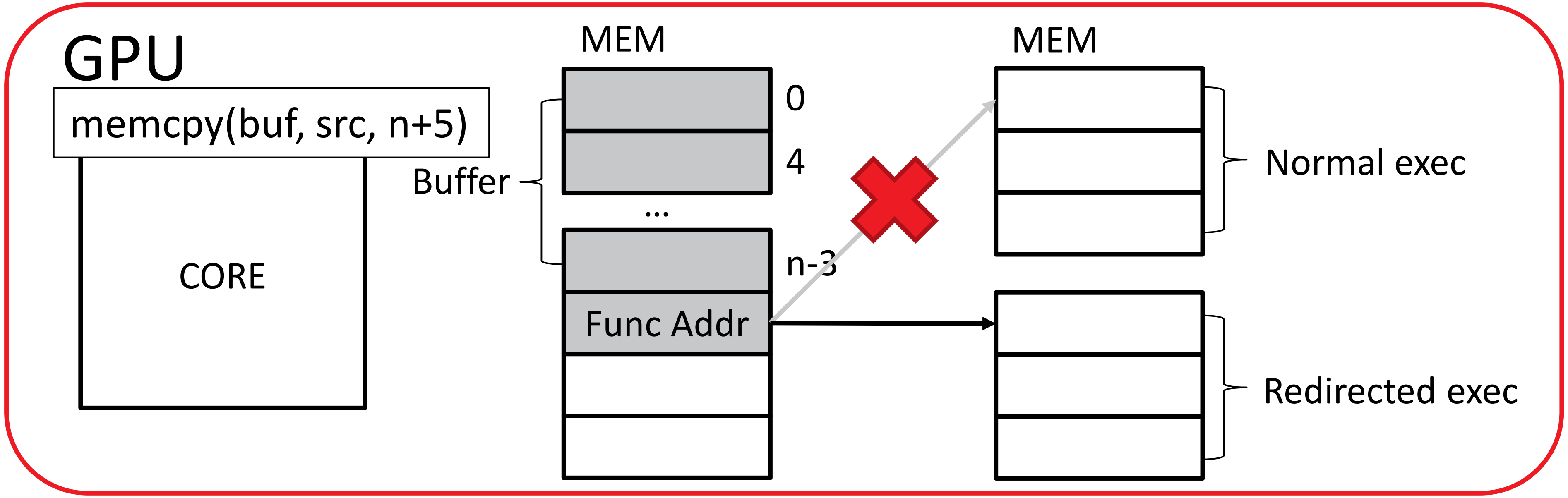

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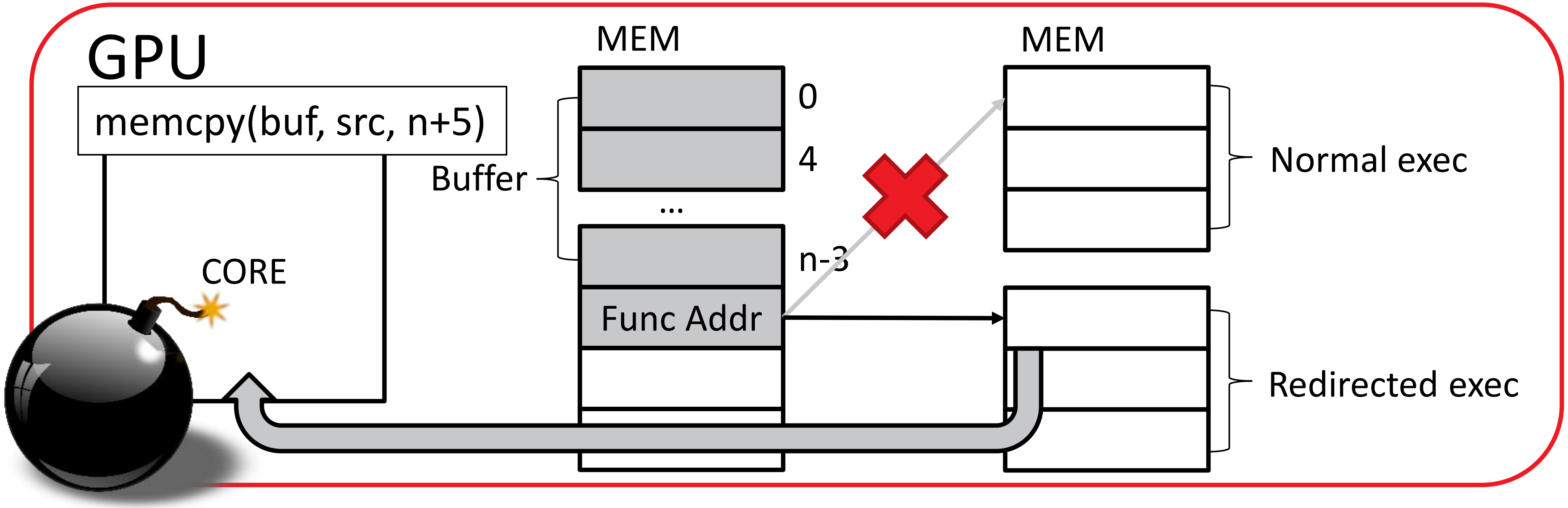

GOALS

clARMOR: AMD Research Memory Overflow Reporter for OpenCL

- Software tool to detect buffer overflows caused by GPU

- Runnable with most OpenCL™ applications

- Low runtime overhead

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BUFFER OVERFLOW DETECTION METHODOLOGY

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

	src[1]	src[2]	…	src[n]	canary	adjacent data
buf	buf+1	buf+2	…	buf+n		

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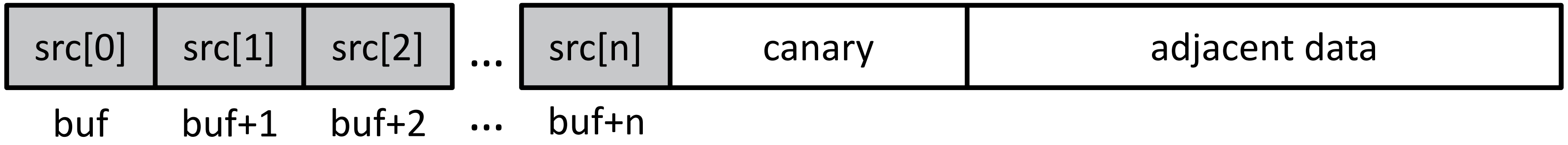

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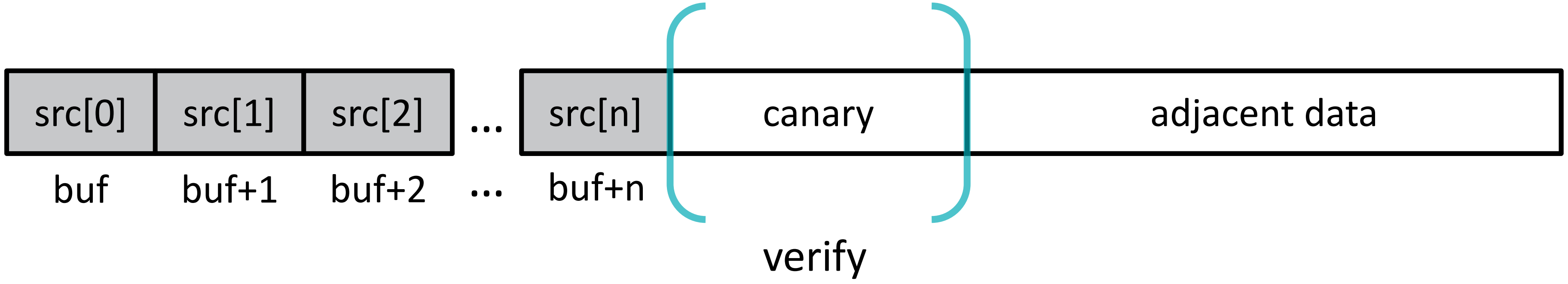

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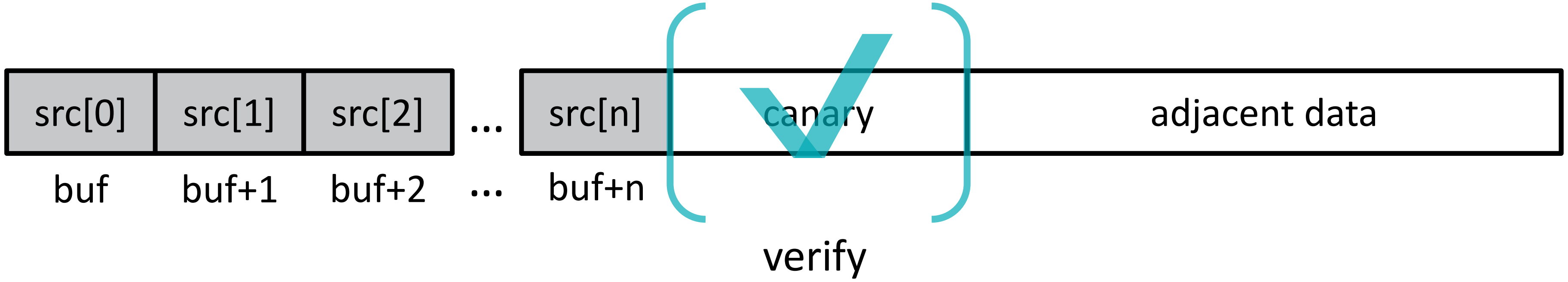

BUFFER OVERFLOW DETECTION METHODOLOGY

CANARY-BASED DETECTION

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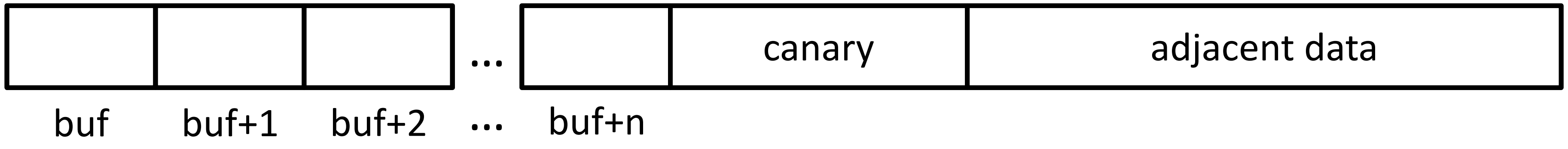

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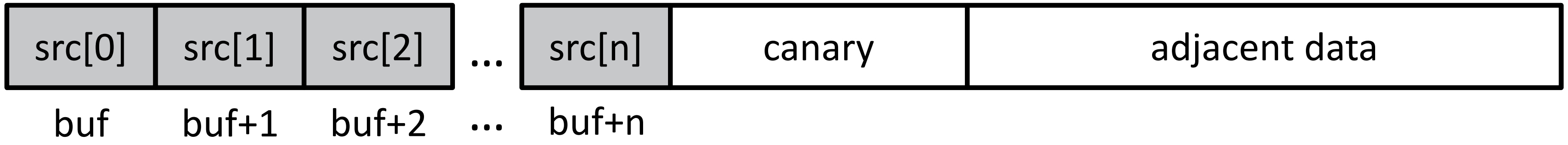

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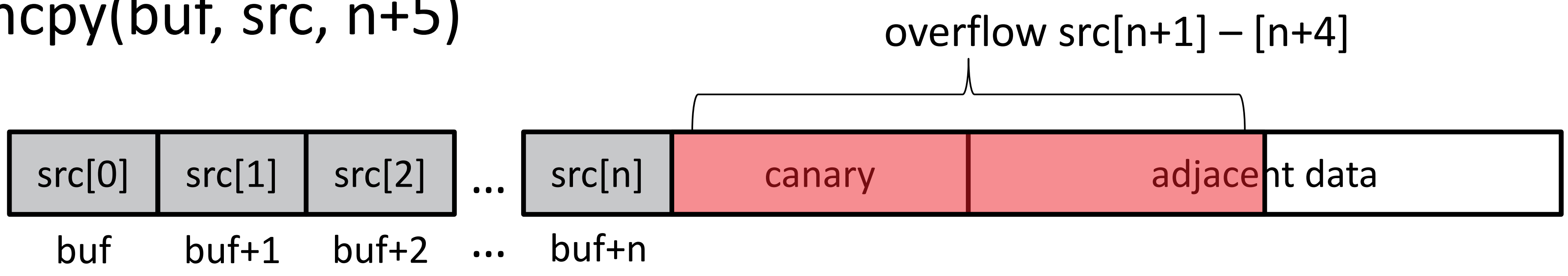

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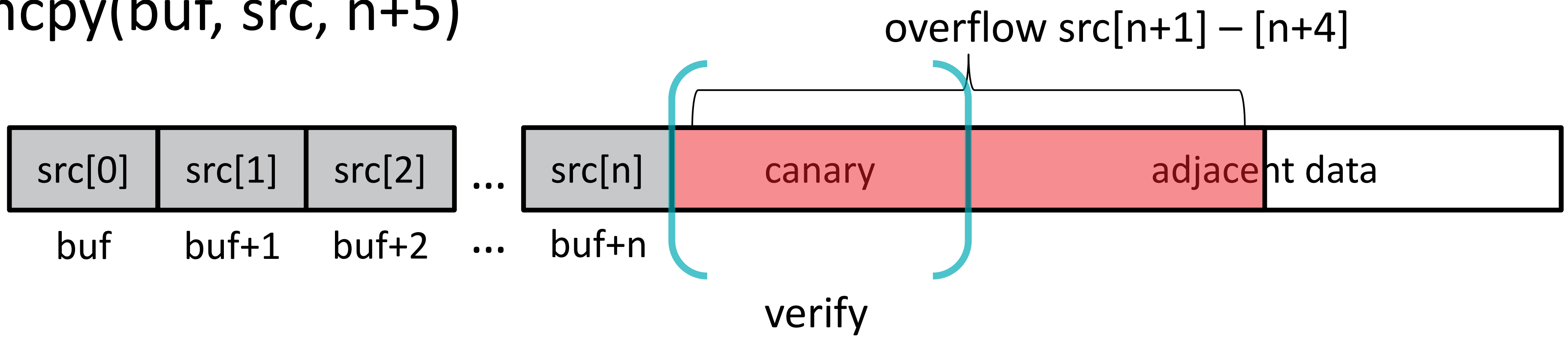

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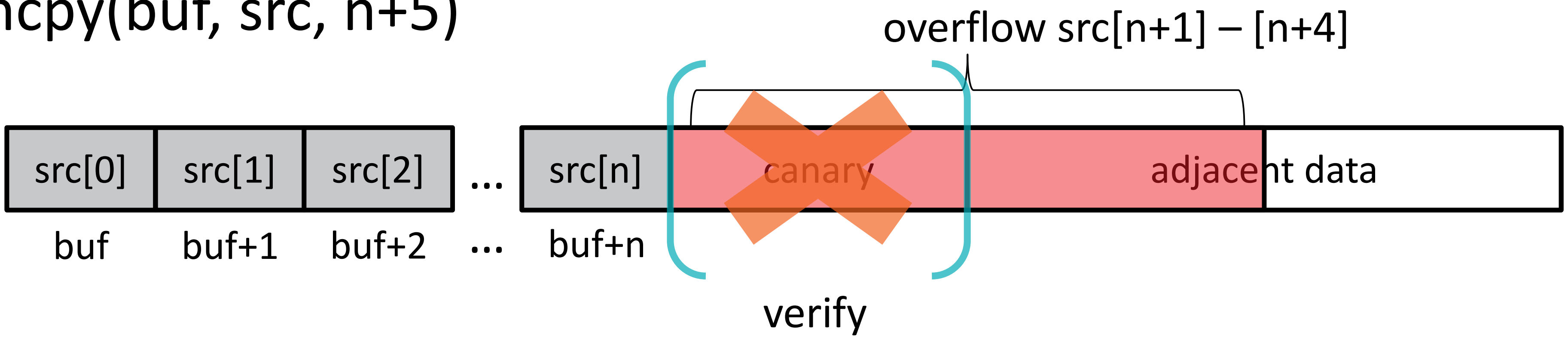

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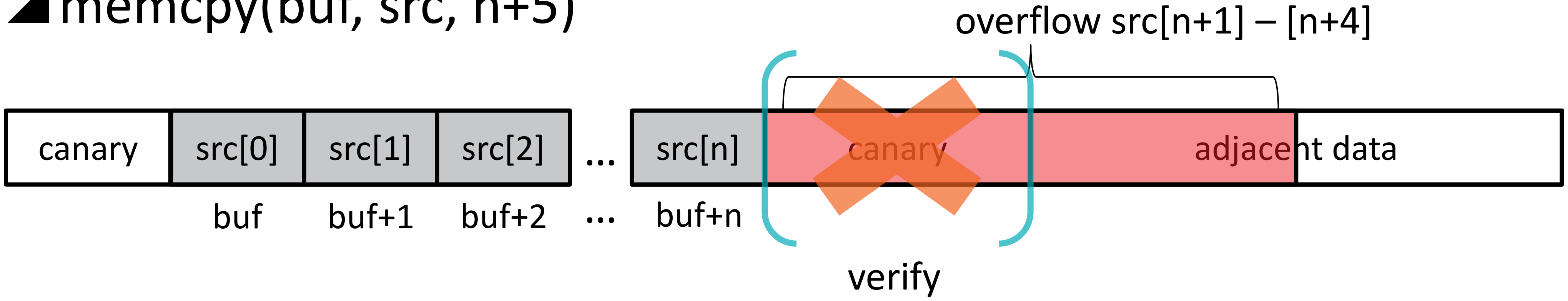

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- Can find underflow as well!

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LAUNCHING AN OPENCL™ KERNEL

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Buffer Create

Buffer

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Set Arguments

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Launch Kernel

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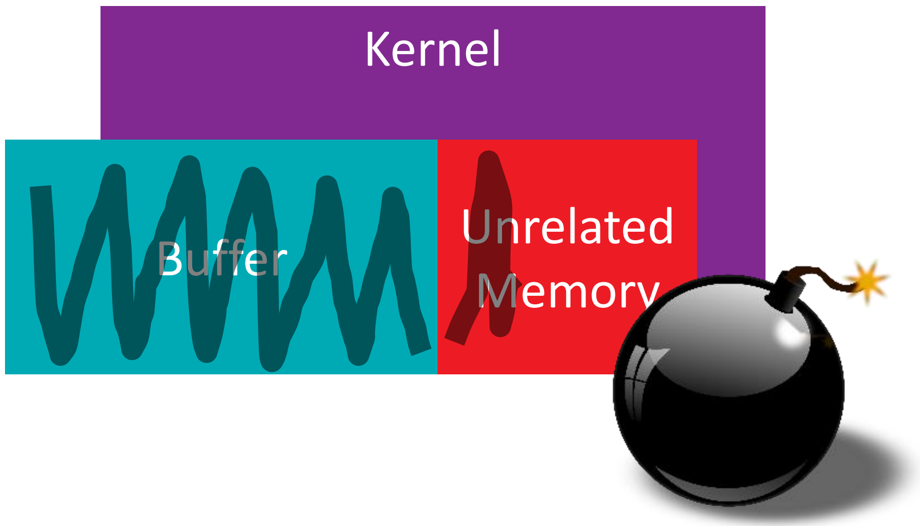

LAUNCHING AN OPENCL™ KERNEL WITH clARMOR

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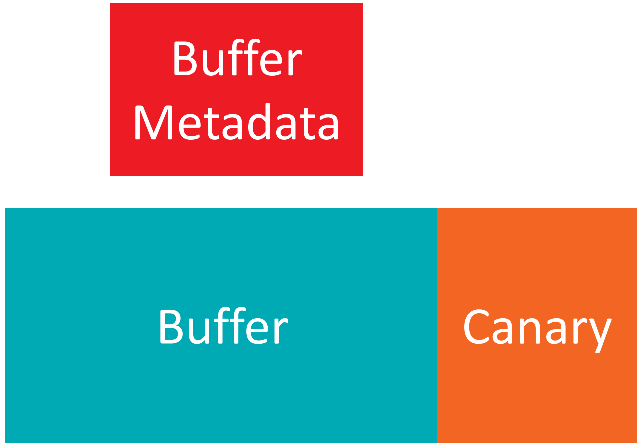

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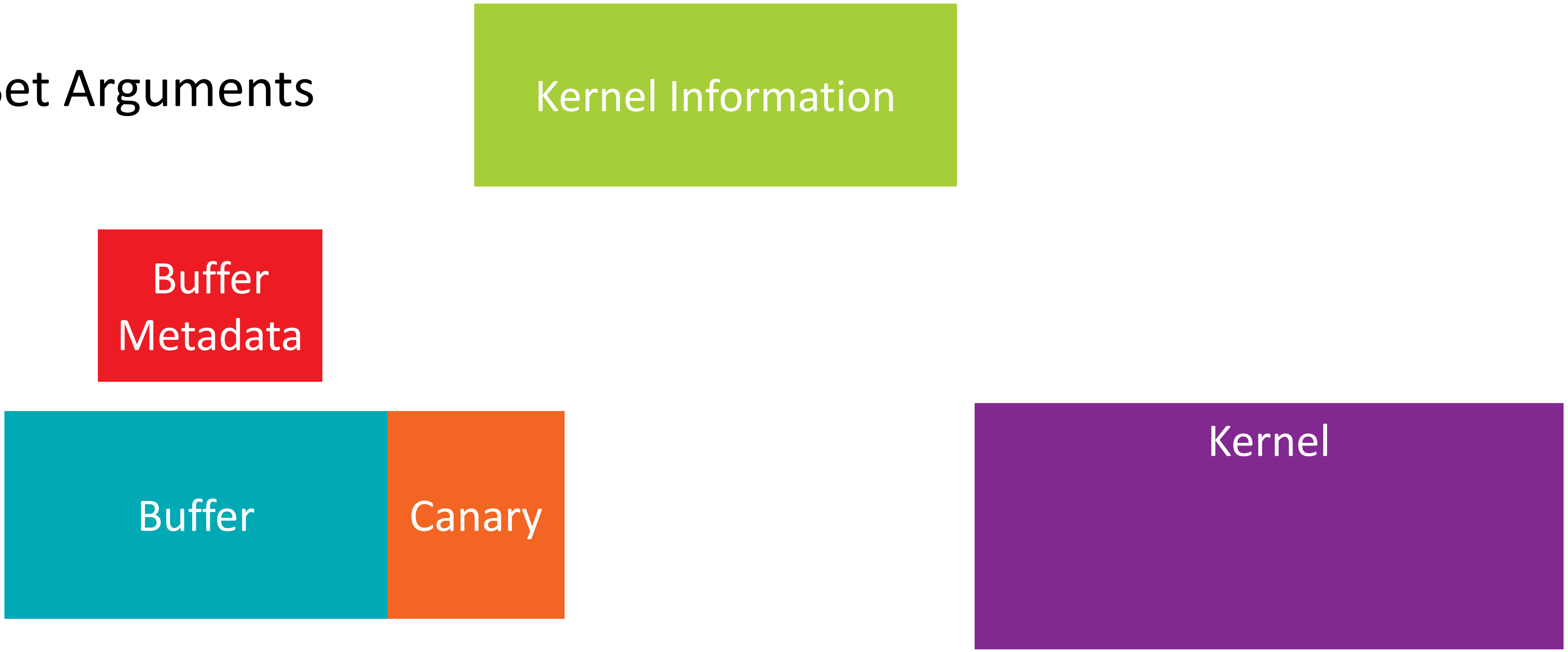

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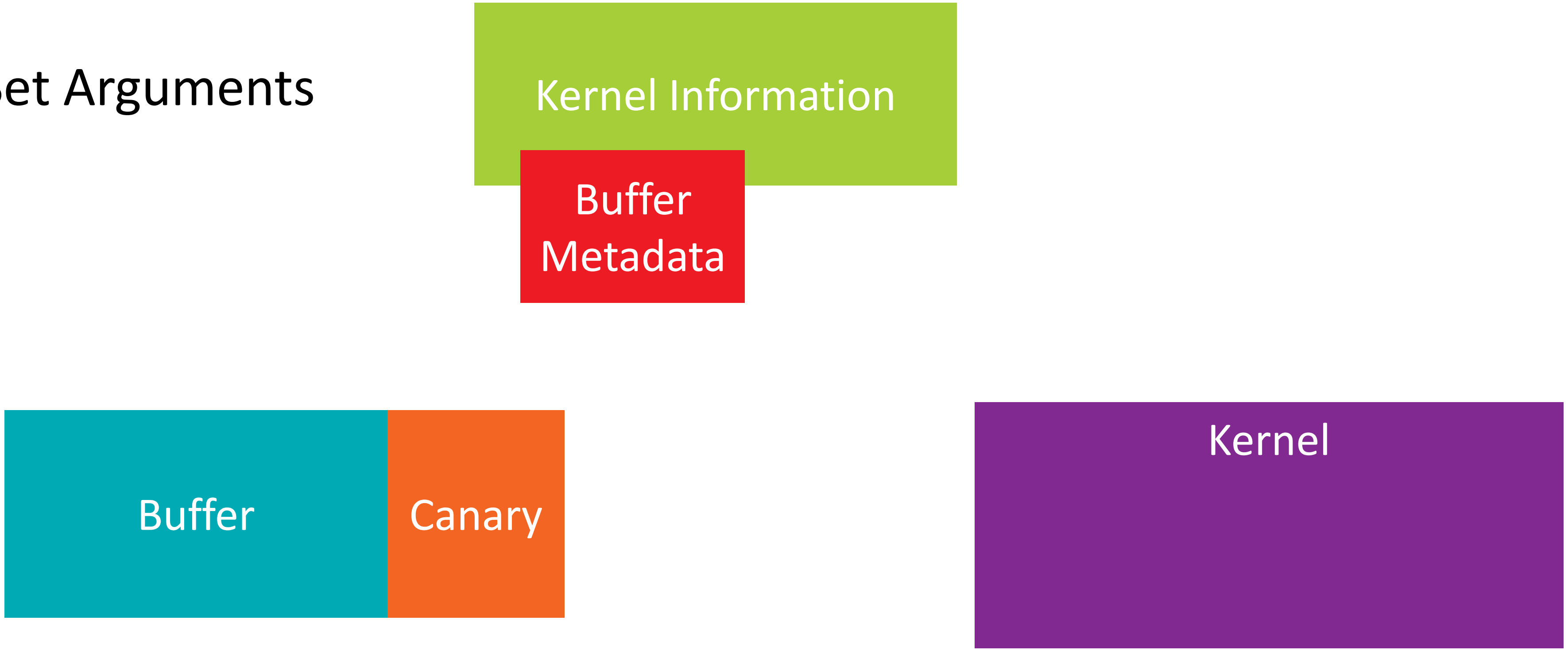

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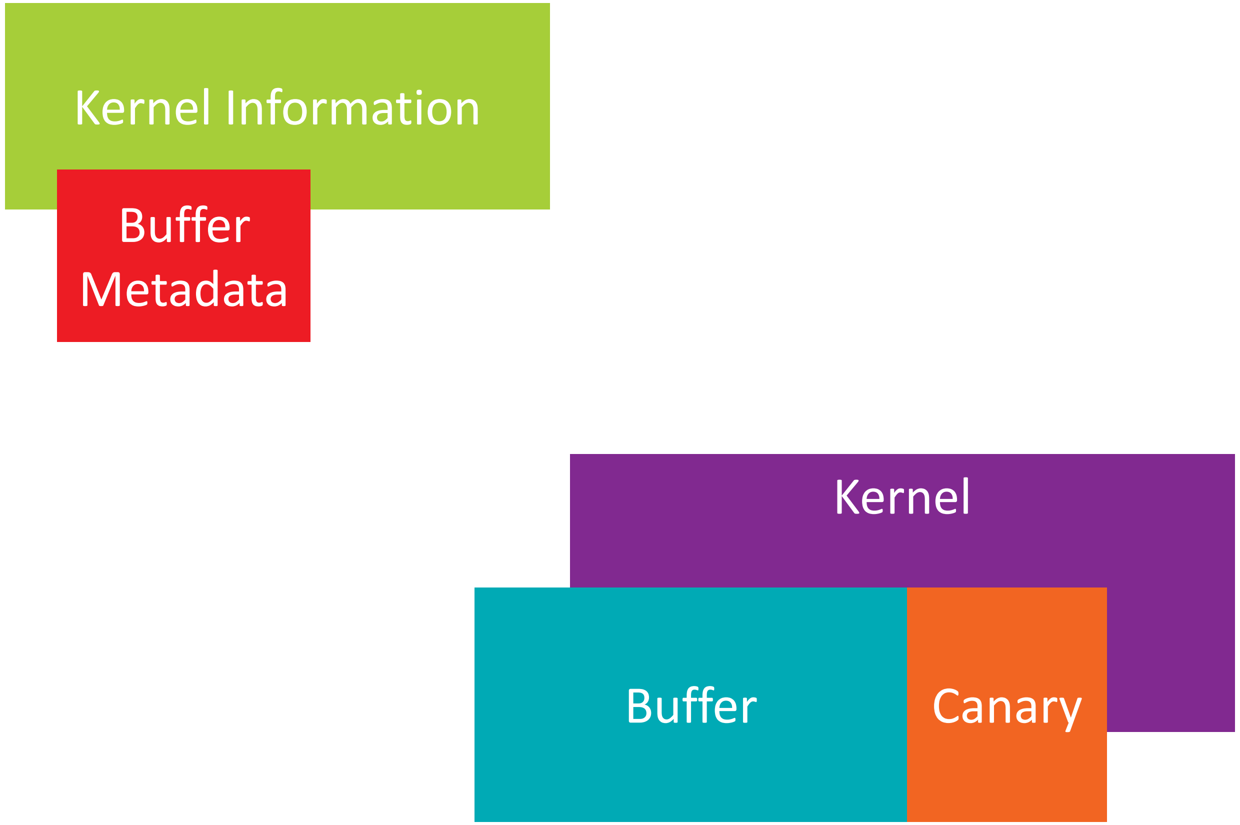

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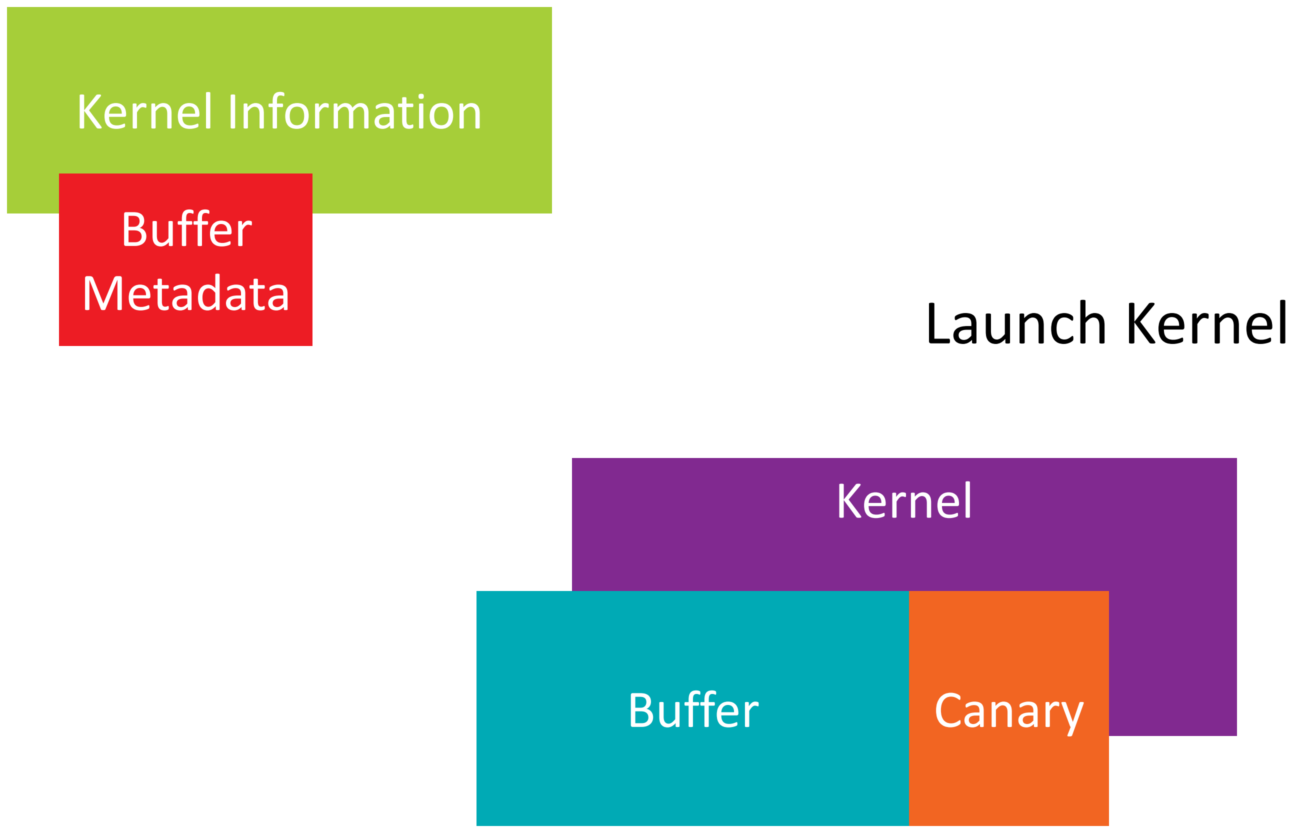

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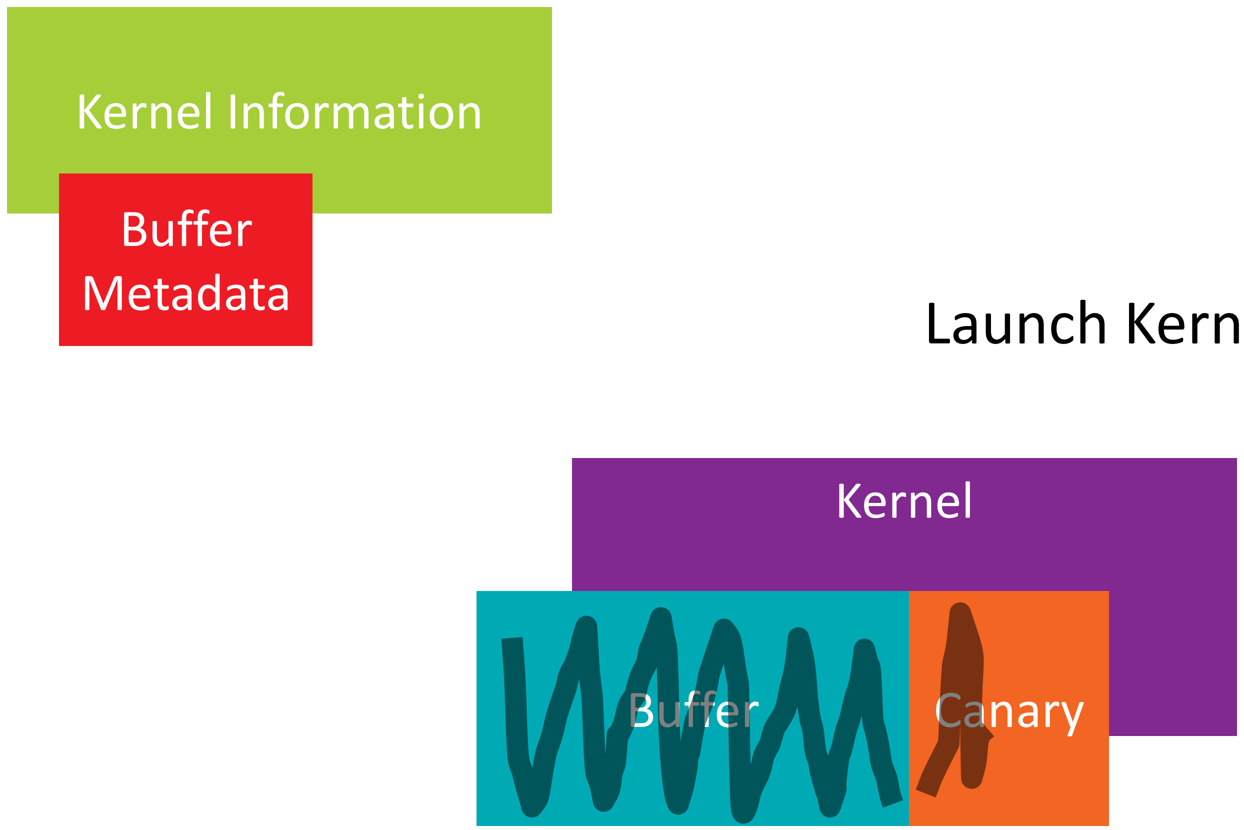

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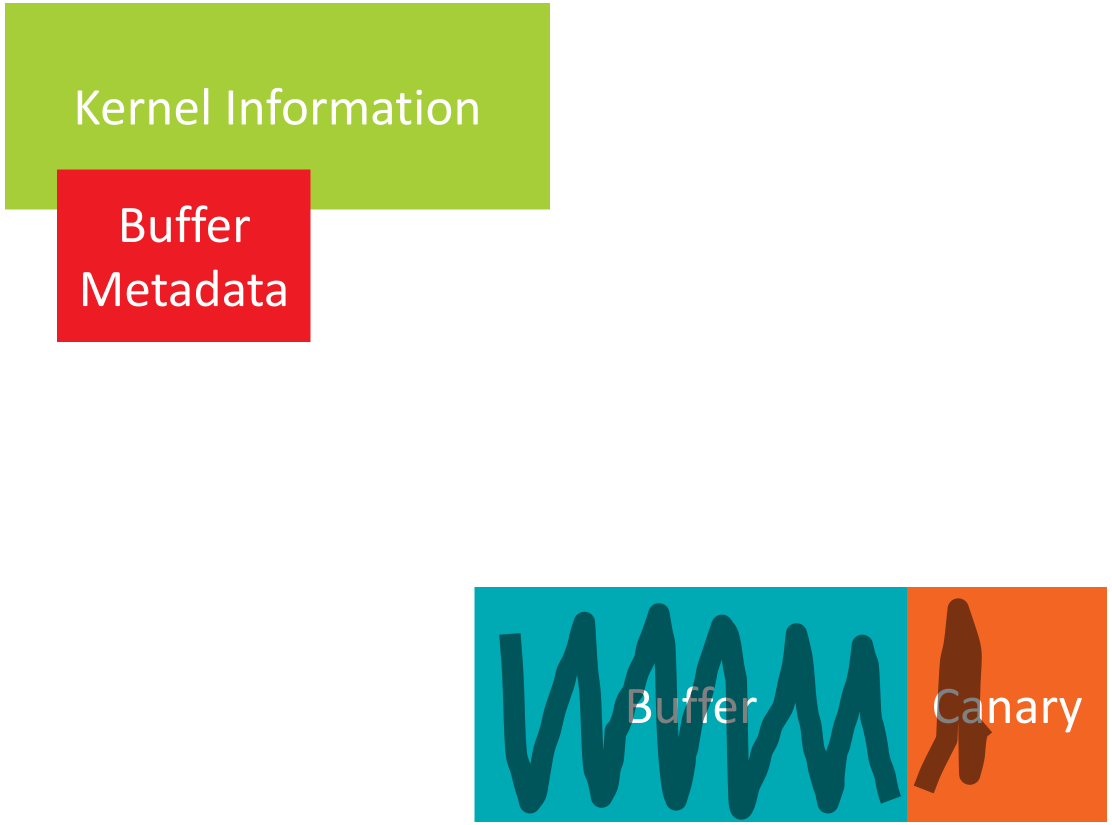

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Kernel Information

Buffer Metadata

Canary Verification

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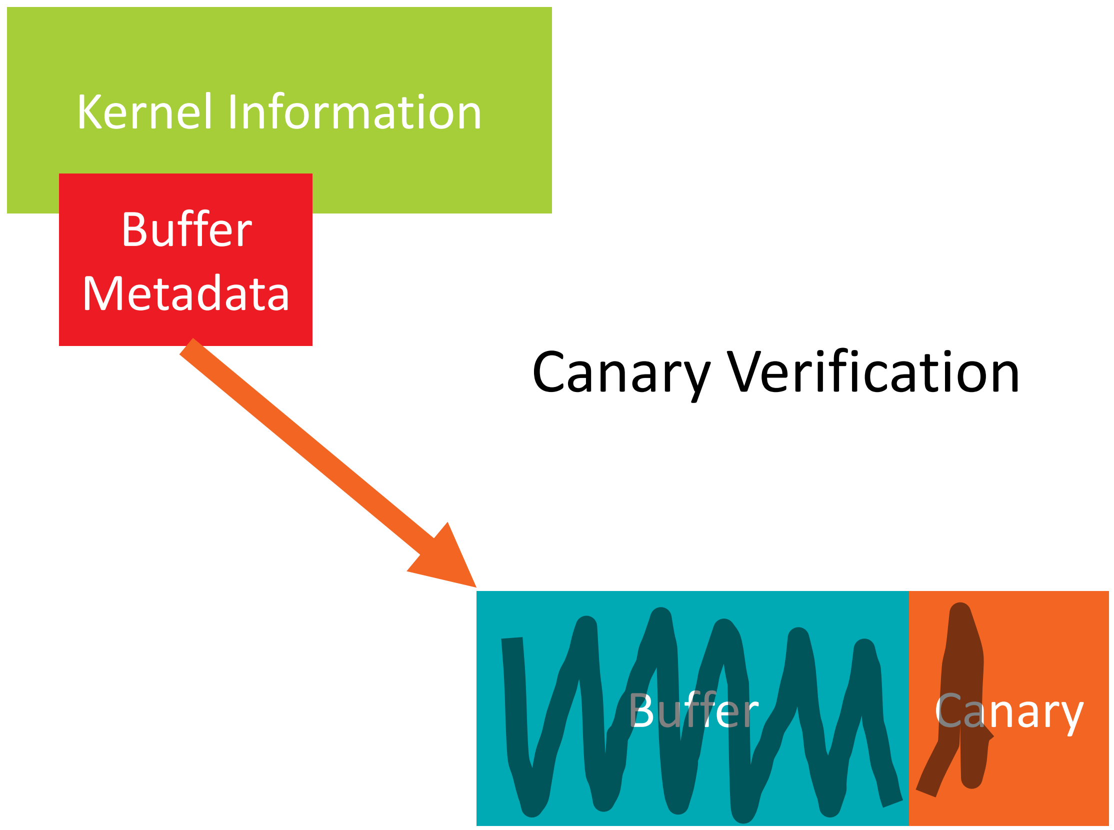

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WRAPPING OPENCL™

clARMOR BETWEEN YOUR APPLICATION AND OPENCL

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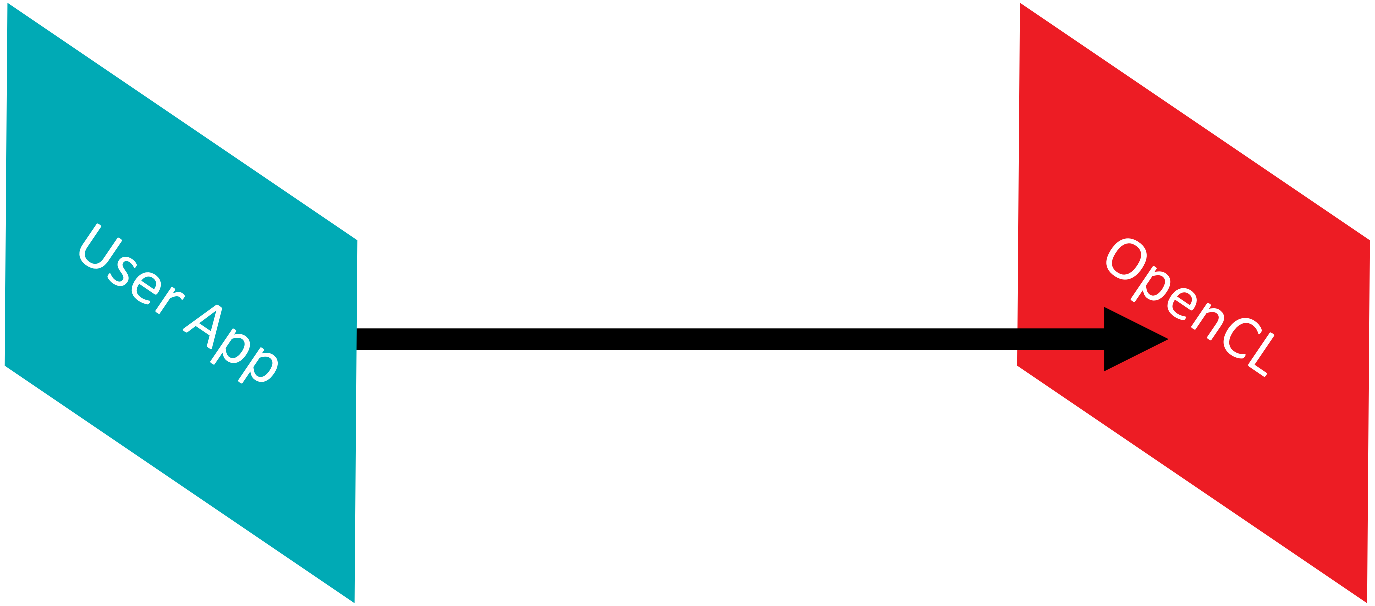
- Call Wrapping
  - Buffer, SVM, and Image creates
  - Argument setters
  - Kernel launches
  - Information functions



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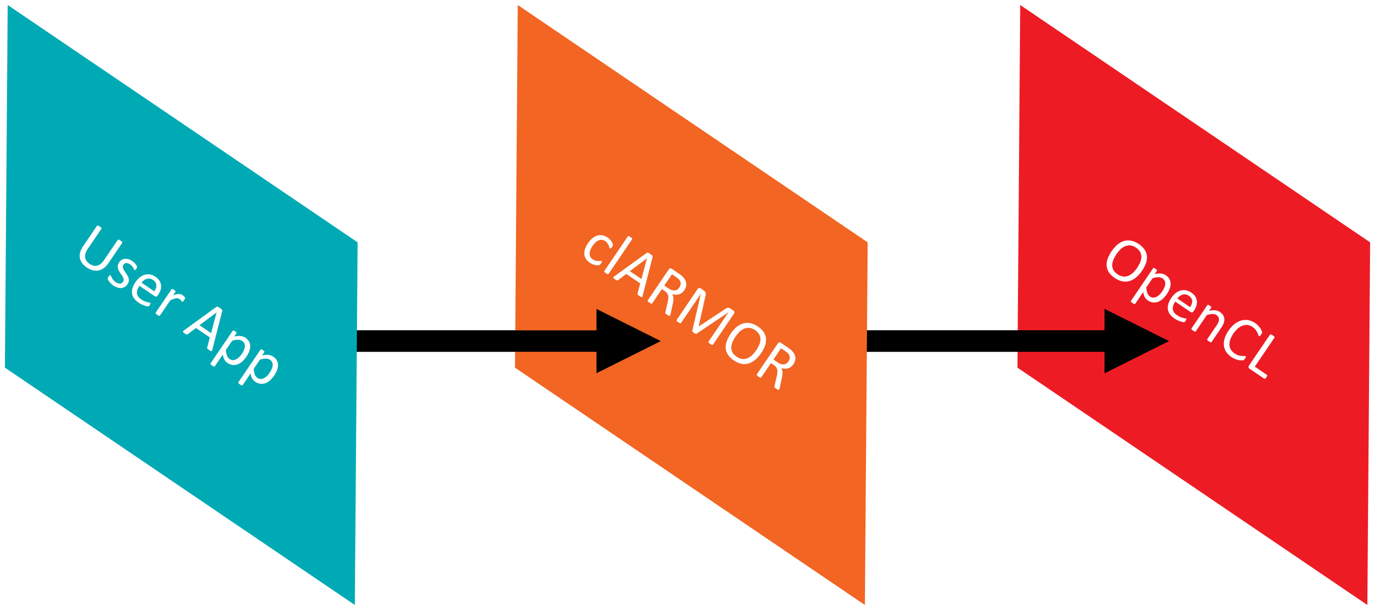

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TEST SETUP

HARDWARE SPECIFICATIONS AND BENCHMARKS SUITES

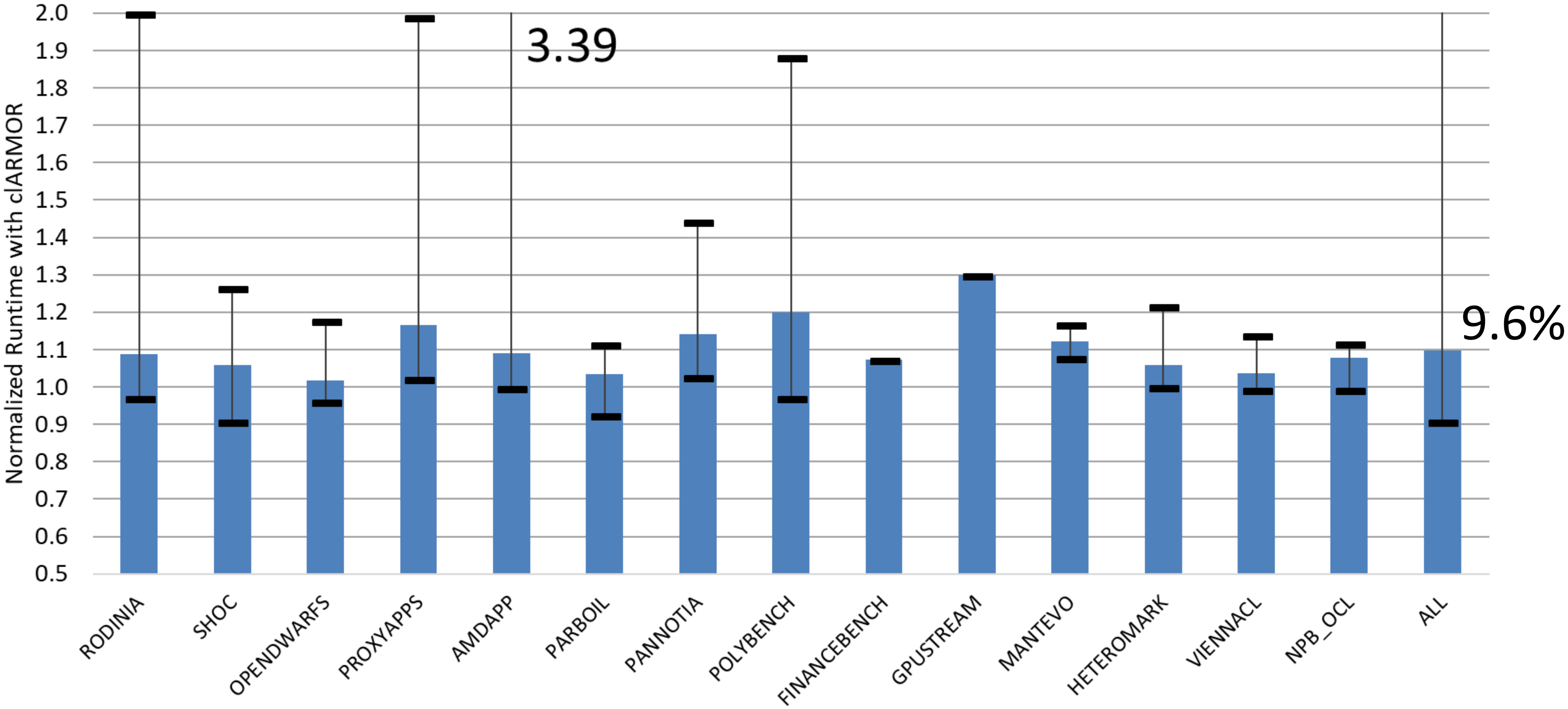
- AMD Ryzen™ 7 1800X CPU
- AMD Radeon™ Vega Frontier Edition discrete GPU
- ROCm 1.7
- 143 benchmarks in 14 benchmark suites

Suite	Num Benchmarks
AMDAPP	33
FINANCEBENCH	1
GPUSTREAM	1
HETEROMARK	9
MANTEVO	2
NPB_OCL	8
OPENDWARFS	7
PANNOTIA	6
PARBOIL	8
POLYBENCH	21
PROXYAPPS	6
RODINIA	19
SHOC	14
VIENNACL	8

PERFORMANCE EVALUATION

APPLICATION RUNTIME: WITH / WITHOUT TOOL

Lower is better



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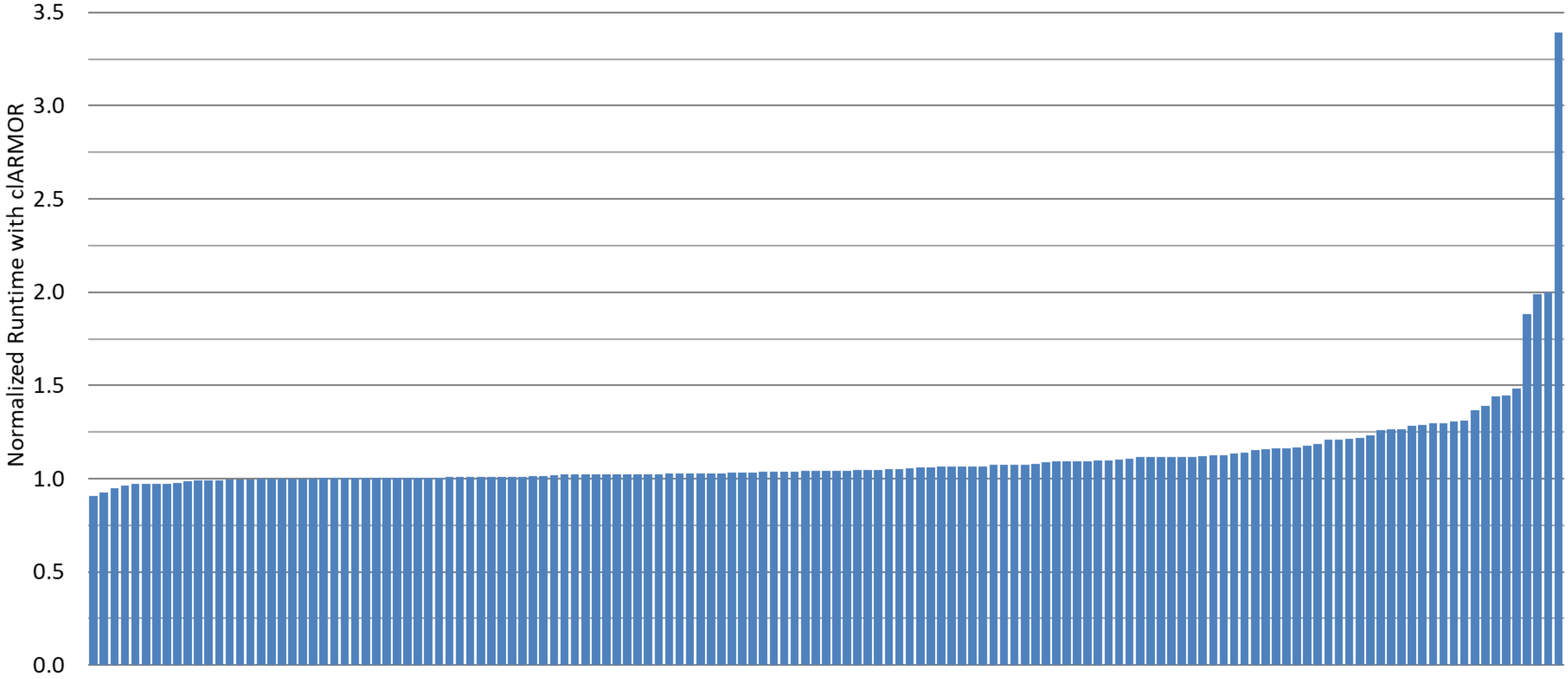

EXAMPLE USAGE

BAD_CL_MEM TEST

```
bin/clarmor tests/bad_cl_mem/bad_cl_mem.exe
```

```
[redacted]:~/tools/clARMOR$ bin/clarmor tests/bad_cl_mem/bad_cl_mem.exe
clARMOR: Final command line to run: LD_PRELOAD='[redacted]/tools/clARMOR/bin/../lib/libclbuff
erwrapper.so.1.0' PATH='[redacted]/tools/clARMOR:[redacted]/bin:[redacted]/.local/bin:/opt/ro
cm/bin/:/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin:/usr/games:/usr/local/ga
mes:/snap/bin'  CLARMOR_LOG_PREFIX="clARMOR: "  CLARMOR_ERROR_EXITCODE=-1  tests/bad_cl_mem/b
ad_cl_mem.exe

clARMOR: Loaded CL_WRAPPER
Searching for platforms...
    Using platform: AMD Accelerated Parallel Processing
Searching for devices...
    Using device: gfx803


Running Bad cl_mem Test...
    Using buffer size: 1048566
Launching 262144 work items to write up to 262144 entries.
This will write 1048576 out of 1048566 bytes in the buffer.
clARMOR:
clARMOR: ATTENTION:
clARMOR: ************* Buffer overflow detected ***********
clARMOR: Kernel: test, Buffer: cl_mem_buffer
clARMOR:    Write Overflow 1 byte(s) past end.
clARMOR:
Done Running Bad cl_mem Test.
clARMOR: Done!
```

EXAMPLE USAGE

GOOD_CL_MEM TEST

```
[redacted]:~/tools/clARMOR$ bin/clarmor tests/good_cl_mem/good_cl_mem.exe
clARMOR: Final command line to run: LD_PRELOAD='[redacted]/tools/clARMOR/bin/../lib/libclbuf
ferwrapper.so.1.0' PATH='[redacted]/tools/clARMOR:[redacted]/bin:[redacted].local/bin:/opt/
rocm/bin/:/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin:/usr/games:/usr/local
/games:/snap/bin'  CLARMOR_LOG_PREFIX="clARMOR: "  CLARMOR_ERROR_EXITCODE=-1  tests/good_cl_
mem/good_cl_mem.exe

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Running Good cl_mem Test...
    Using buffer size: 1048576
Launching 262144 work items to write up to 262144 entries.
This will write 1048576 out of 1048576 bytes in the buffer.
Done Running Good cl_mem Test.
clARMOR: Done!
```

BONUS DETAILS

- What do the wrapped OpenCL™ library calls have to do?
  - Buffer and Image creates
  - Argument setters
  - Kernel launches
  - Information functions
- What are we doing to make the check faster?

WRAPPING THE OPENCL™ API

BUFFER AND IMAGE CREATION

- Buffer Creation
  - Calls to ***clCreateBuffer*** or ***clSVMAlloc***
    - Allocate buffer
    - Create sub buffer for user
    - Surround with canary

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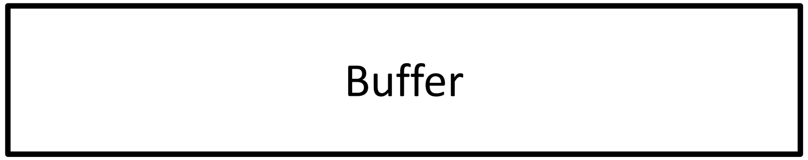

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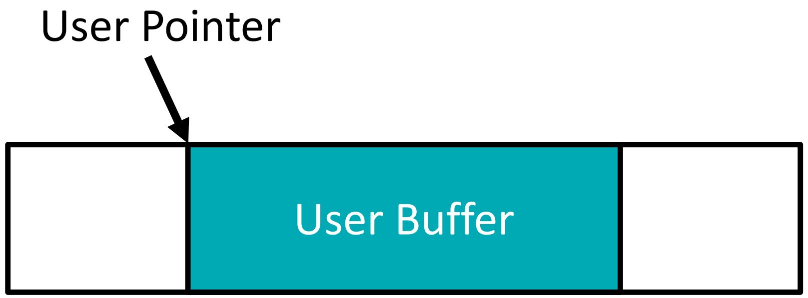

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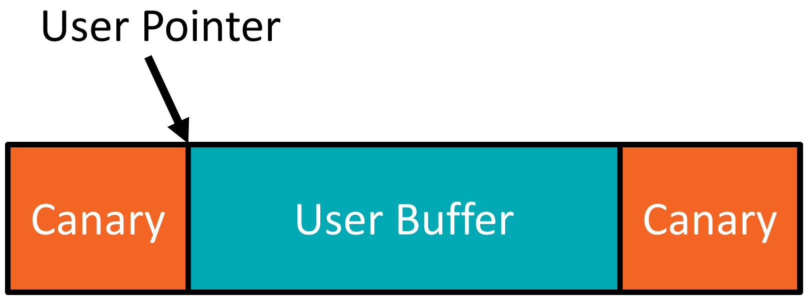

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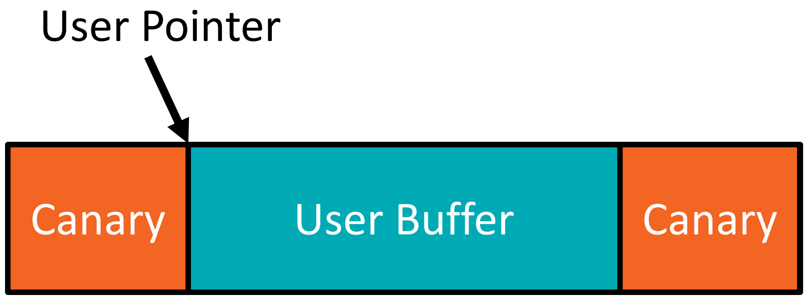
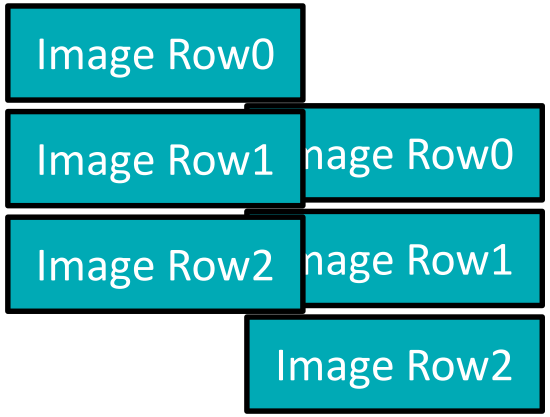


- Image Creation
  - Calls to ***clCreateImage***, ***clCreateImage2D***, or ***clCreateImage3D***
  - Potential for multi dimensional overflow
  - Add canary regions to each dimension



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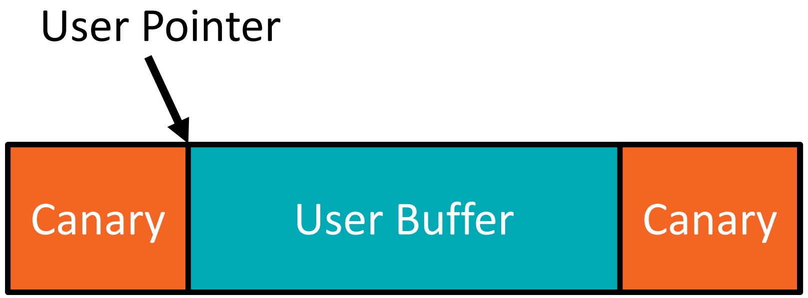

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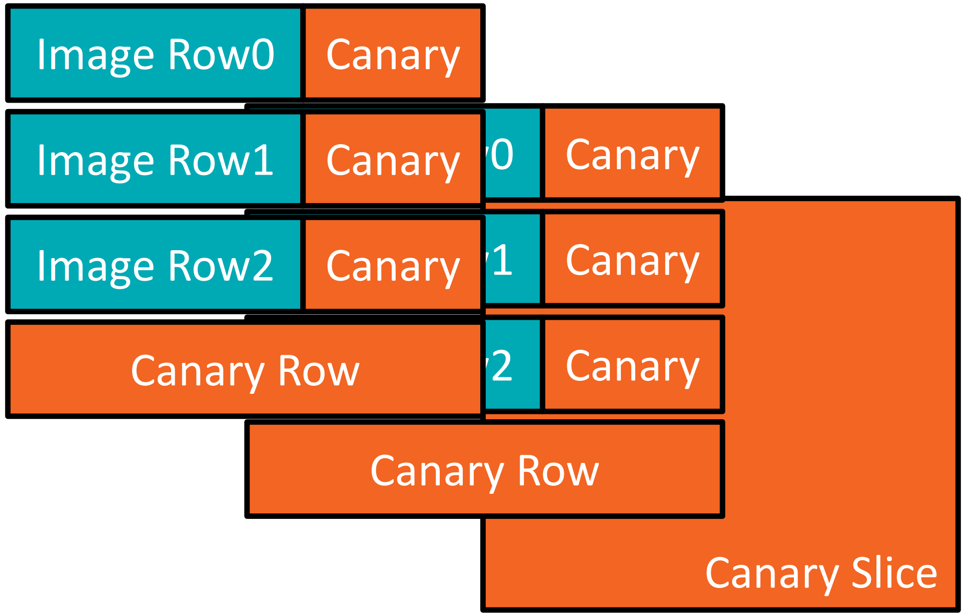

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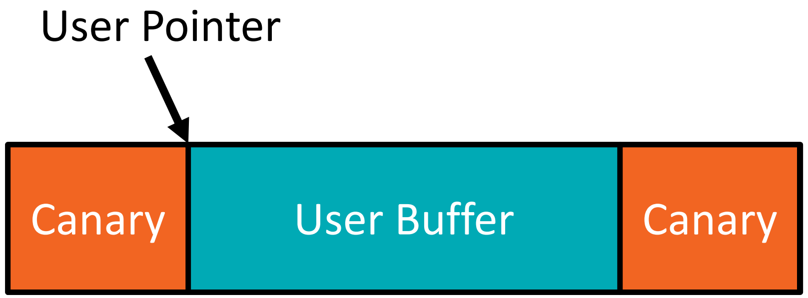

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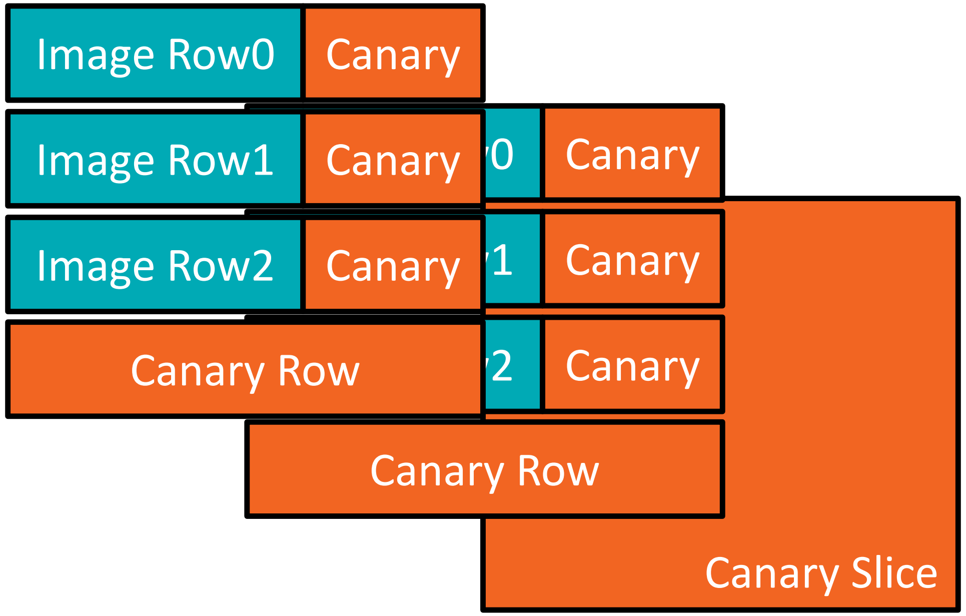

- Annotations for location of canaries, etc.

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BUFFER CREATION FROM EXISTING ALLOCATIONS

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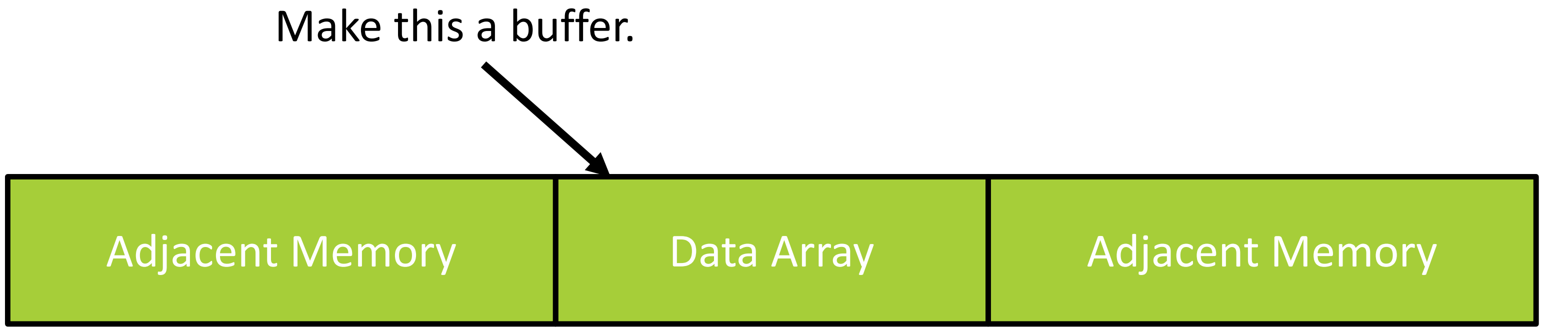

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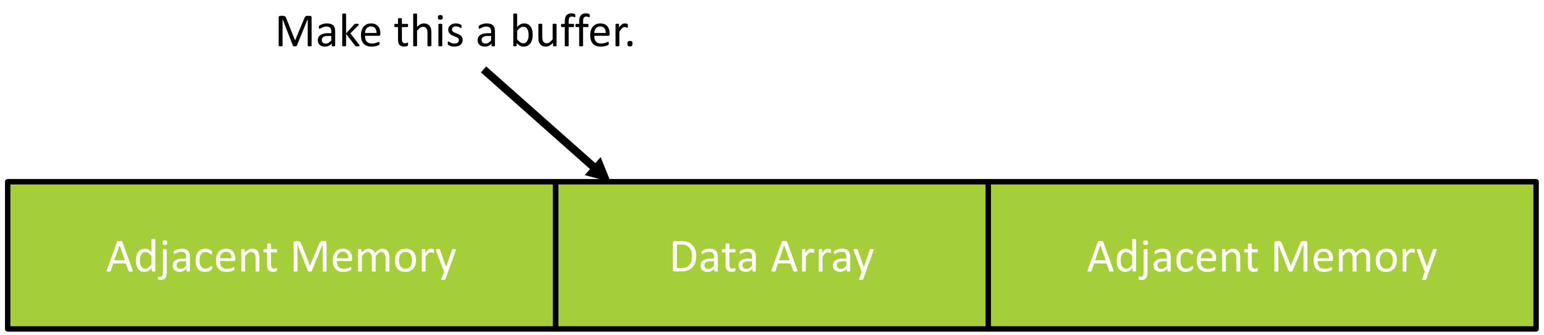

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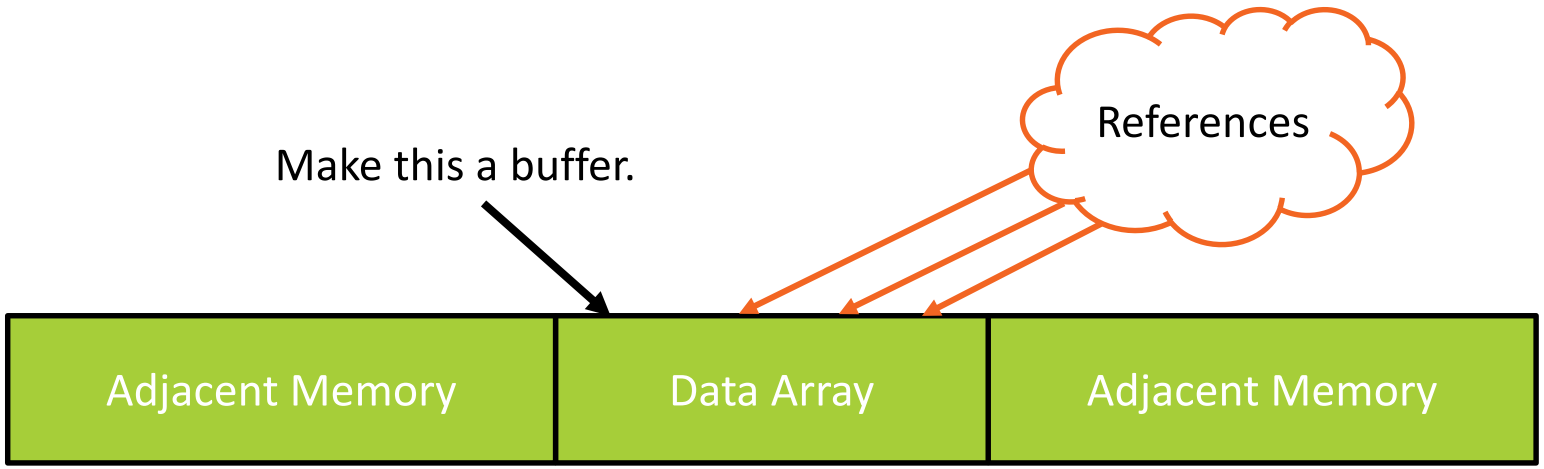

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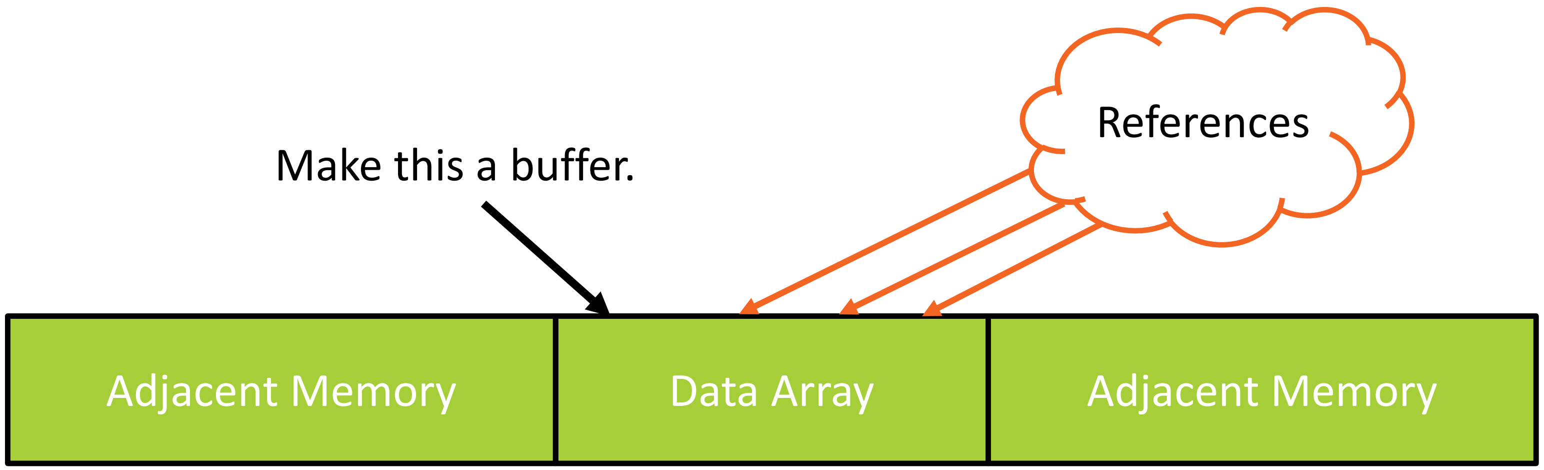

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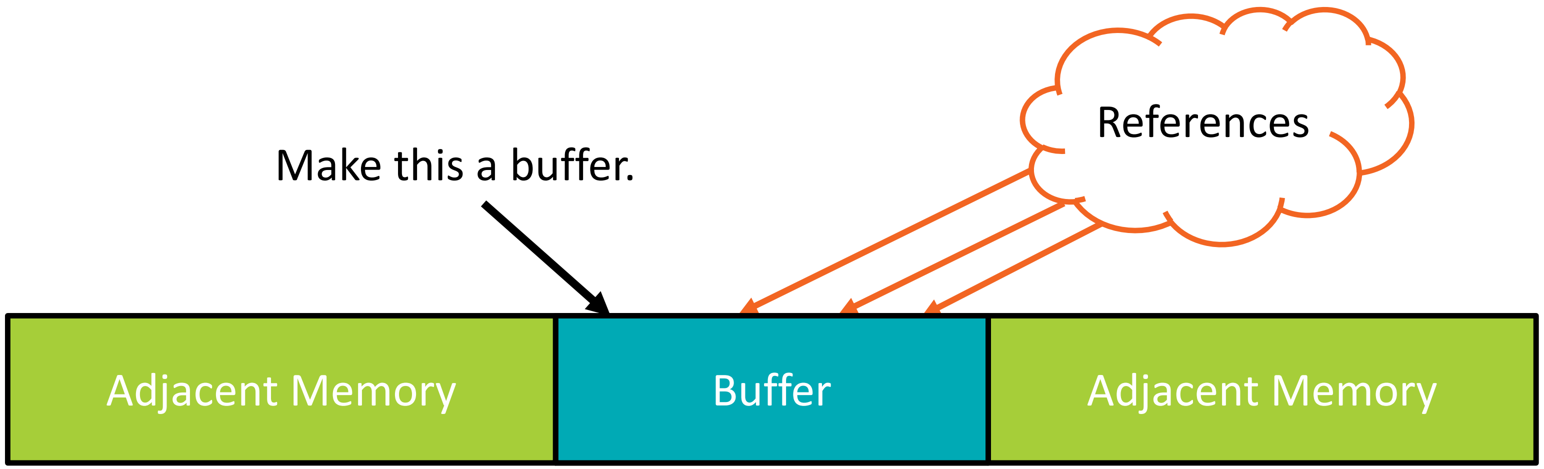

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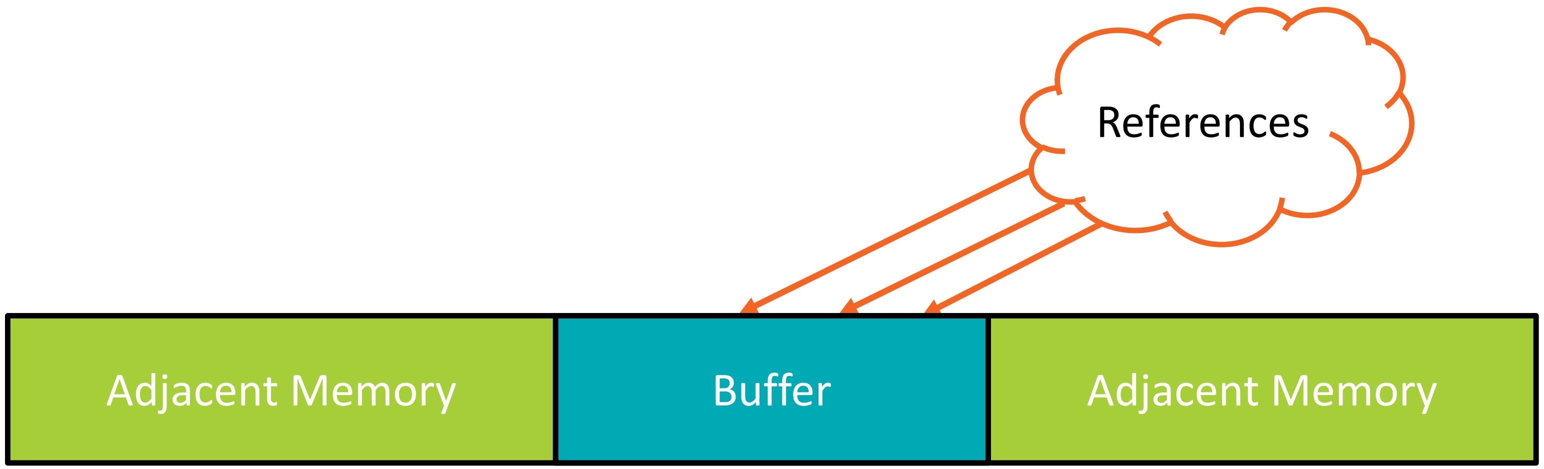

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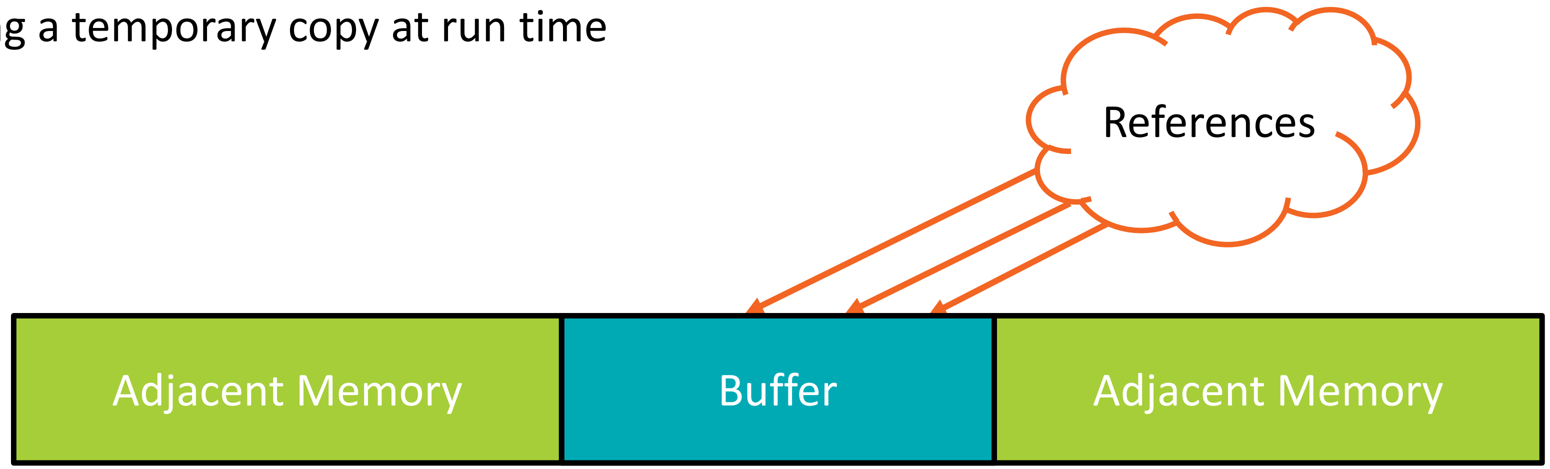

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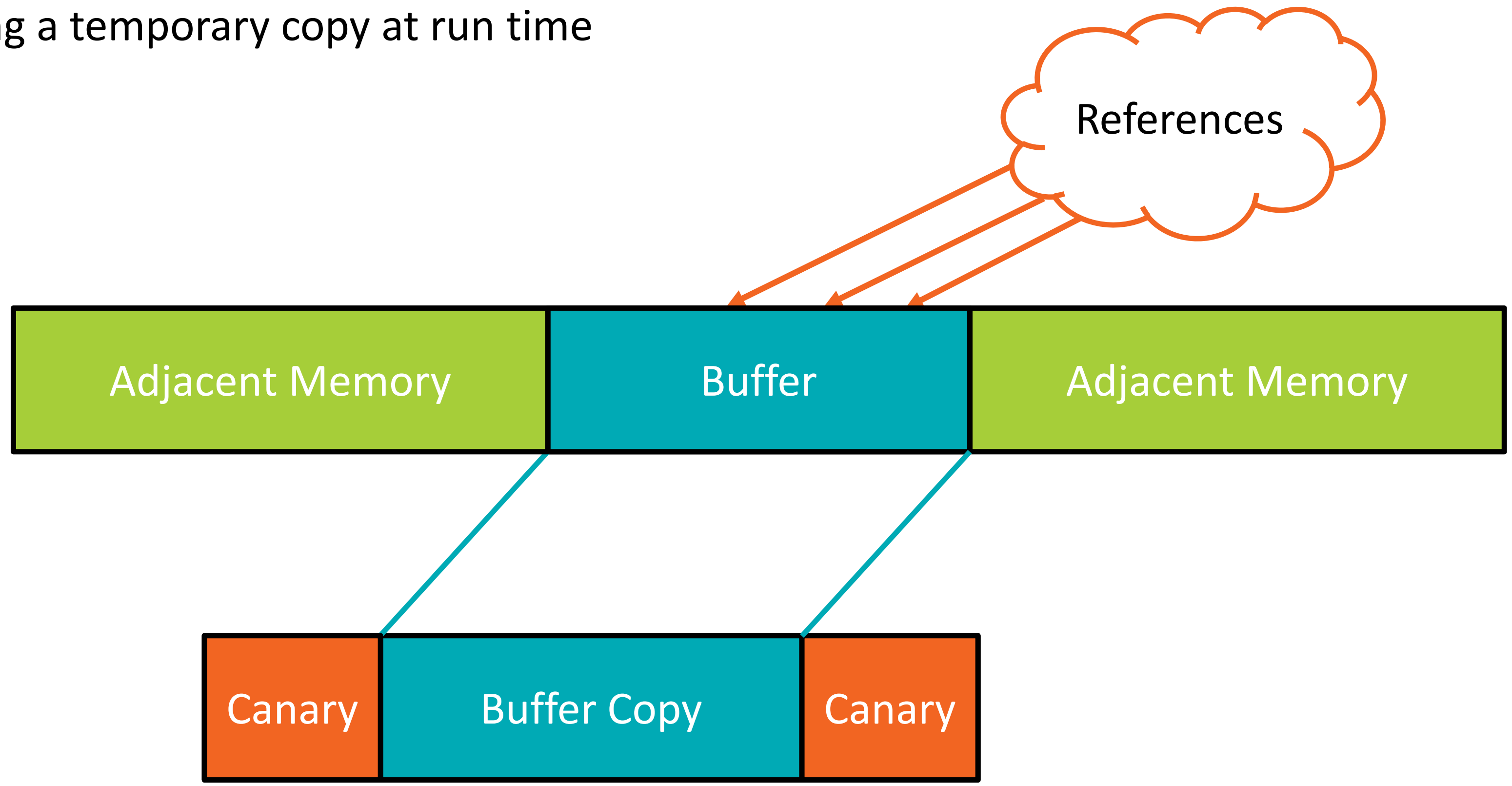

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SET ARGUMENTS

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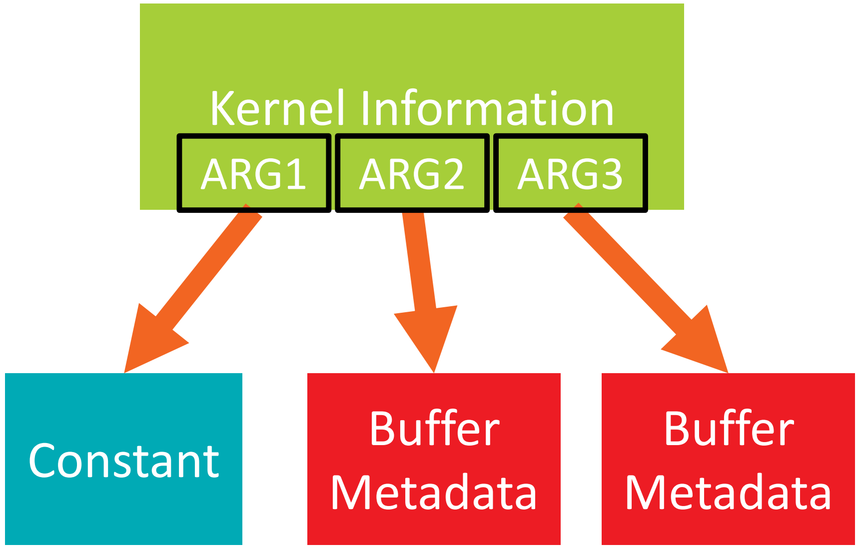
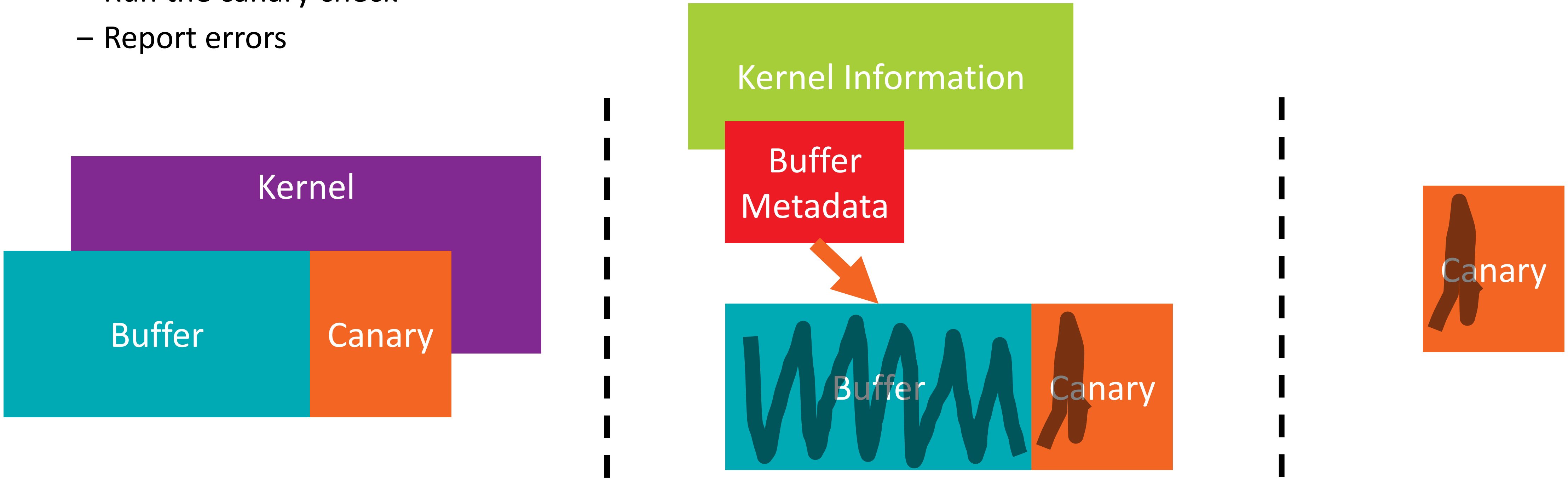


WRAPPING THE OPENCL™ API

KERNEL LAUNCH

- Do the work of detecting buffer overflows
- On call to ***clEnqueueNDRangeKernel***
  - Enqueue the kernel
  - Retrieve affected buffers
  - Run the canary check
  - Report errors



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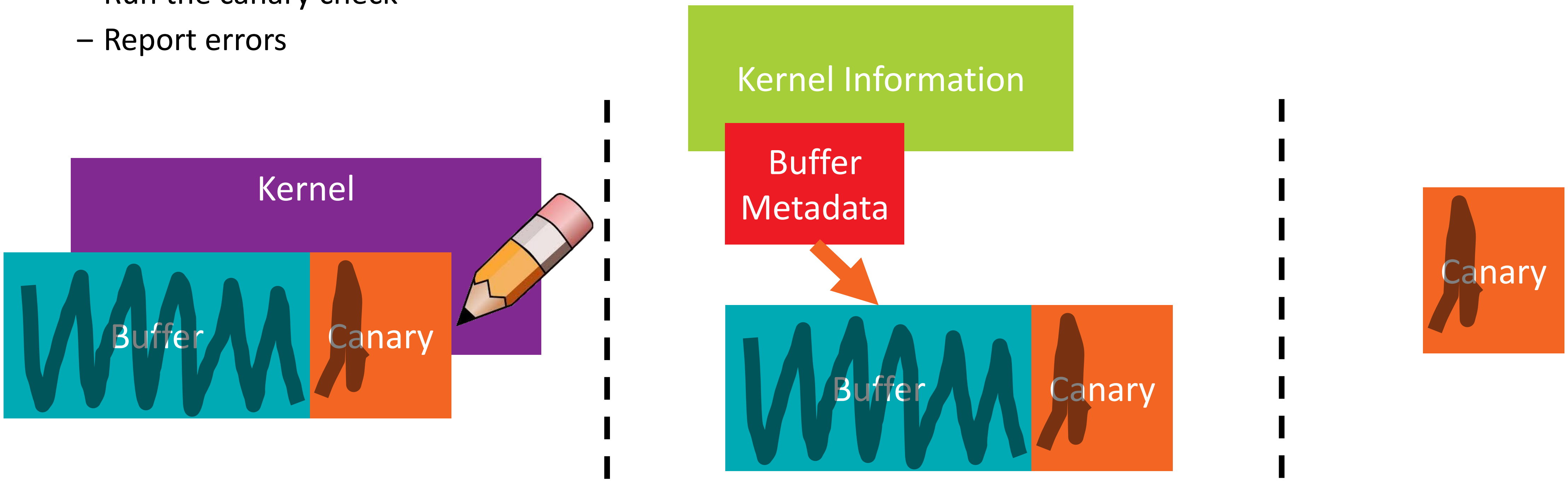

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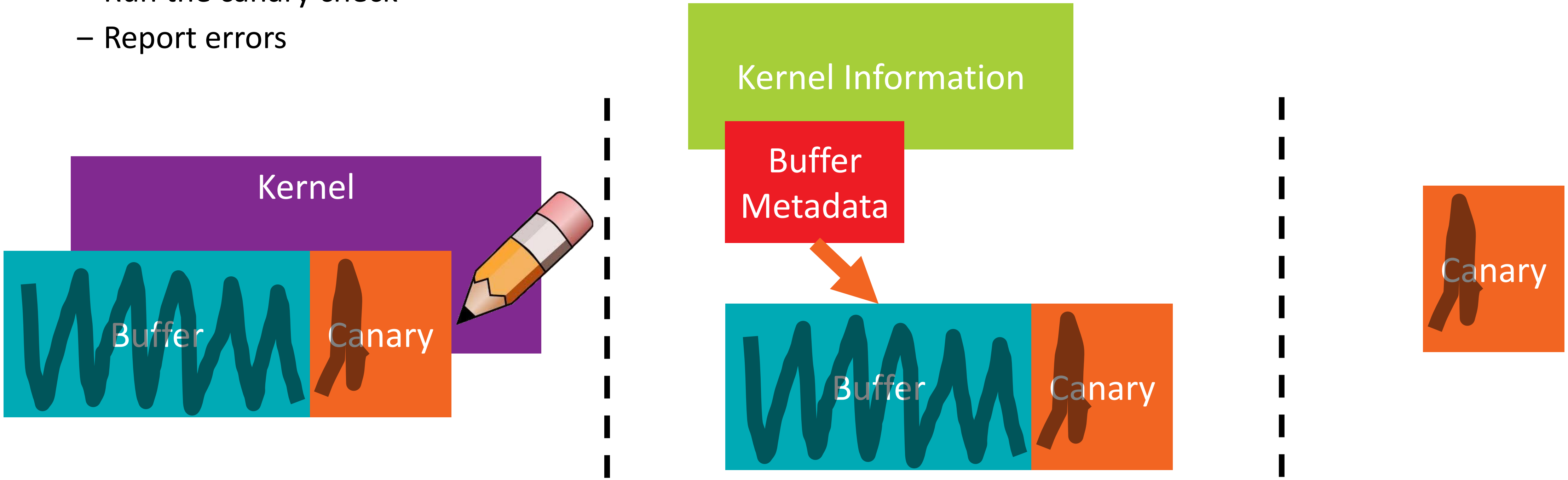

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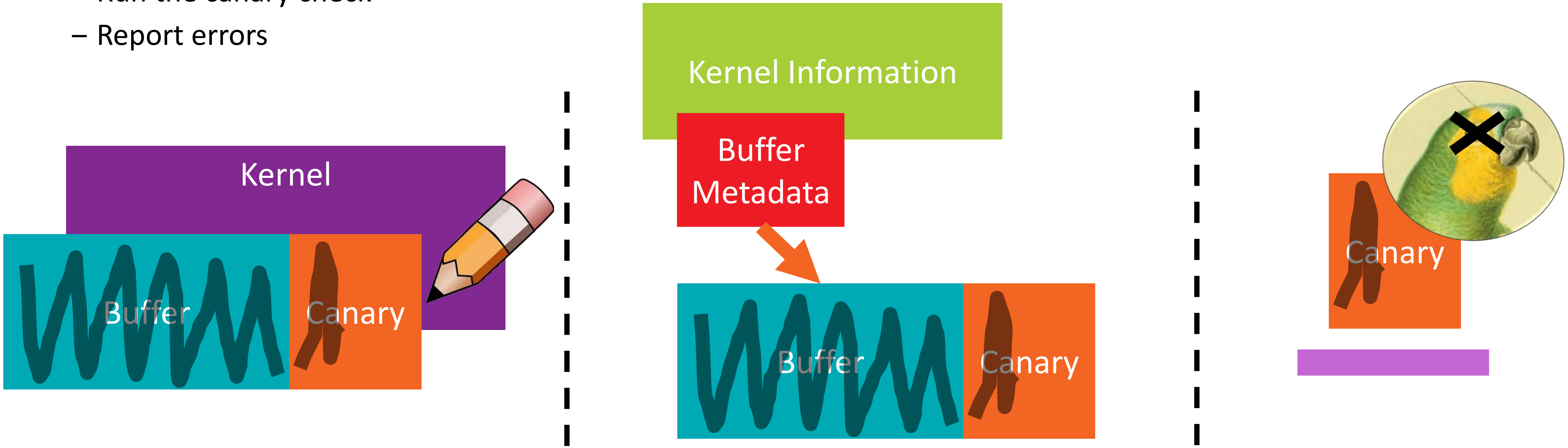


WRAPPING THE OPENCL™ API

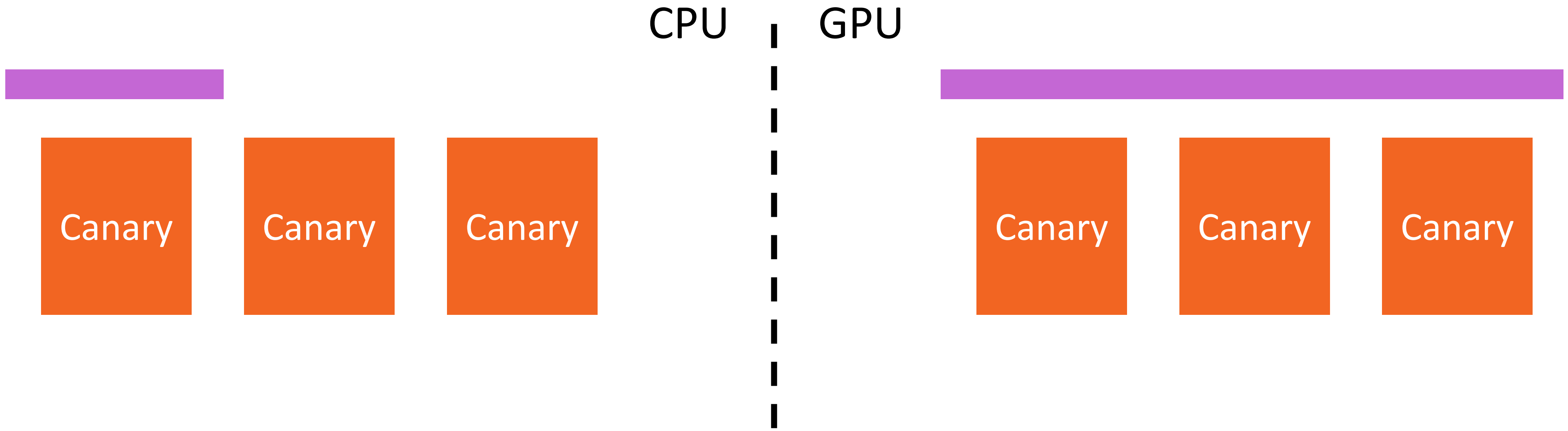
GETTERS AND SETTERS

- GetMemObjectInfo, GetImageInfo
  - Reserve space for canaries
- Enqueue Functions
  - Read / Write / Fill / Copy
  - Buffer / BufferRect / Image

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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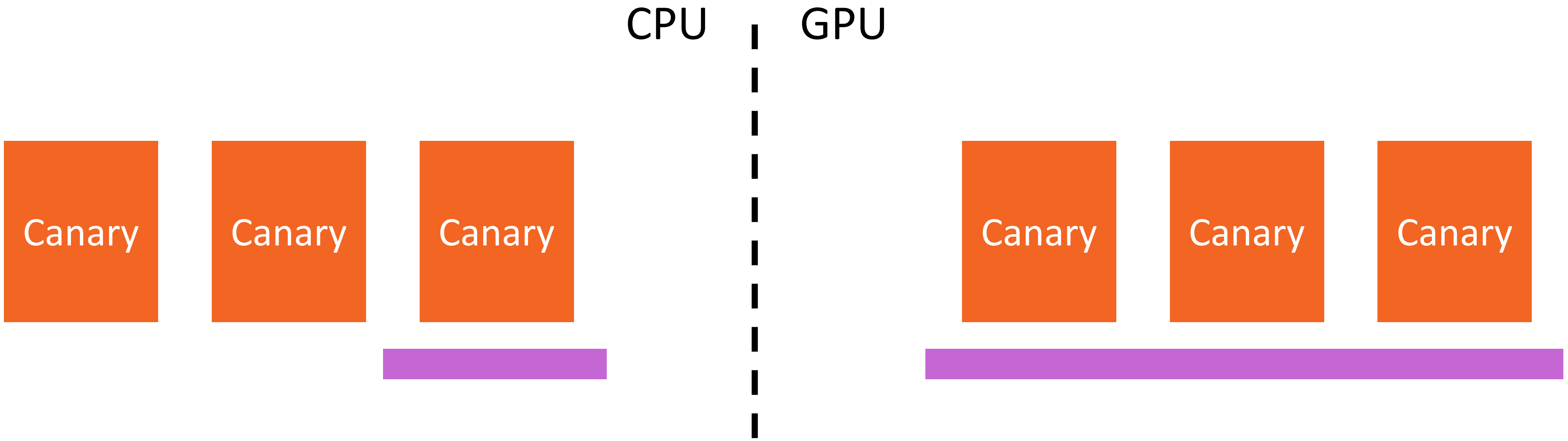

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USING OPENCL™ EVENTS TO INCREASE THROUGHPUT

- 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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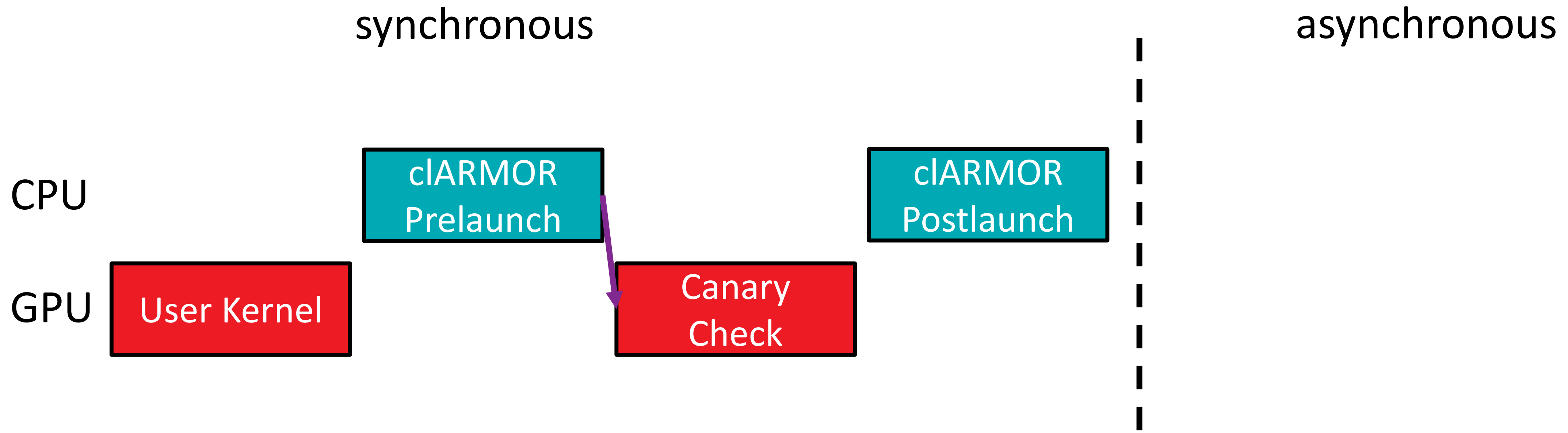

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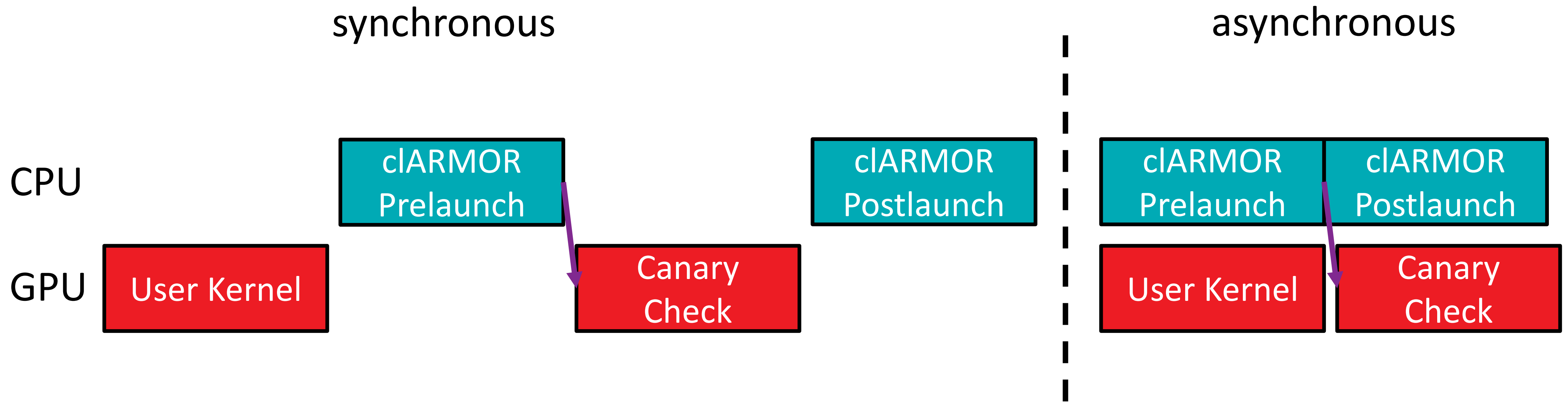

CONCLUSION

clARMOR IS READY FOR YOU TO USE

- Canary-based detection scheme finds GPU write overflows
  - Memory buffers, Sub buffers, SVM, Images
  - Overflow and Underflow detection
- Works for most OpenCL™ applications
  - Running on GPU or CPU, not vendor specific
- Near real-time detection
  - 9.7% average overhead

- Open Sourced
  - https://github.com/ROCm-Developer-Tools/clARMOR - MIT
- Technical Details
  - *Dynamic buffer overflow detection for GPGPUs*, CGO 2017

DISCLAIMER & ATTRIBUTION

AMD

ANALYSIS OF TOOL OVERHEAD WITH SNAP_MPI

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Example SNAP_MPI kernel launch

ANALYSIS OF TOOL OVERHEAD WITH SNAP_MPI

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CPU

Application Prelaunch

GPU

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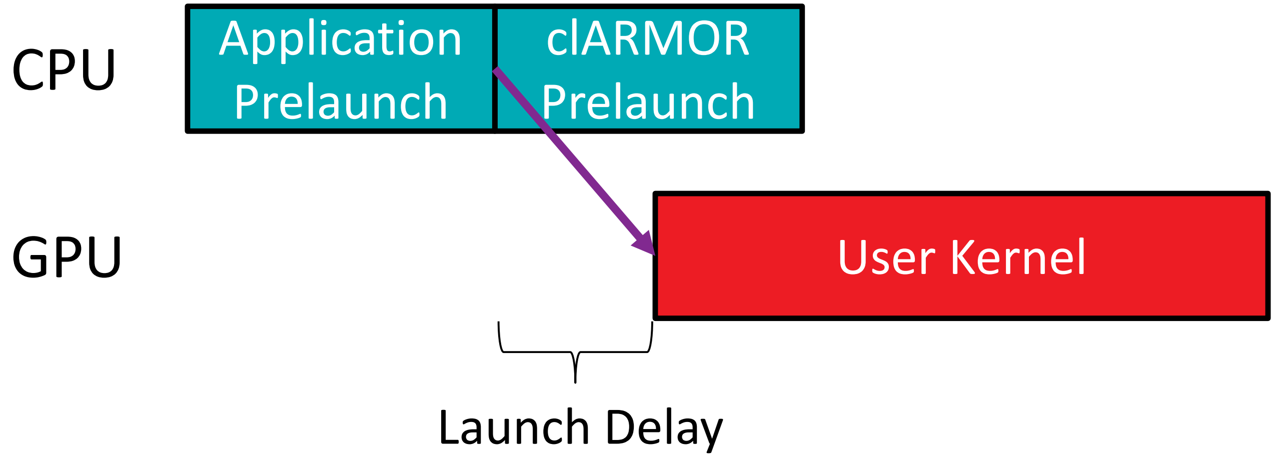

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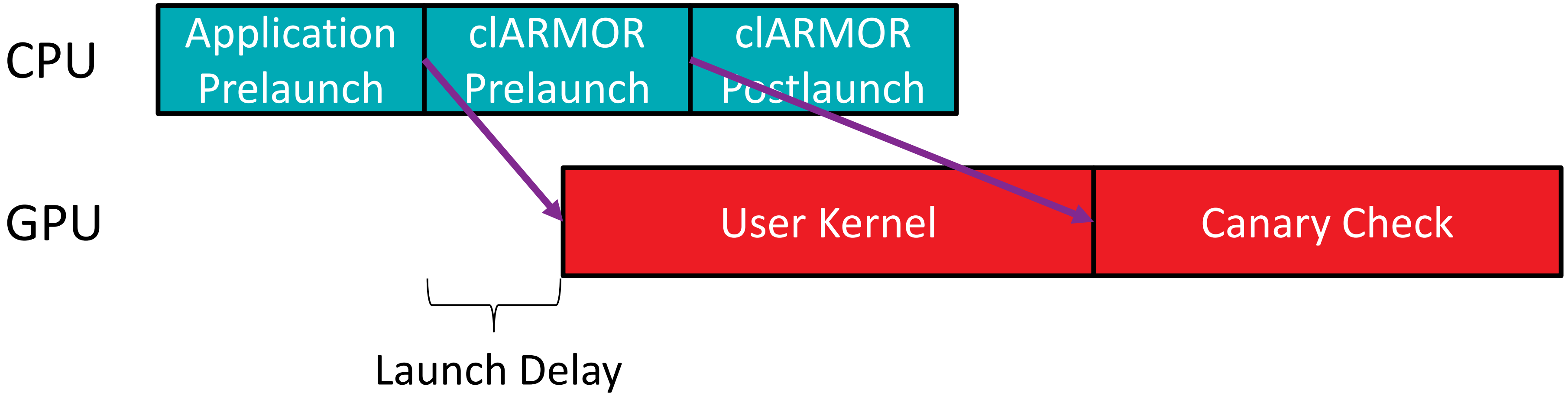

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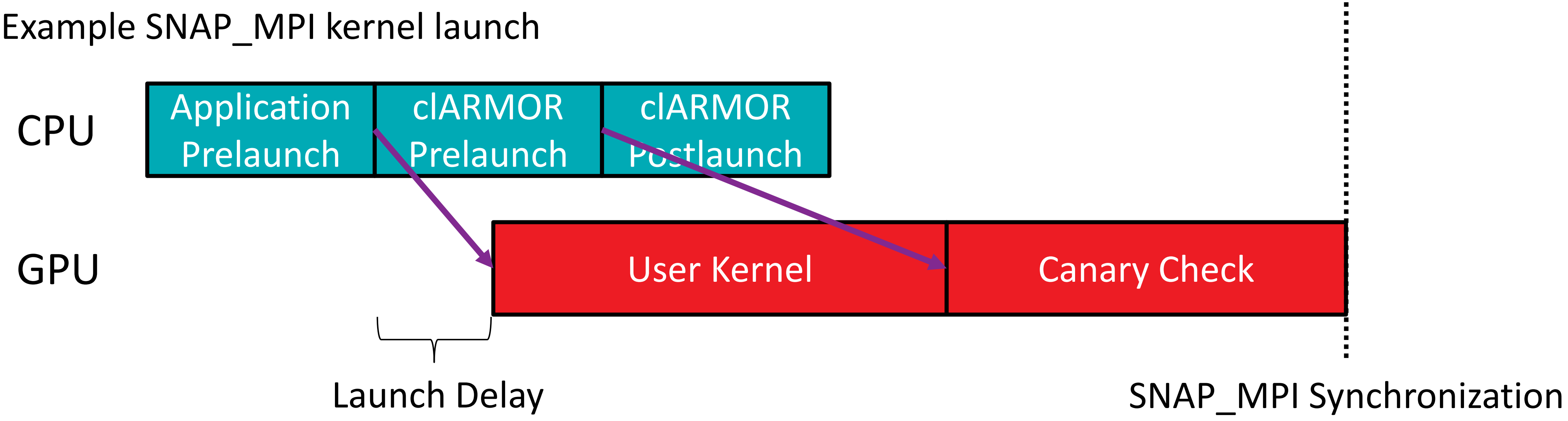

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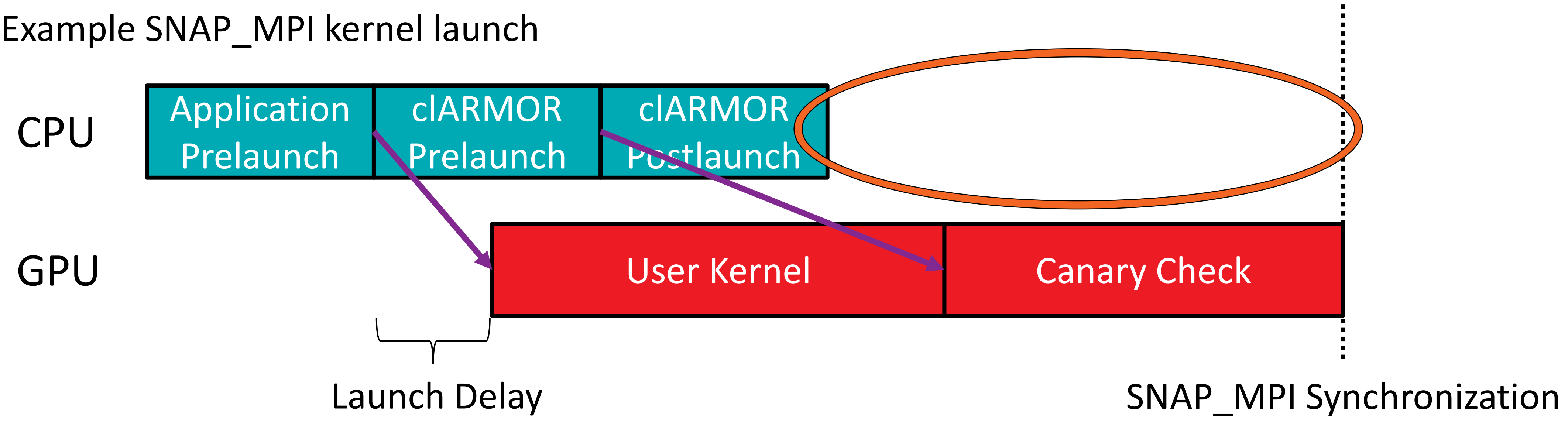

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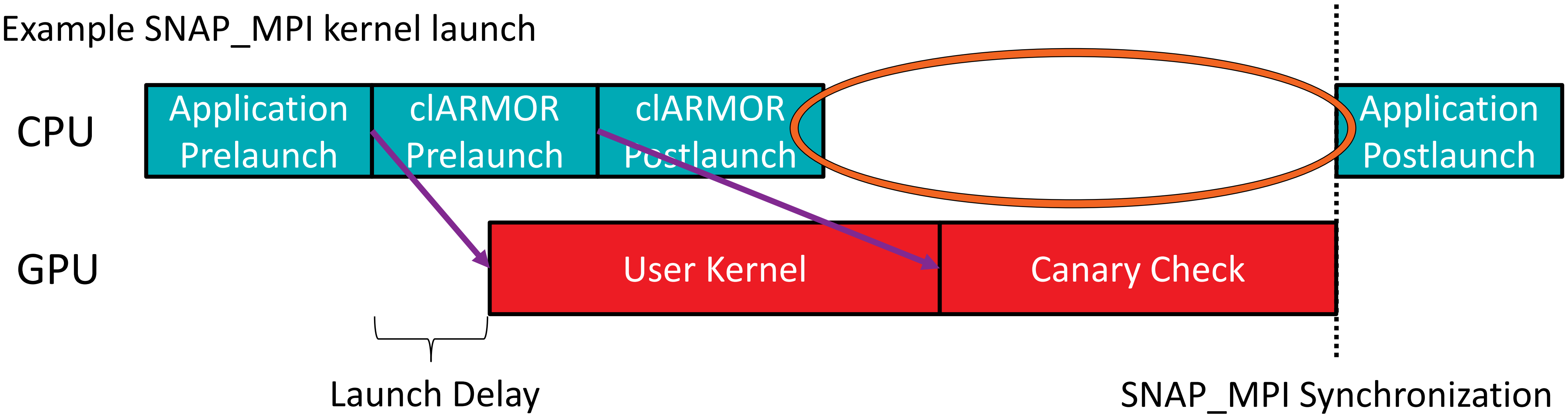

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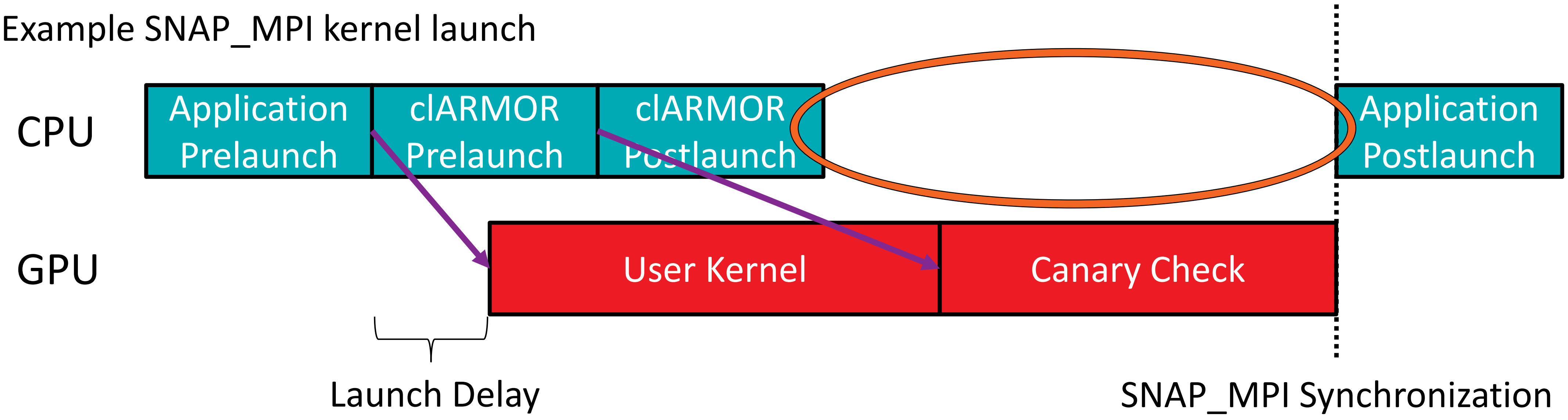

Possible improvement for SNAP_MPI kernel launch

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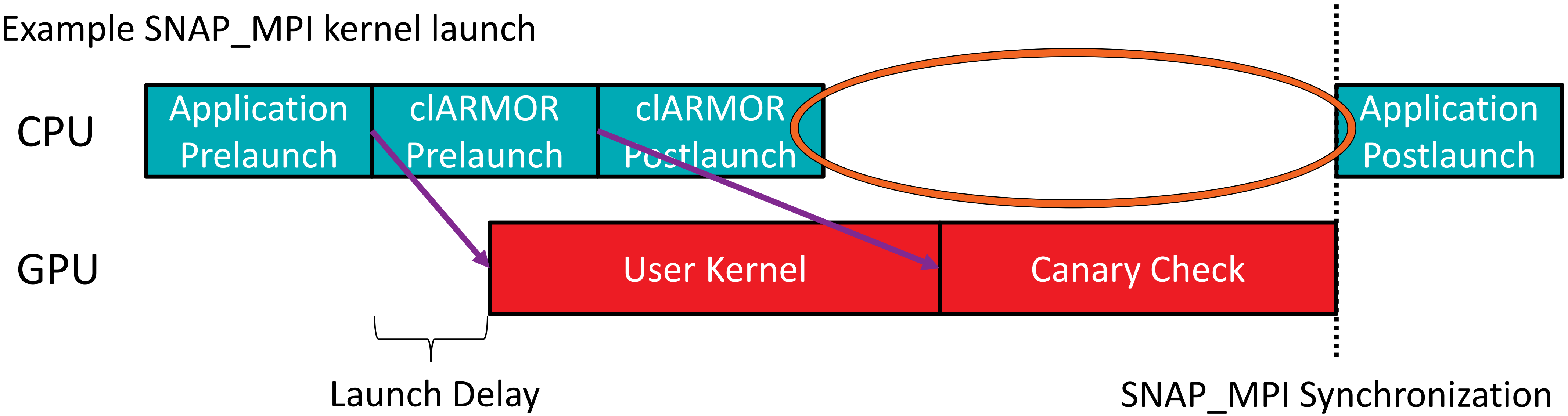

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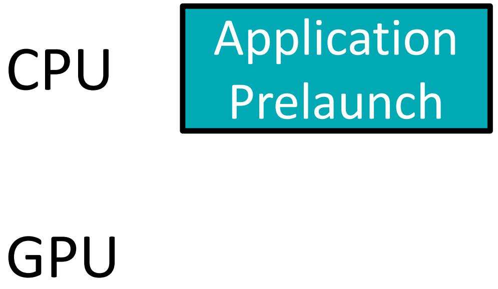

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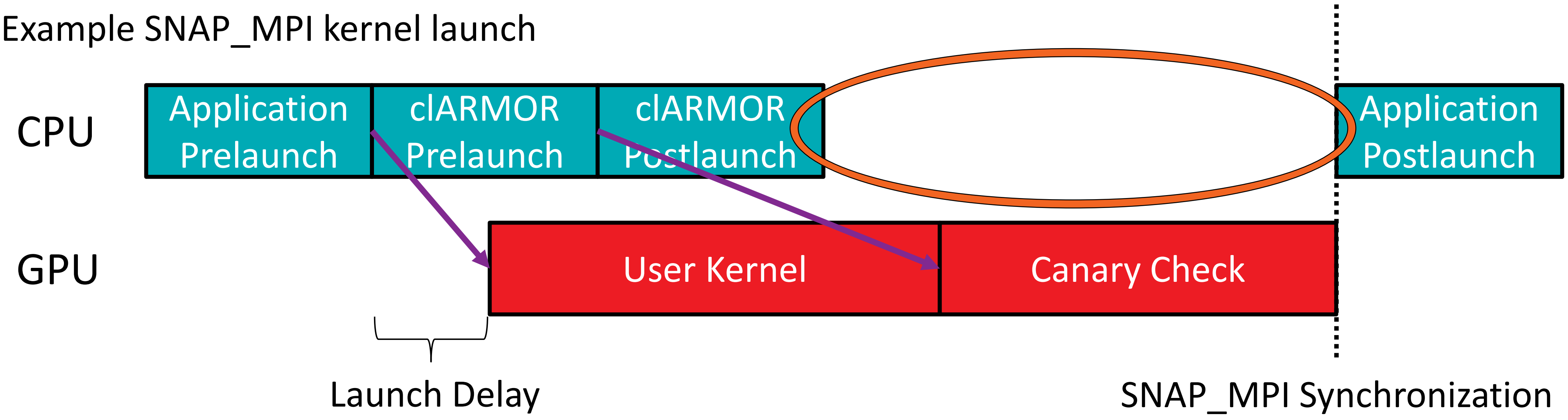

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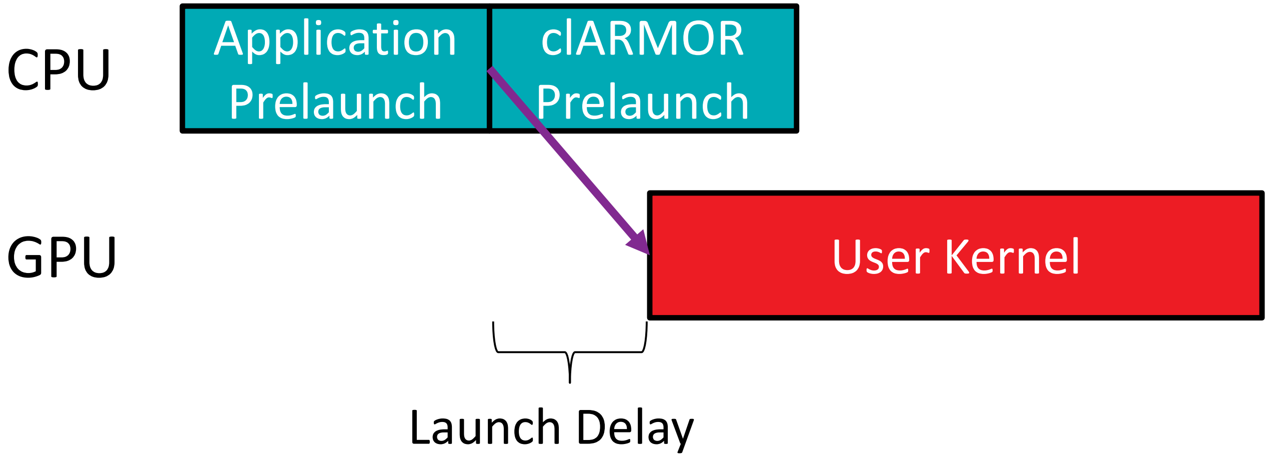

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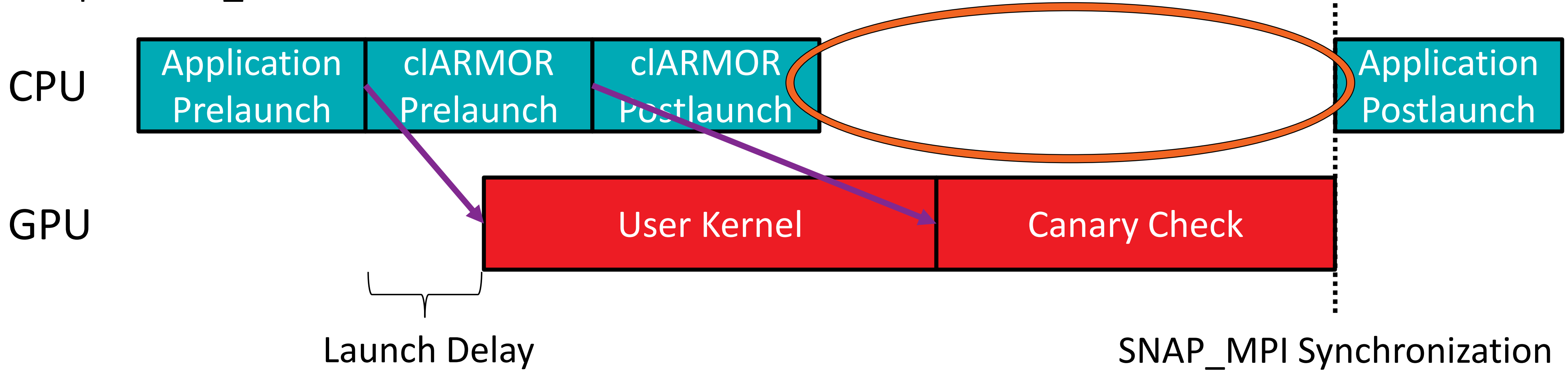

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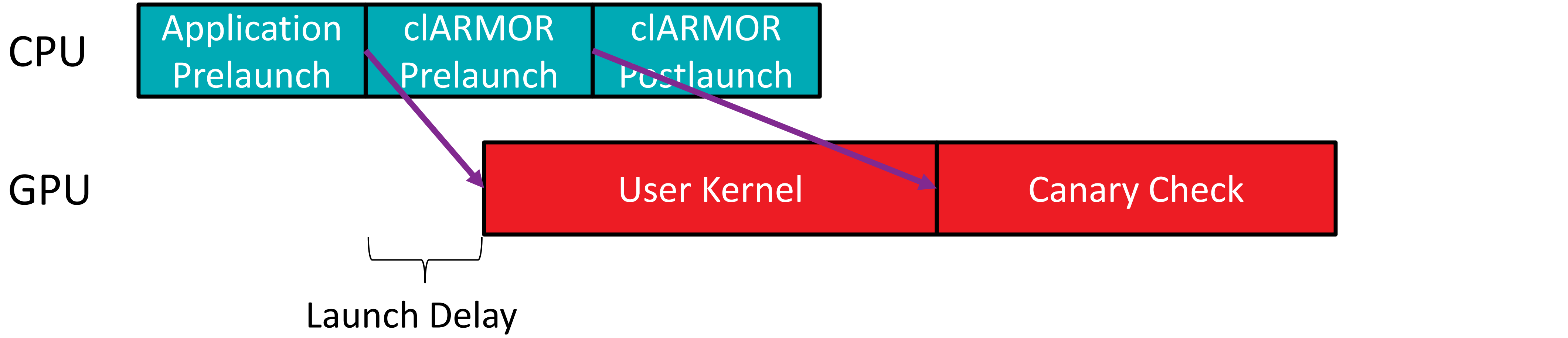

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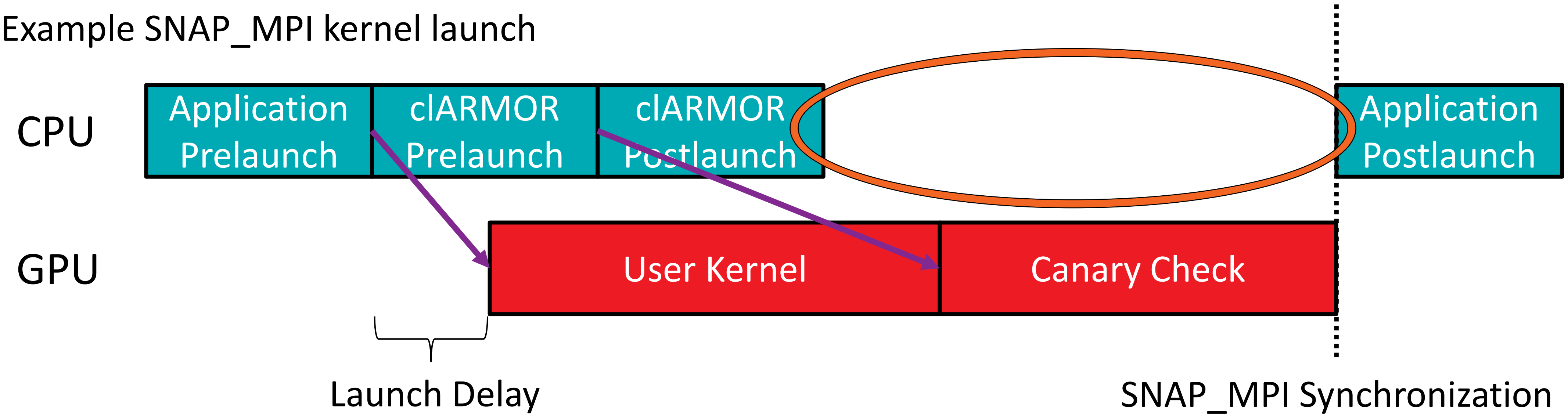

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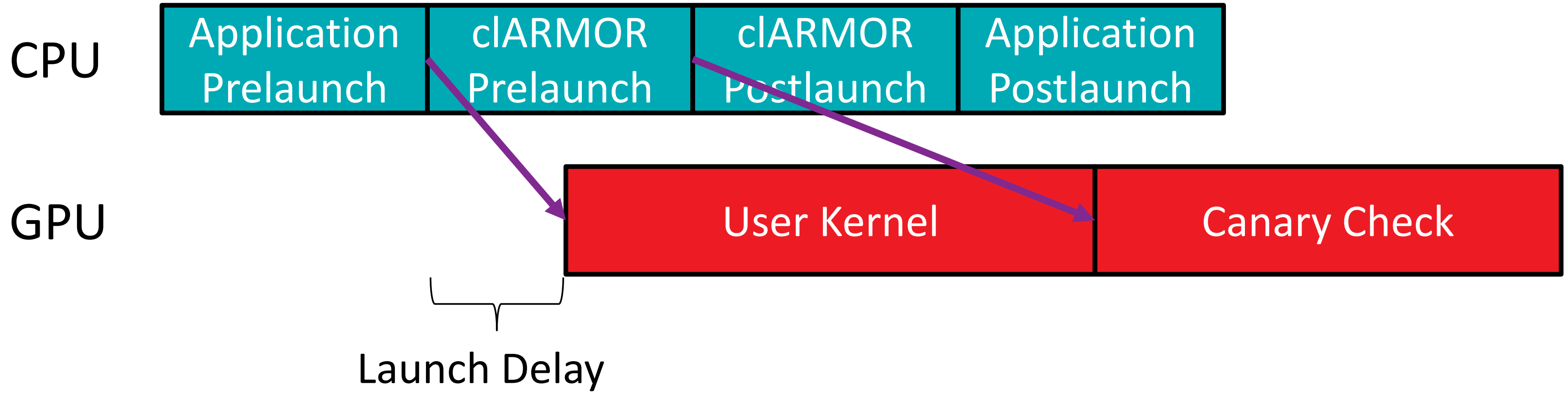
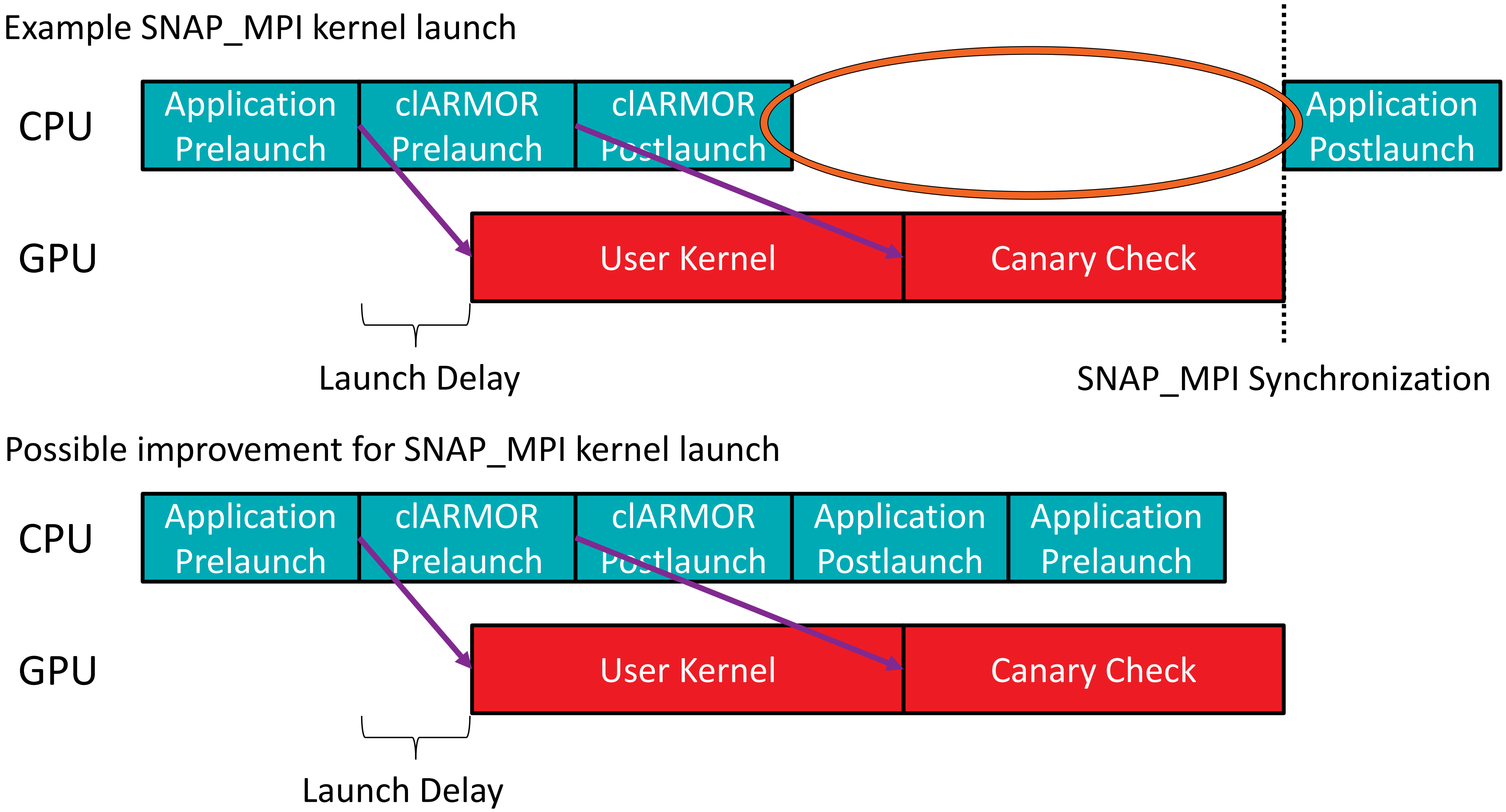
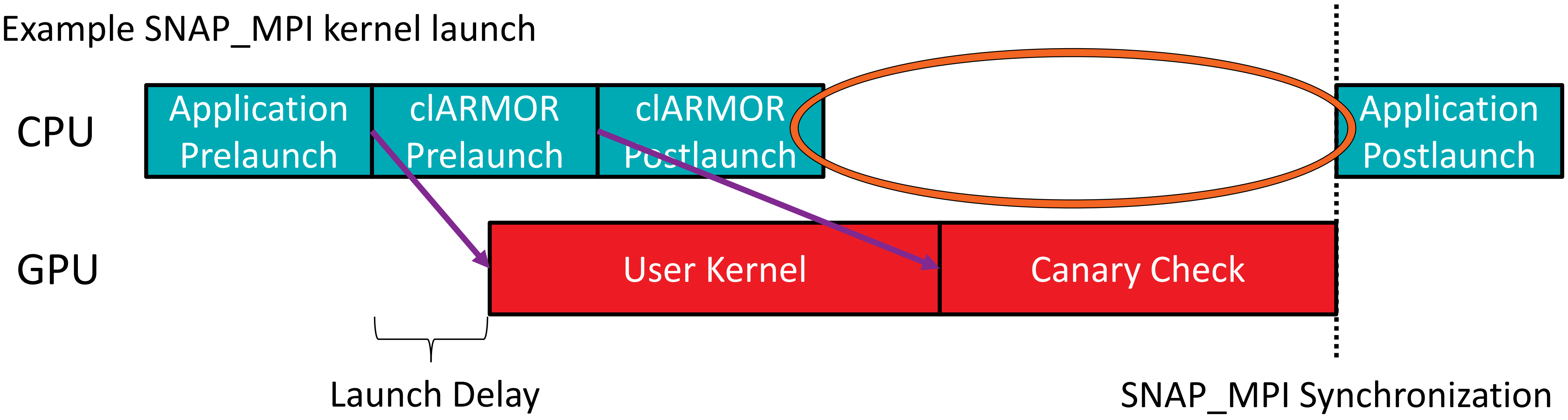


ANALYSIS OF TOOL OVERHEAD WITH SNAP_MPI

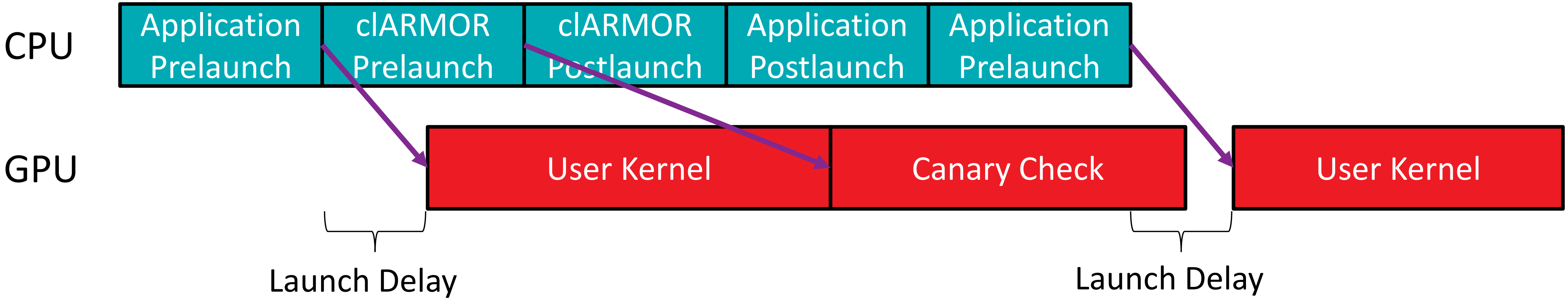


ANALYSIS OF TOOL OVERHEAD WITH SNAP_MPI

Example SNAP_MPI kernel launch



Possible improvement for SNAP_MPI kernel launch



Hetero-Mark OpenCL™ 1.2 SW Overflow Error

Kernel

```
__kernel void sw_compute0(…
        const unsigned M_LEN,
        …
        __global double *cu,
        … ) {
  int x = get_global_id(0);
  int y = get_global_id(1);
  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),
        reinterpret_cast<void *>(&cu_));
…
err = clEnqueueNDRangeKernel(cmdQueue_,
        kernel_sw_compute0_, 2, NULL, globalSize,
        localSize, 0, NULL, NULL);
```

Hetero-Mark OpenCL™ 1.2 SW Overflow Error

Kernel

```
__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

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size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

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  cu[(y + 1) * M_LEN + x] = <input_equation>
        …
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cu_ = clCreateBuffer(context_, CL_MEM_READ_WRITE,
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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

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Host

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size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

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Host

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size_t sizeInBytes = sizeof(double) * m_len_ * n_len_;
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        kernel_sw_compute0_, 2, NULL, globalSize,
        localSize, 0, NULL, NULL);
```

Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

Kernel

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

Host

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

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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

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

x = m - 1

y = n - 1

Host

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

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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

Kernel

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

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

$x = m - 1$

$y = n - 1$

Host

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

Kernel

```
__kernel void sw_compute0(…
        const unsigned M_LEN,
        …
        __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
```

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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const size_t globalSize[2] = {m_len_, n_len_};
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```

Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

Kernel

```
__kernel void sw_compute0(…
        const unsigned M_LEN,
        …
        __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);
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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

Kernel

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__kernel void sw_compute0(…
        const unsigned M_LEN,
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  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,
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Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

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  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
(n) * 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,
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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
```

➡ 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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AMD

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  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
(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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  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

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

Hetero-Mark OpenCL™ 1.2 SW Overflow Error

AMD

Kernel

```
__kernel void sw_compute0(…
        const unsigned M_LEN,
        …
        __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
(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

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```

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(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
```

$$\cancel{m*n - 1} + m <= \cancel{m*n -} 1$$

x = m - 1

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(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

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```
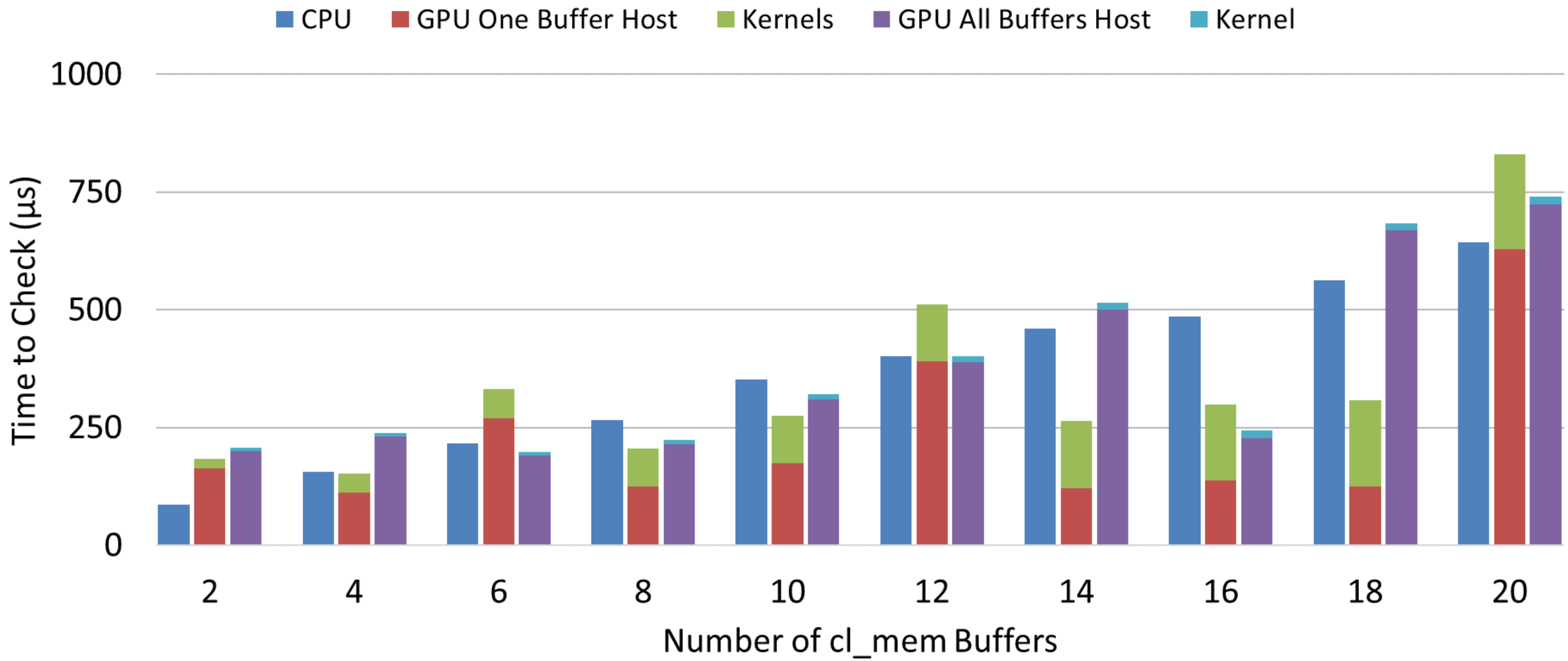
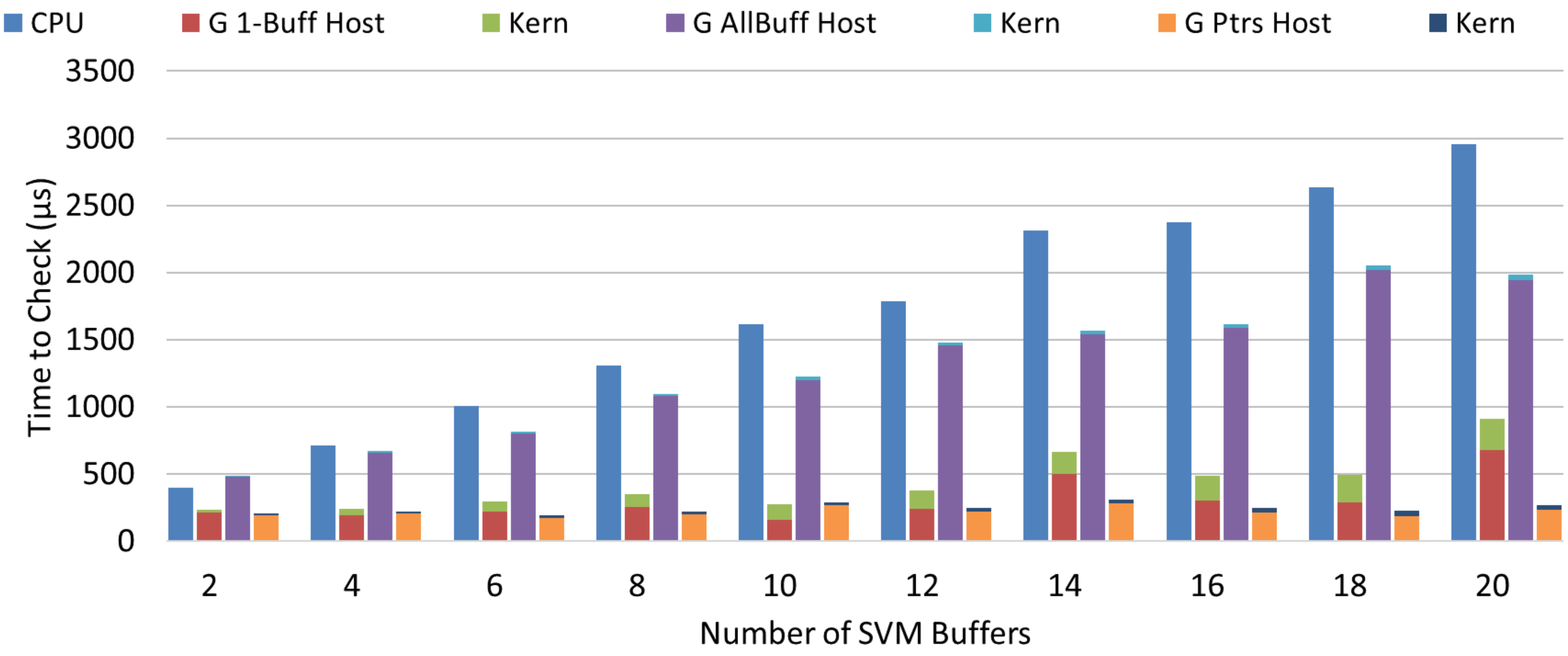
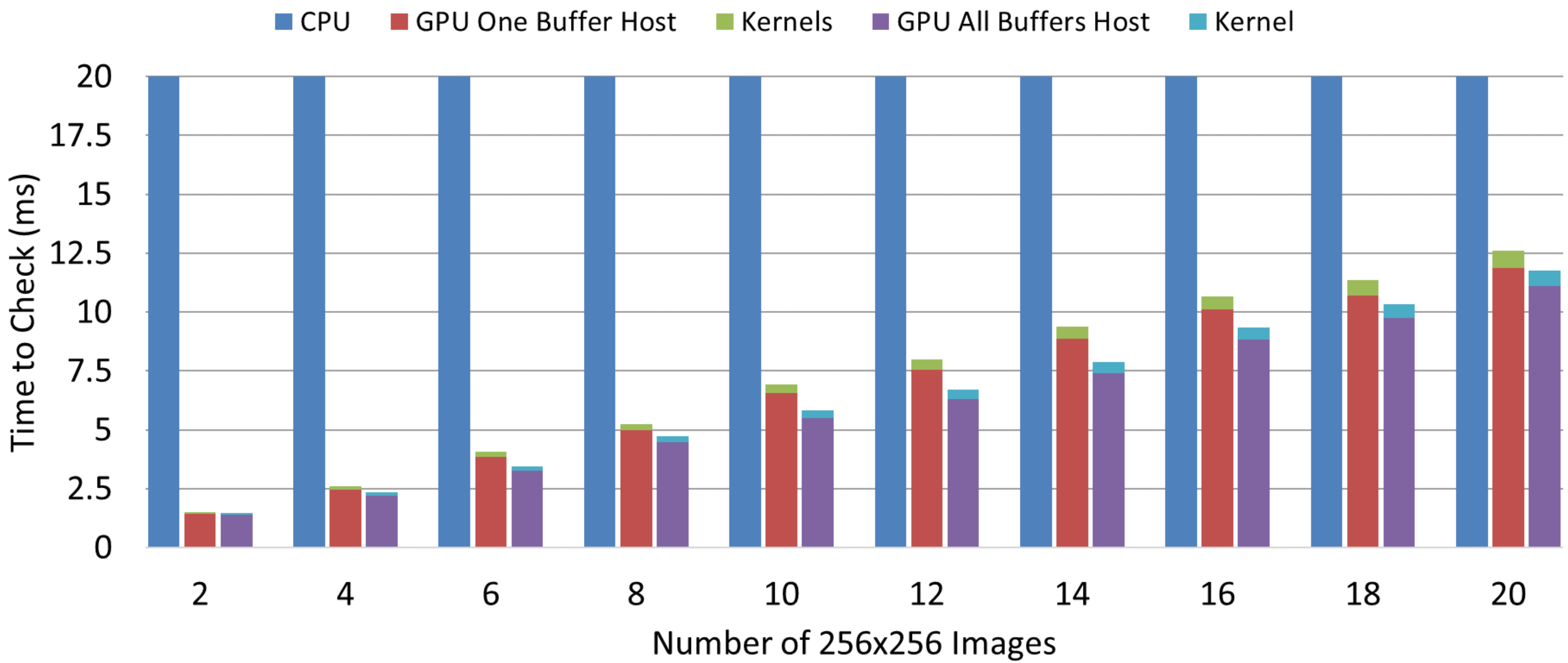

EXAMPLE ERROR

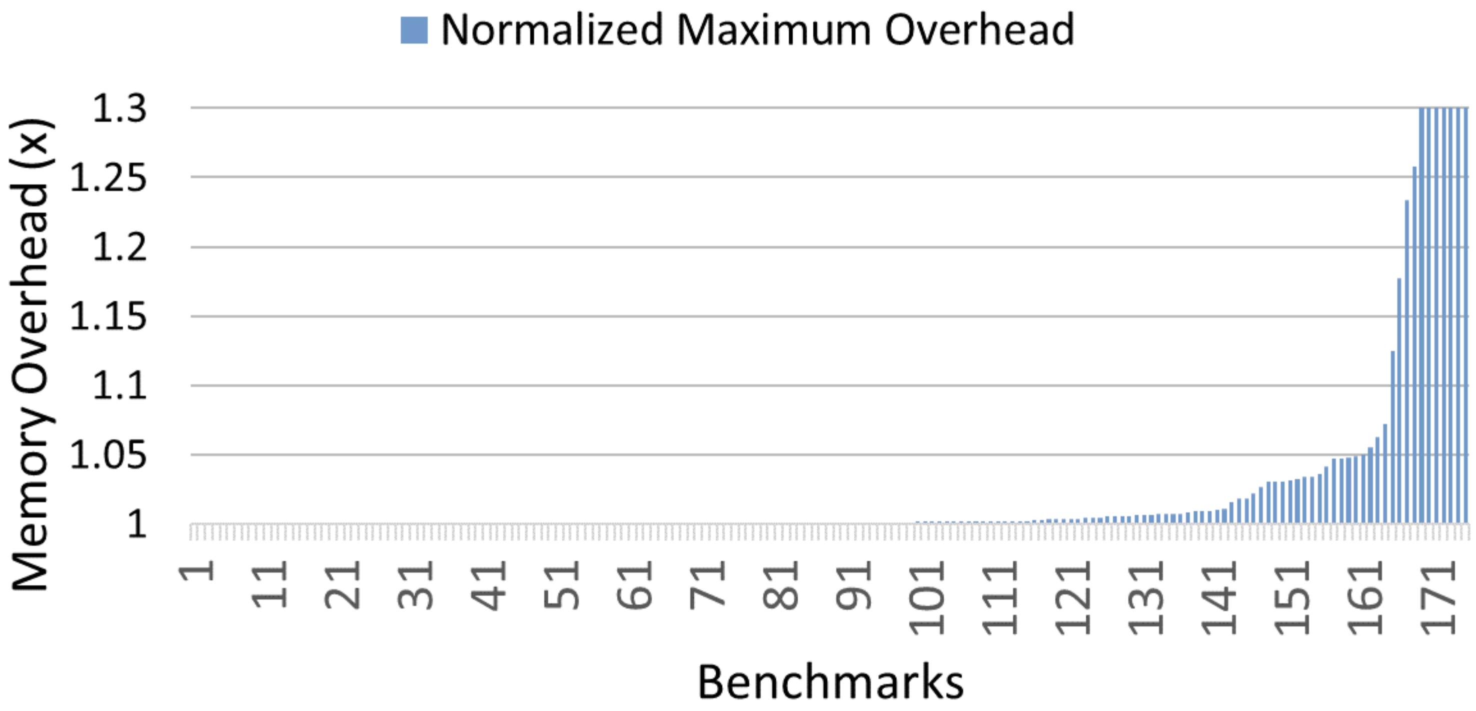
```
clARMOR: Loaded CL_WRAPPER
clARMOR:
clARMOR: ATTENTION:
clARMOR: ************** Buffer overflow detected ************
clARMOR: Kernel: sw_compute0, Buffer: cu
clARMOR:     First observed writing 1 byte(s) past the end.
clARMOR:
clARMOR: Exiting application because of buffer overflow.
```


CPU
GPU One Buffer Host
Kernels
GPU All Buffers Host
Kernel
1000
750
500
250
0
Time to Check (µs)
2
4
6
8
10
12
14
16
18
20
Number of cl_mem Buffers

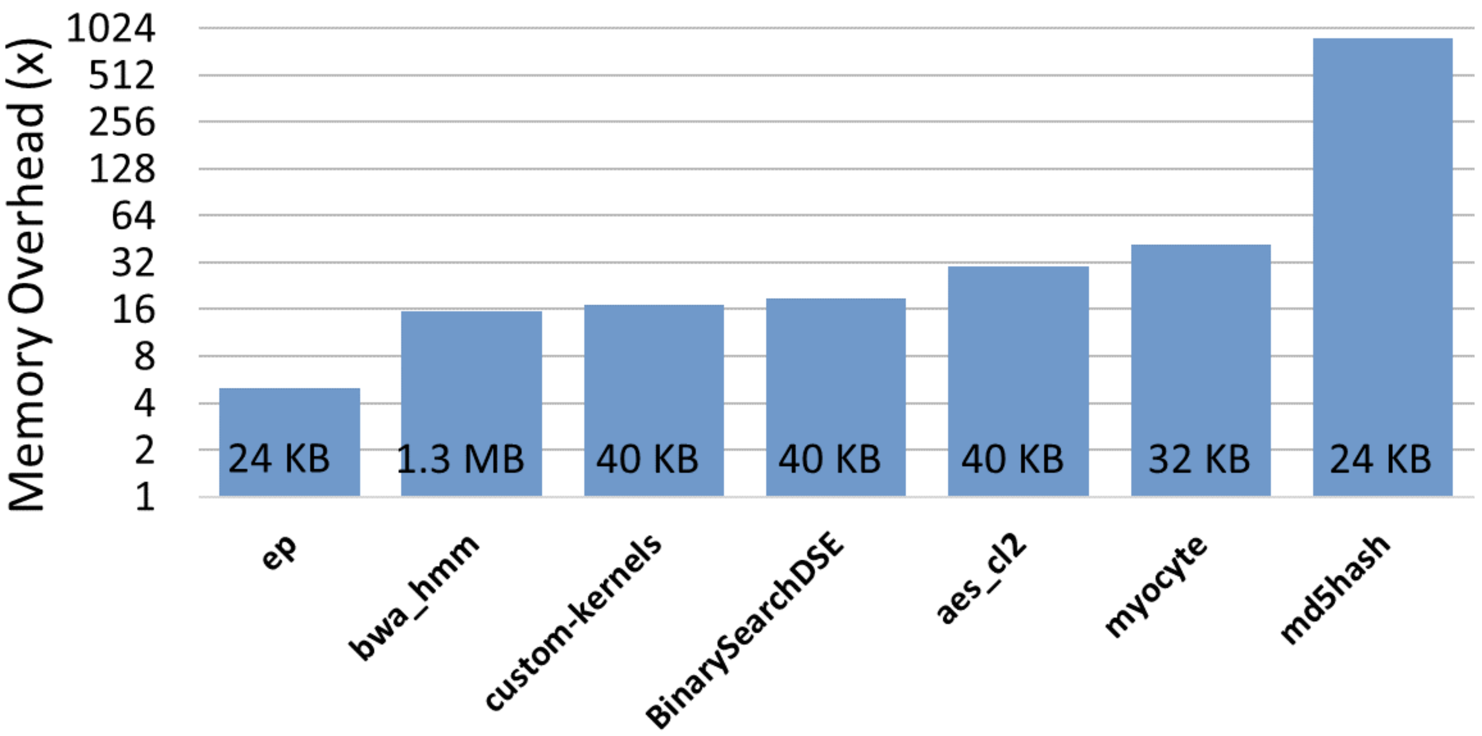

CPU
G 1-Buff Host
Kern
G AllBuff Host
Kern
G Ptrs Host
Kern
Time to Check (µs)
0
500
1000
1500
2000
2500
3000
3500
2
4
6
8
10
12
14
16
18
20
Number of SVM Buffers



CPU
GPU One Buffer Host
Kernels
GPU All Buffers Host
Kernel
Time to Check (ms)
0
2.5
5
7.5
10
12.5
15
17.5
20
2
4
6
8
10
12
14
16
18
20
Number of 256x256 Images



Normalized Maximum Overhead
Memory Overhead (x)
1.3
1.25
1.2
1.15
1.1
1.05
1
1
11
21
31
41
51
61
71
81
91
101
111
121
131
141
151
161
171
Benchmarks



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

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
  - OpenCL 2.0 sw, 4 errors
- SNU OpenCL
  - CG (data races resulting in negative indexing, underflow)
- Note: These have been reported, and most fixed.

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- [ ] Detect GPU Buffer Overflows
- [x] Compatible With Most OpenCL™
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CONSEQUENCES OF BUFFER OVERFLOWS

DEGRADING USER EXPERIENCE, AND SECURITY RISKS

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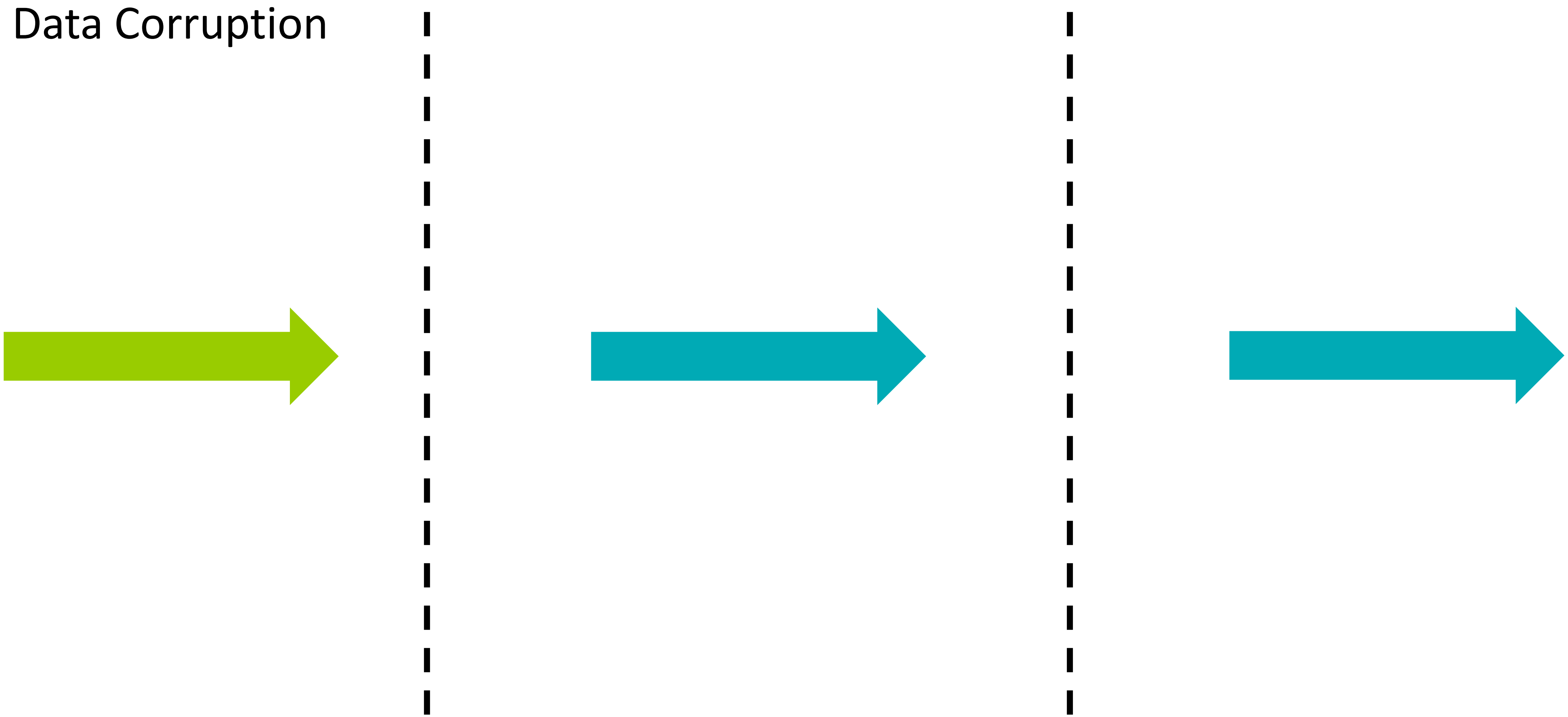
Data Corruption

CONSEQUENCES OF BUFFER OVERFLOWS

DEGRADING USER EXPERIENCE, AND SECURITY RISKS



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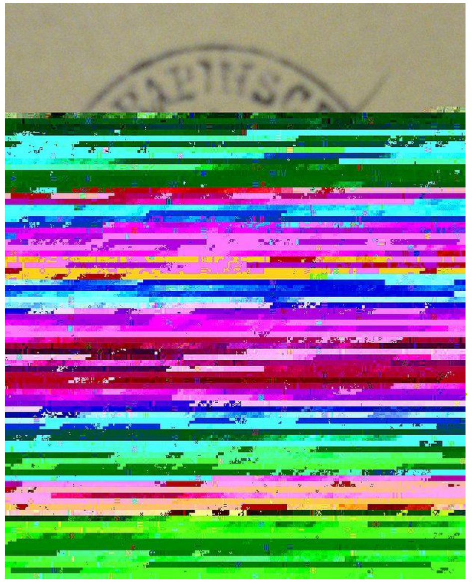

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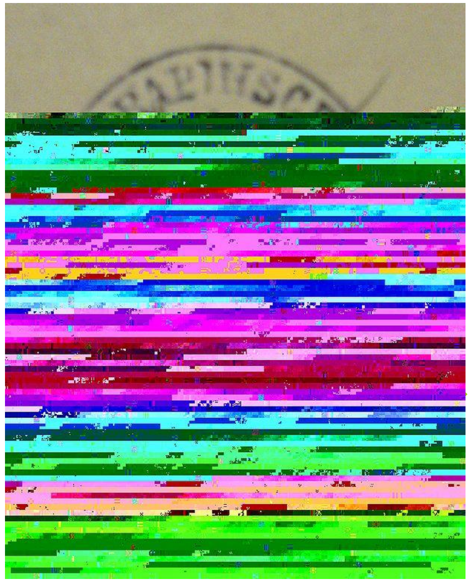

Segmentation Faults

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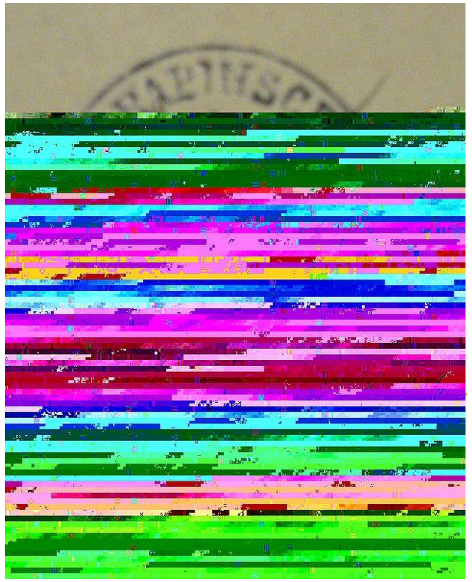

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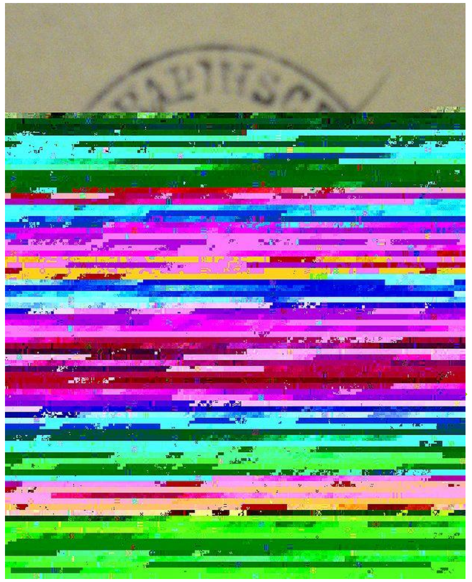

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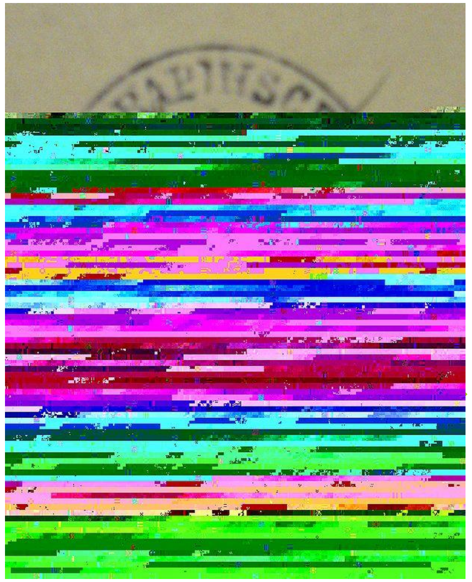

Segmentation Faults

Altered Control Flow

(Security Subversion)

CONSEQUENCES OF BUFFER OVERFLOWS

DEGRADING USER EXPERIENCE, AND SECURITY RISKS

AMD

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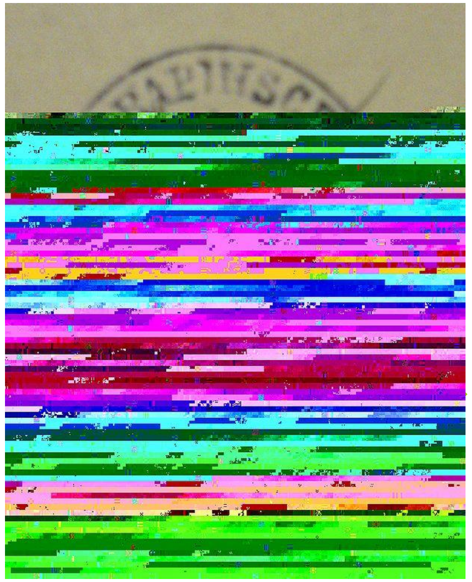

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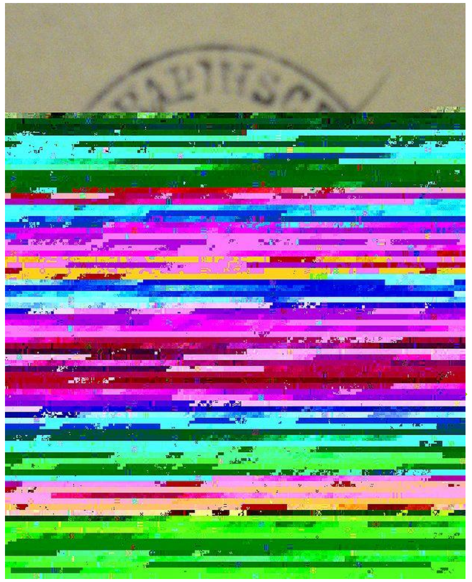

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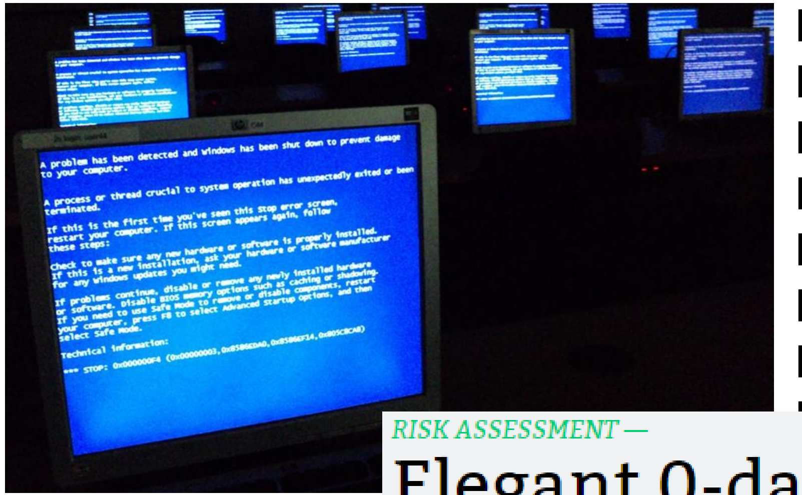

Altered Control Flow

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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