Pinpointing Resource Wastage with Profiling

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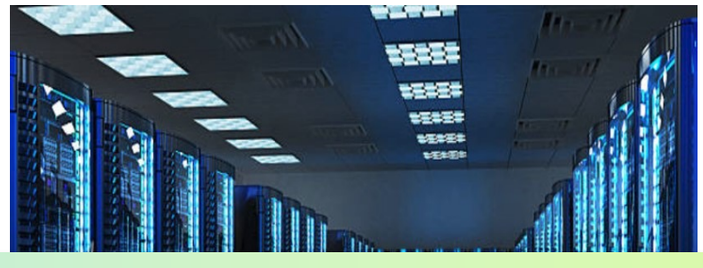
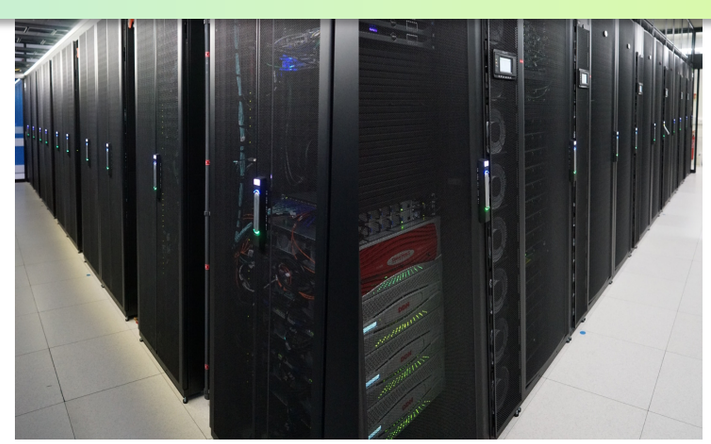
Resource Concerns are Everywhere





Programs need to be efficient at all scales

Time is Money

Drop sales by 1%
every 0.1s of latency

Drop traffic by 20%
every 0.5s of latency

Drop visitors by 40%
after 3s of latency

Classic Profiling Techniques

- Identify hotspot — high resource utilization
  - Time
  - CPU usage
  - Cache misses
  - Memory allocations
- Limitations
  - Not tell if resources are “**well spent**”
  - Need significant manual efforts to investigate root causes

Pinpoint resource wastage instead of utilization

Agenda

Profiling

- CPU memory wastage — ICSE'19, FSE'19, ICSE'22, CGO'23, TACO'23, CGO'26
- GPU memory wastage — ASPLOS'23, USENIX ATC'24, ASPLOS'26 (under review)

Wasteful Memory Operations

Silent load

```
x = A[i];
y = A[i];     y = x;
```

Silent store

```
A[i] = 10;
   x = A[i];
A[i] = 10;
```

Dead store

```
A[i] = 0;
A[i] = 10;
```

Two operations involved:
one is silent/dead
because of the killing one

Solution: binary analysis

A Motivating Example: SPEC CPU2006 Hmmer

- The compiler may do harm than good

Unoptimized

```
for (k = 1; k <= M; k++) {
  mc[k] = mpp[k-1] + tpmm[k-1];   First store
  if ((sc = ip[k-1] + tpim[k-1]) > mc[k])
    mc[k] = sc;   Second store      Used
```

-O3 optimized

```
1 for (k = 1; k <= M; k++) {
2    R1 = mpp[k-1] + tpmm[k-1];
3    mc[k] = R1;   Dead store
4    if ((sc = ip[k-1] + tpim[k-1]) > R1)
5      mc[k] = sc;   Second store
```

The compiler: they "alias" to same memory location

Necessity of Binary Analysis

```
1 for (k = 1; k <= M; k++) {
2    R1 = mpp[k-1] + tpmm[k-1];
3    [redacted]
4    if ((sc = ip[k-1] + tpim[k-1]) > R1)
5      mc[k] = sc;
```

```
else
   mc[k] = R1;
```

Dead store

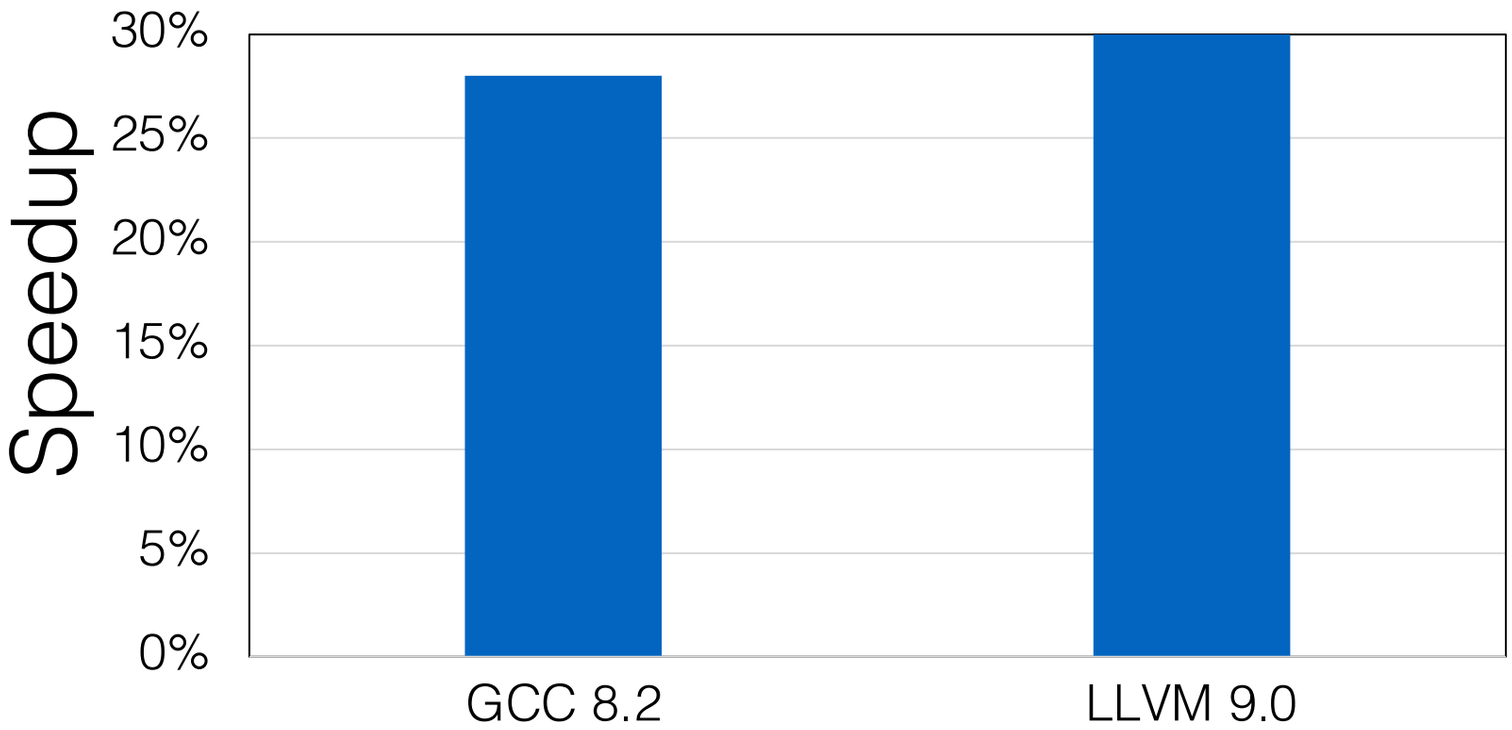
```
1 mov %r10,%rax,4), %ecx
2 add 0x0(%r13,%rax,4),%ecx   #mpp[k-1]+tpmm[k-1]
3 mov %ecx, 0x4(%rdx)         #assign mc[k]
```

The value of mc[k] in memory location 0x4(%rdx) is unused

```
10 mov %ecx, 0x4(%rdx)        #assign mc[k]
```

Optimization: conditional check

Hmmer's Speedup after Optimization



User Inputs

- Rodinia-3.1 backprop

```
1 for (j = 1; j <= ndelta; j++) {
2    new_dw = ETA * delta[j];
3    w[k][j] += new_dw;
4 }
```

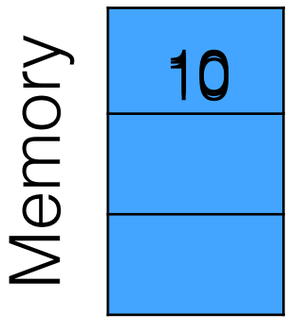
Optimization

```
1 for (j = 1; j <= ndelta; j++) {
2    if (delta[j] == 0) continue;
3    new_dw = ETA * delta[j];
4    w[k][j] += new_dw;
5 }
```

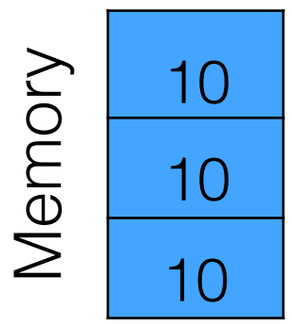
Optimization: conditional check
Speedup: 13%

Type of Silent Loads

- Temporal silent load
  - Repeatedly load the same value from the same memory location

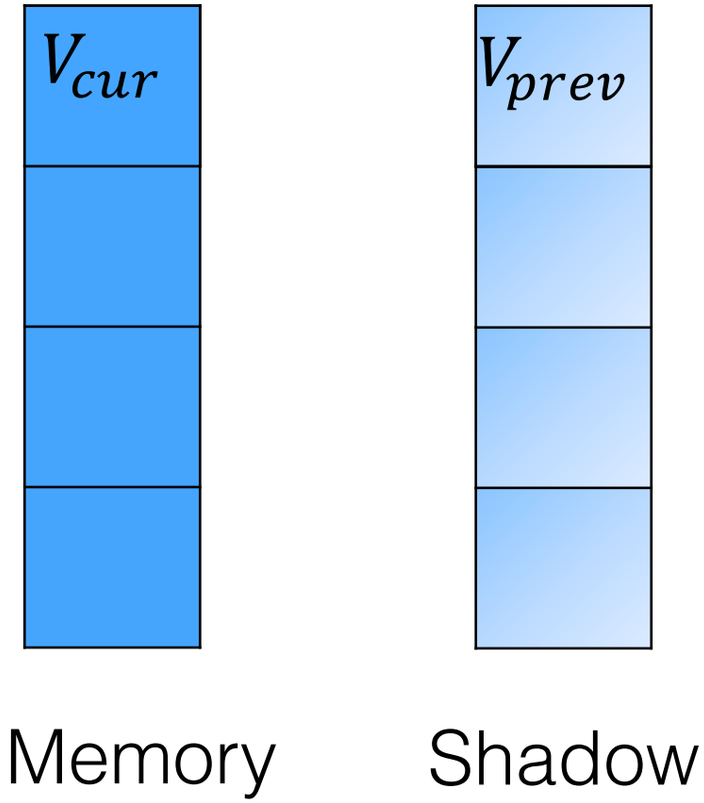


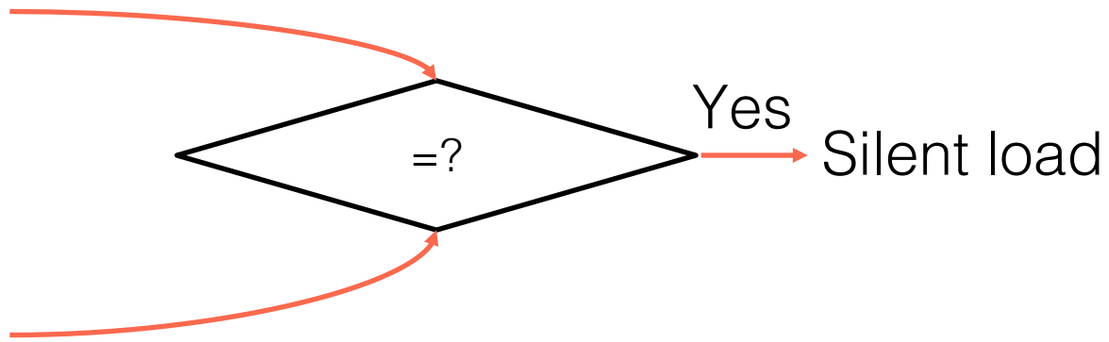
- Spatial silent load
  - Repeatedly load the same value from nearby memory locations



Temporal Silent Load Detection

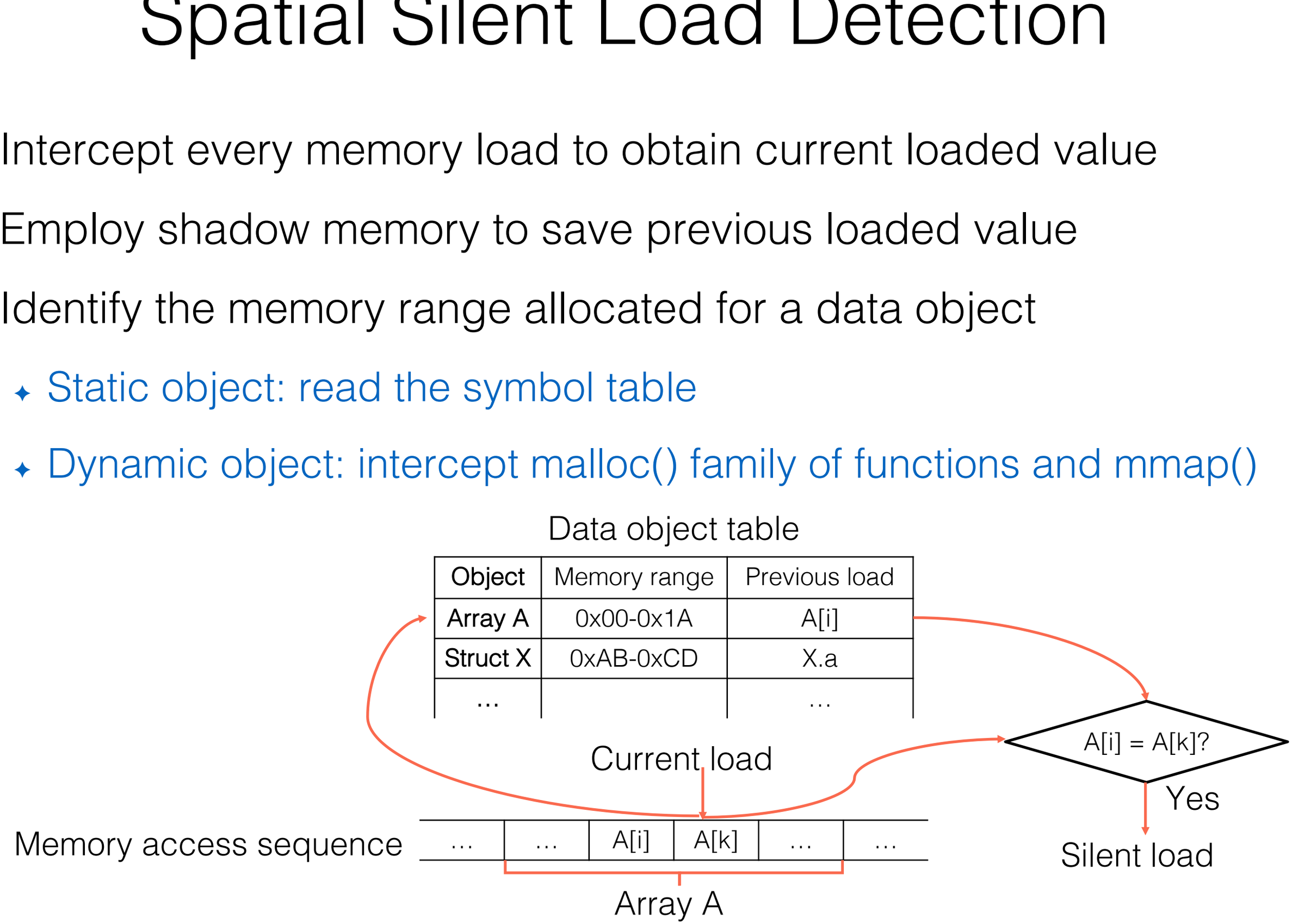
- Intercept every memory load to obtain current loaded value (V_{cur})
- Employ shadow memory to save previous loaded value (V_{prev})





Spatial Silent Load Detection

- Intercept every memory load to obtain current loaded value
- Employ shadow memory to save previous loaded value
- Identify the memory range allocated for a data object
  - Static object: read the symbol table
  - Dynamic object: intercept malloc() family of functions and mmap()



Case Studies

	Program		SLoC	Inefficiency	% of silent load reduction	Speedup
Benchmark	SPEC CPU2006	lbm	3K	Redundant computation	60%	1.25x
	SPEC CPU2017	imagick_r	274K	Redundant computation	51%	1.25x
	Rodinia-3.1	lavaMD	800	Redundant function calls	93%	1.39x
		srad_v1	600	Inefficient register usage	29%	1.11x
		srad_v2	200	Inefficient register usage	32%	1.12x
		particlefilter	600	Linear search	97%	9.8x
Application	Apache Avro-1.8.2		46K	Missing inline substitution	37%	1.19x
	Hoard-3.12		22K	Redundant computation	2%	1.14x
	MASNUM-2.2		121K	Linear search	36%	1.79x
	USQCD Chroma-3.43		929K	Missing inline substitution	7%	1.06x
	Shogun-6.0		546K	Missing inline substitution	2%	1.06x
	Facebook Stack RNN		2K	Redundant computation	15%	1.09x

Agenda

Profiling

CPU memory wastage

ICSE'19, FSE'19, ICSE'22, CGO'23, TACO'23, CGO'26

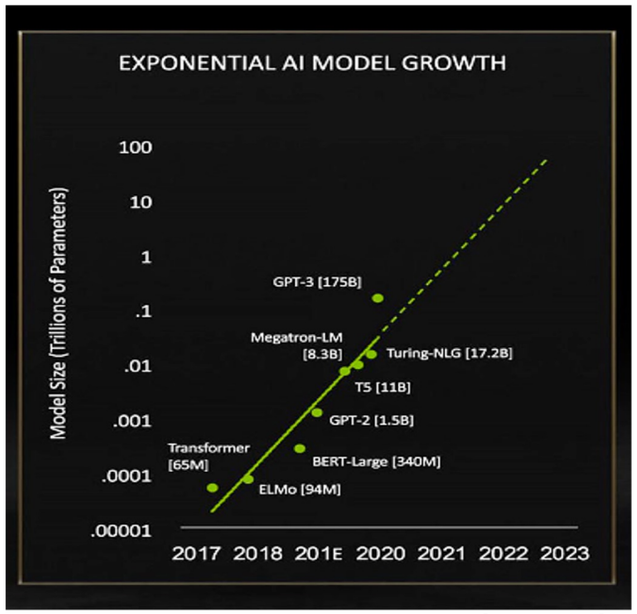
GPU memory wastage

ASPLOS'23, USENIX ATC'24, ASPLOS'26 (under review)

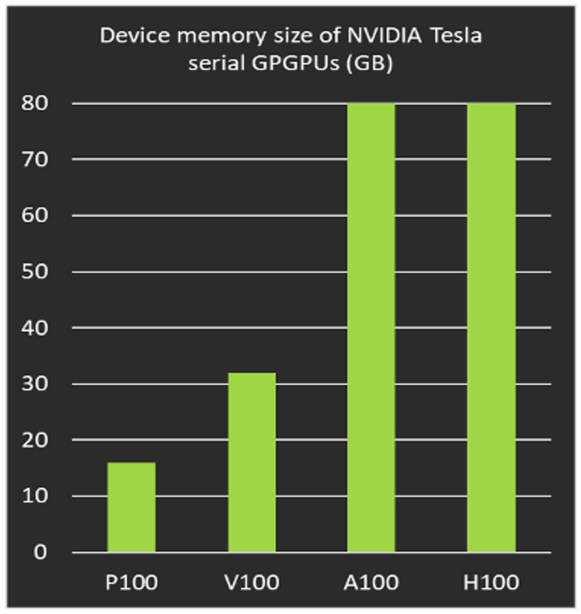
GPU Memory

- Problem 1: Fast-growing memory demand in DL
  - ✦ The trend of developing deeper and wider neural networks

    A trillion-parameter model with 3D parallelism requires 300+ A100 GPUs
- Problem 2: Slow-growing GPU memory budget
  - ✦ HBM must fit in small package space and chip periphery
  - ✦ Compared to increasing memory capacity, reducing memory latency is GPU vendors' top priority



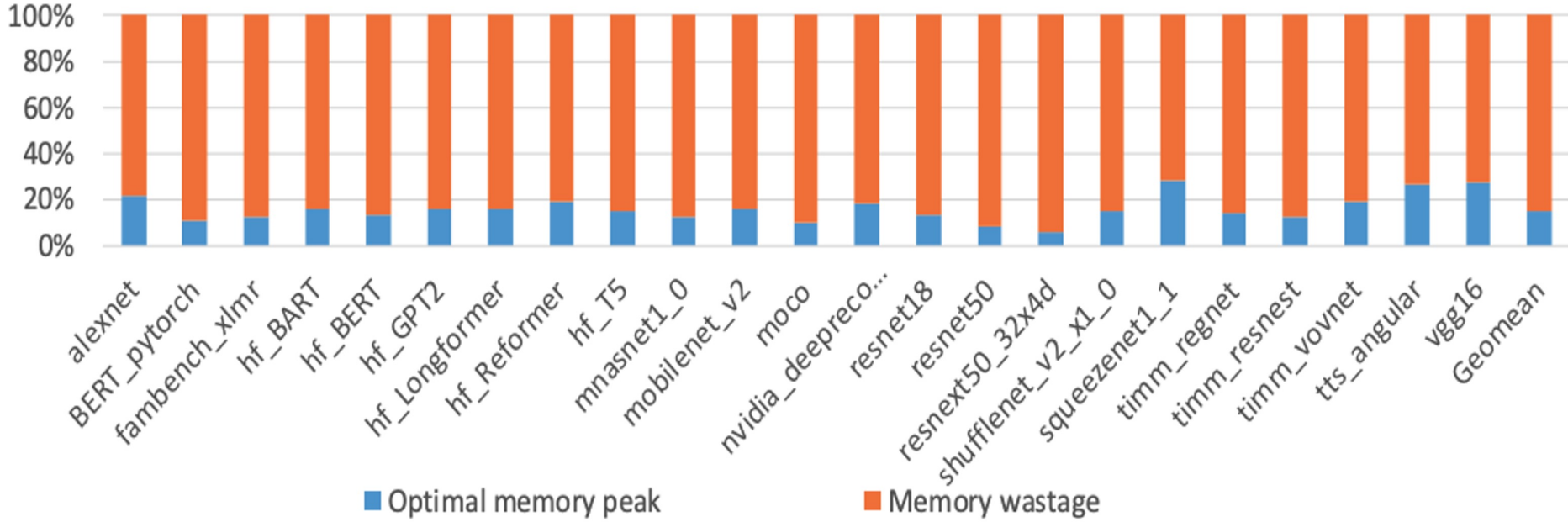
Fast-growing memory demand



Slow-growing GPU memory budget

GPU Memory

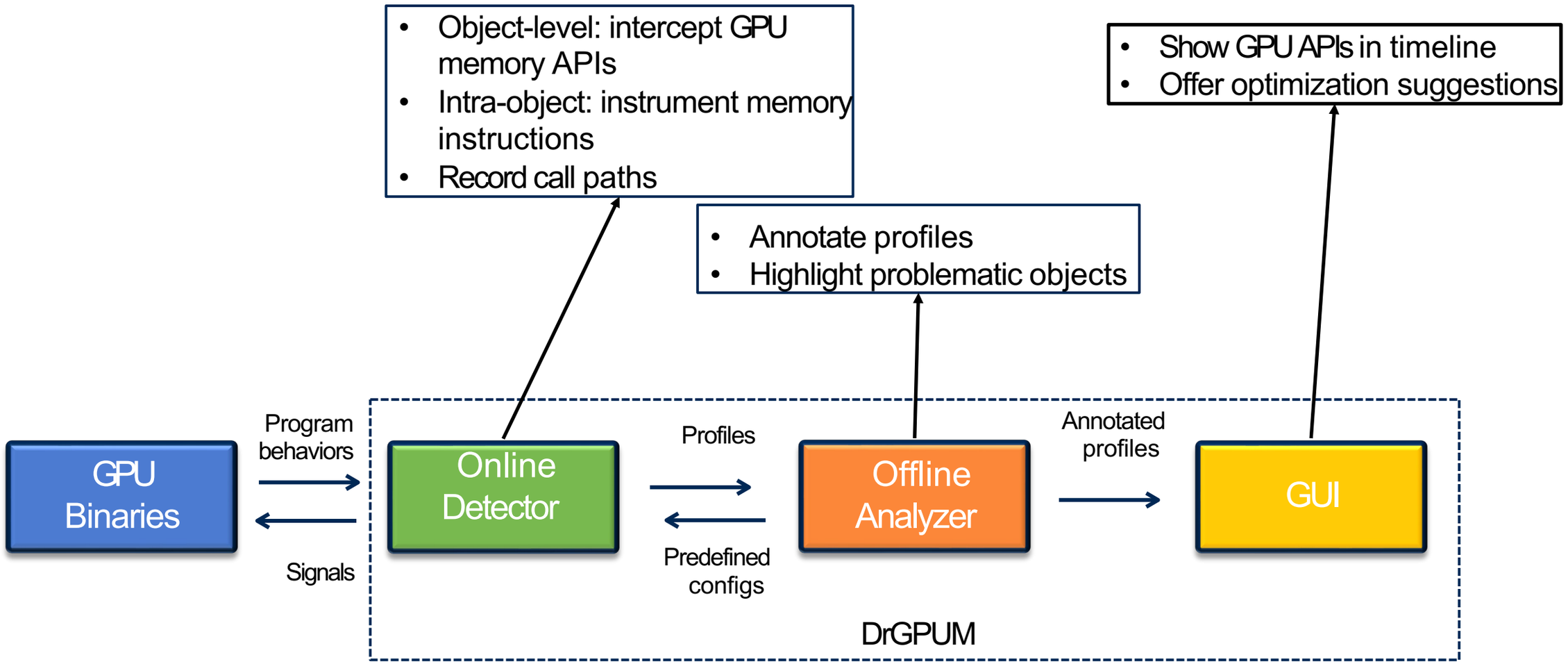
- Problem 3: Memory wastage is significant and pervasive across DL workloads



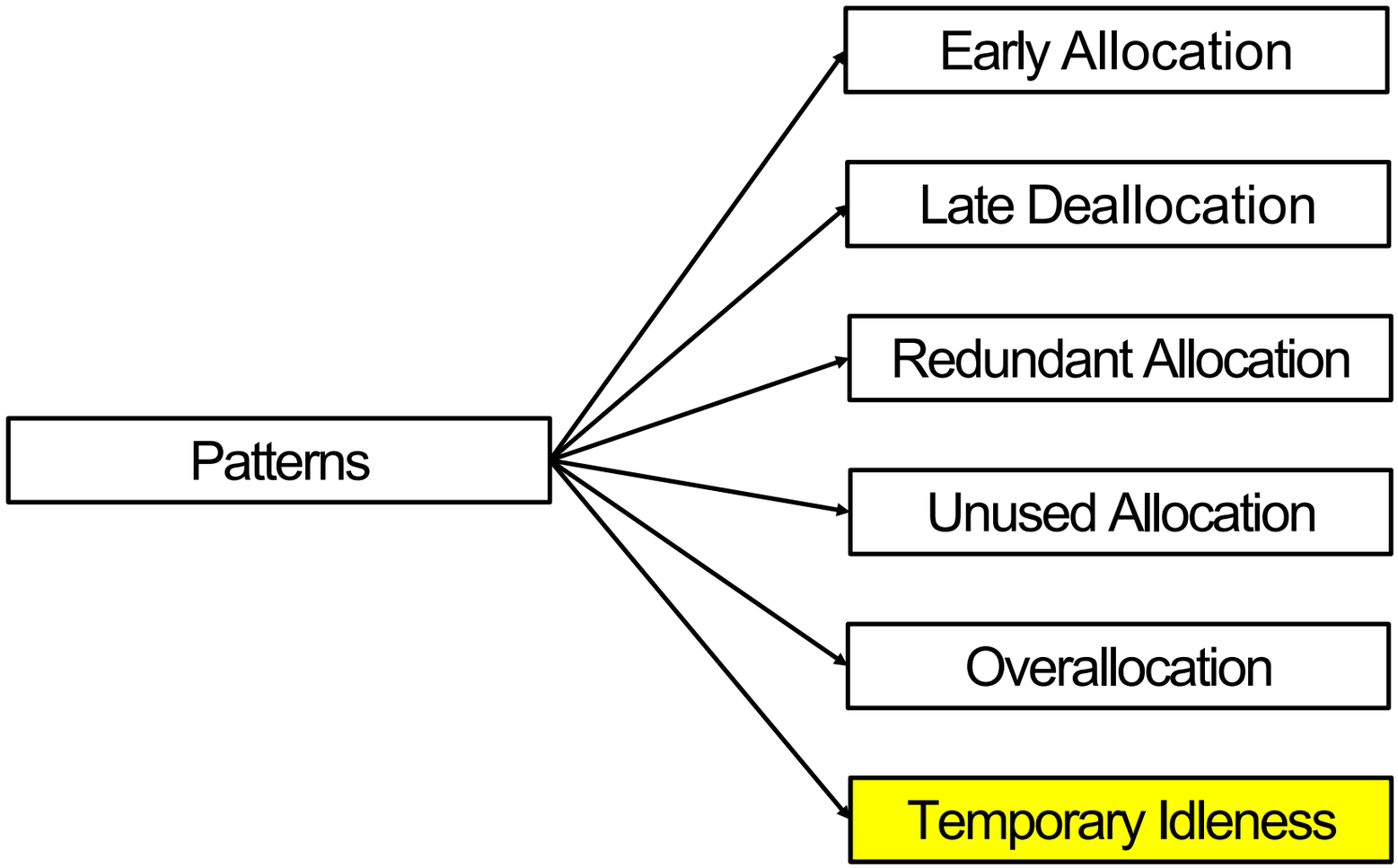
Memory wastage in popular DL models

Our Solution: DrGPUM

- A data-object-centric GPU profiler, including
  - Object-level analysis (e.g., arrays and tensors)
  - Intra-object analysis (e.g., individual elements in an array/tensor)

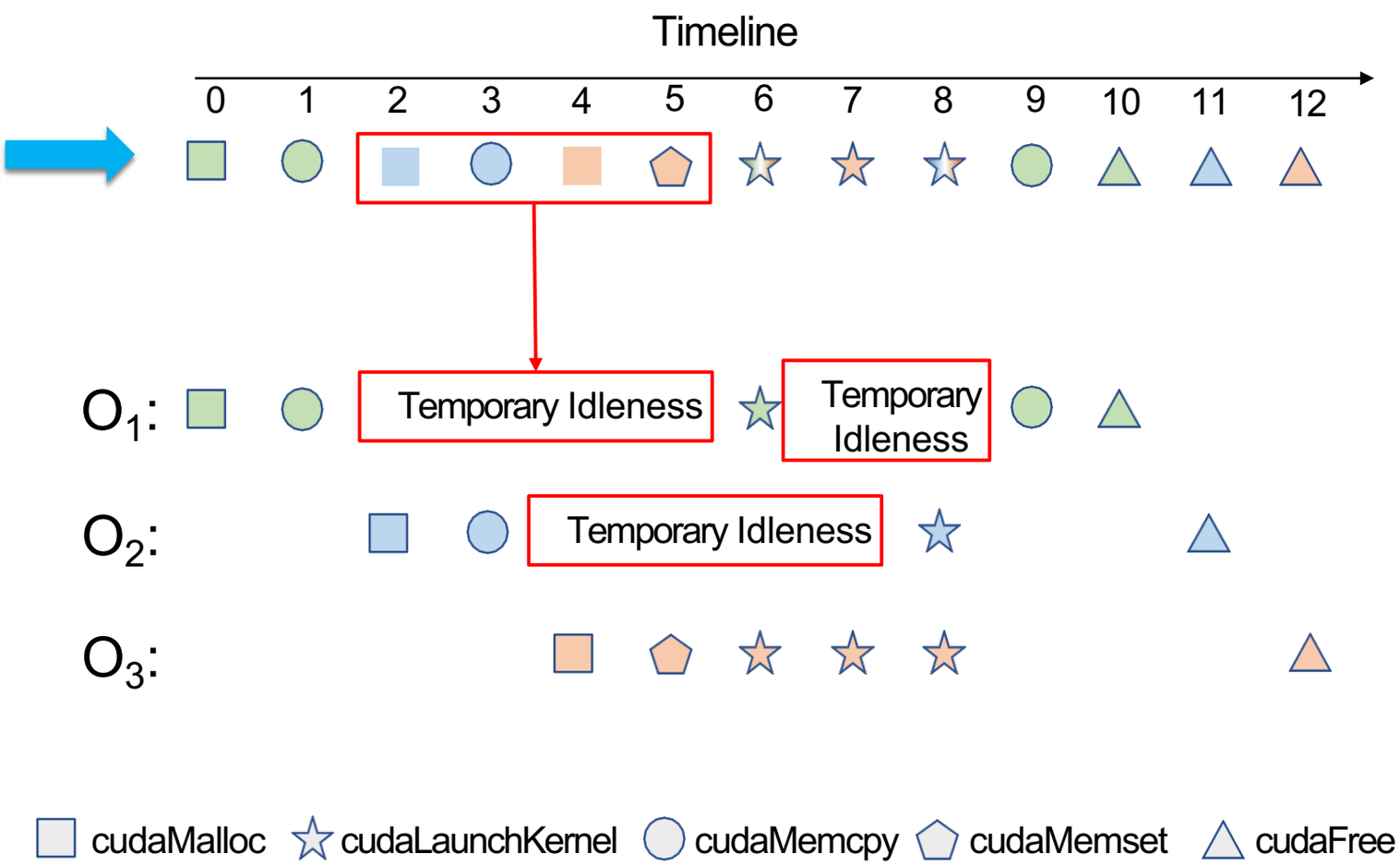


Identified Patterns of Memory Wastage



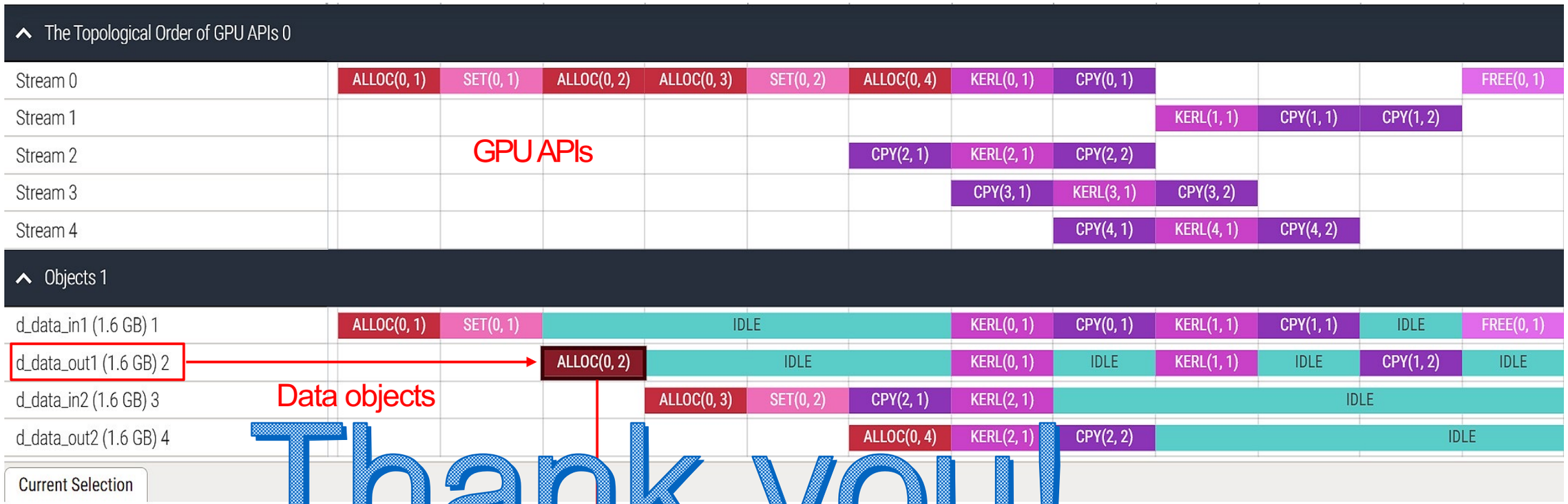
Late Deallocation

```
1. cudaMalloc(void*& O1, size)
2. cudaMemcpy(O1, hostptr, size,
cudaMemcpyDefault)

3. cudaMalloc(void*& O2, size)
4. cudaMemcpy(O2, hostptr, size,
cudaMemcpyDefault)

5. cudaMalloc(void*& O3, size)
6. cudaMemset(O3, 0, size)

7. kernel1<<<block, grid>>>(O1, O3)
8. kernel2<<<block, grid>>>(O3)
9. kernel3<<<block, grid>>>(O2, O3)

10.cudaMemcpy(hostptr, O3, size,
cudaMemcpyDefault)

11. cudaFree(O1)
12. cudaFree(O2)
13. cudaFree(O3)
```



Demo

- SimplyMultiCopy
  - A multi-stream program released with NVIDIA CUDA Toolkit



Thank you!

ALLOC(i, j): j^{th} cudaMalloc on Stream i
SET(i, j): j^{th} cudaMemset on Stream i
CPY(i, j): j^{th} cudaMemcpy on Stream i
KERL(i, j): j^{th} kernel launch on Stream i
FREE(i, j): j^{th} cudaFree on Stream i