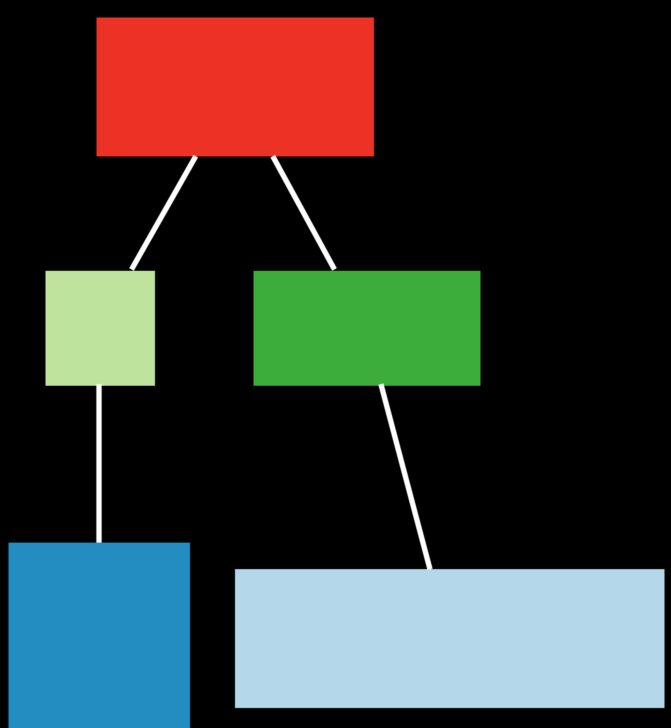
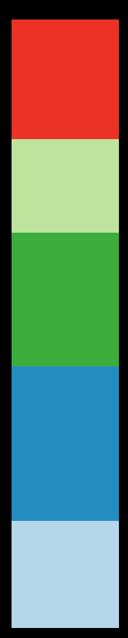
Is It Possible to Code an Efficient Software Switch?

Linearizing the Heap, and the Pervasive Use of Hardware Accelerators



Nick Mitchell
along with Ioana Baldini, Peter Sweeney
IBM T.J. Watson Research Center

July 31, 2014



What Nick Does:

Work with IBM customers and developers to make their applications run well

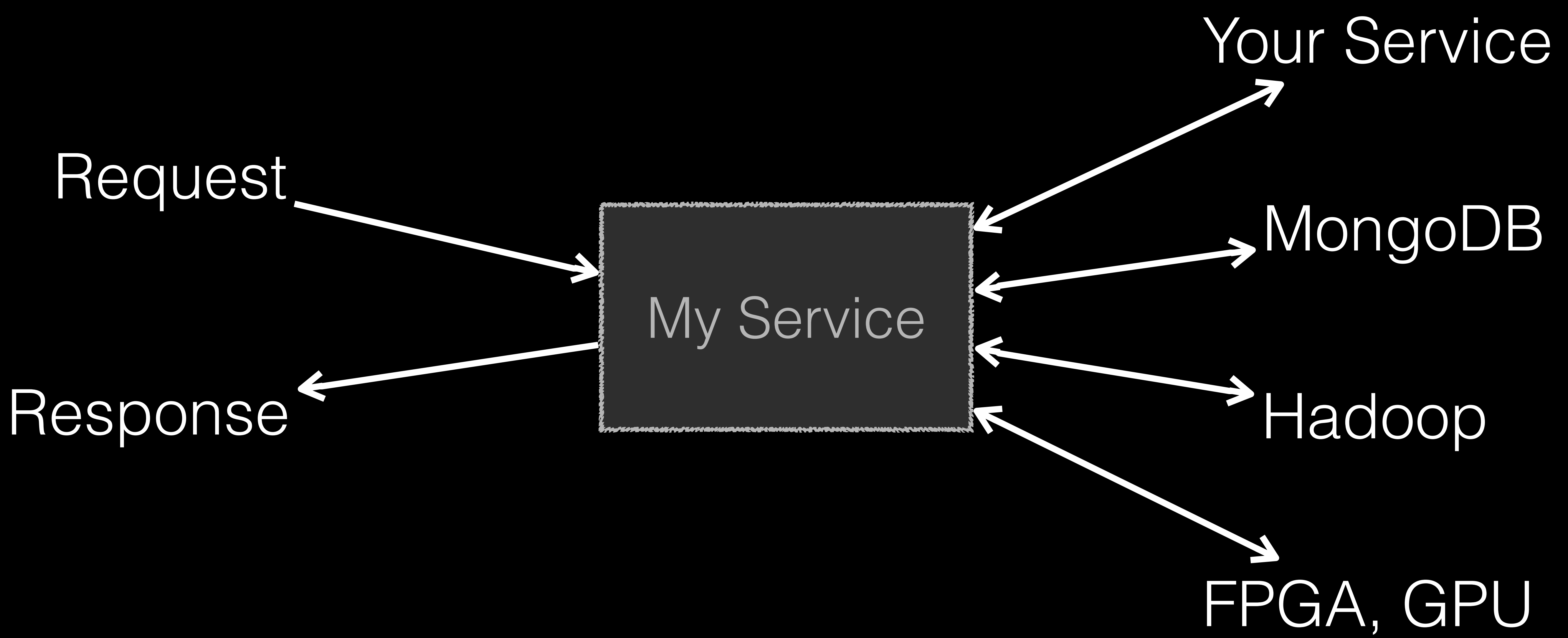
the data herein is backed by thousands of real apps

Summer School Means

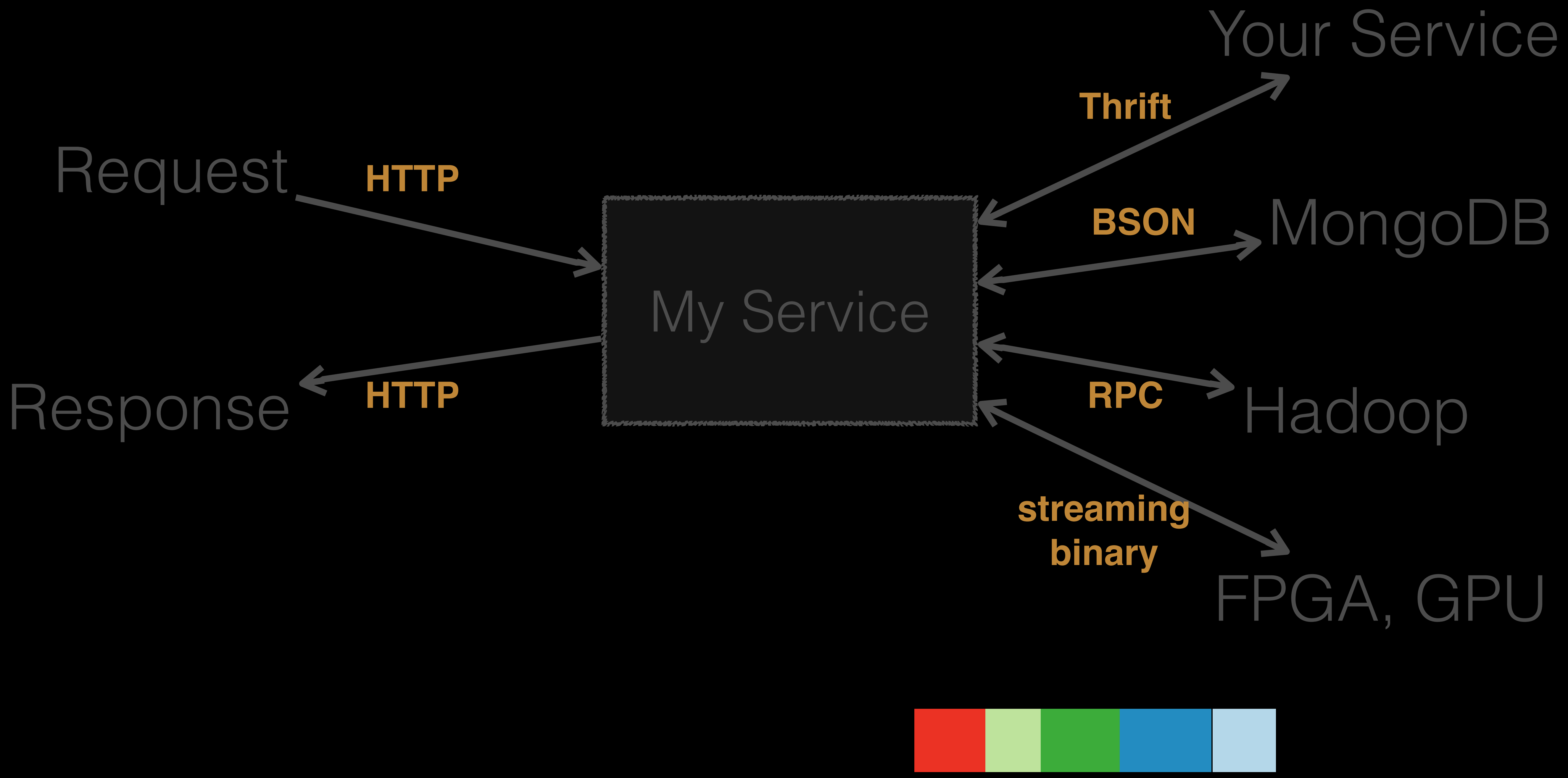
Nick Learns At Least As Much From You, As You From Him

0. The Apps

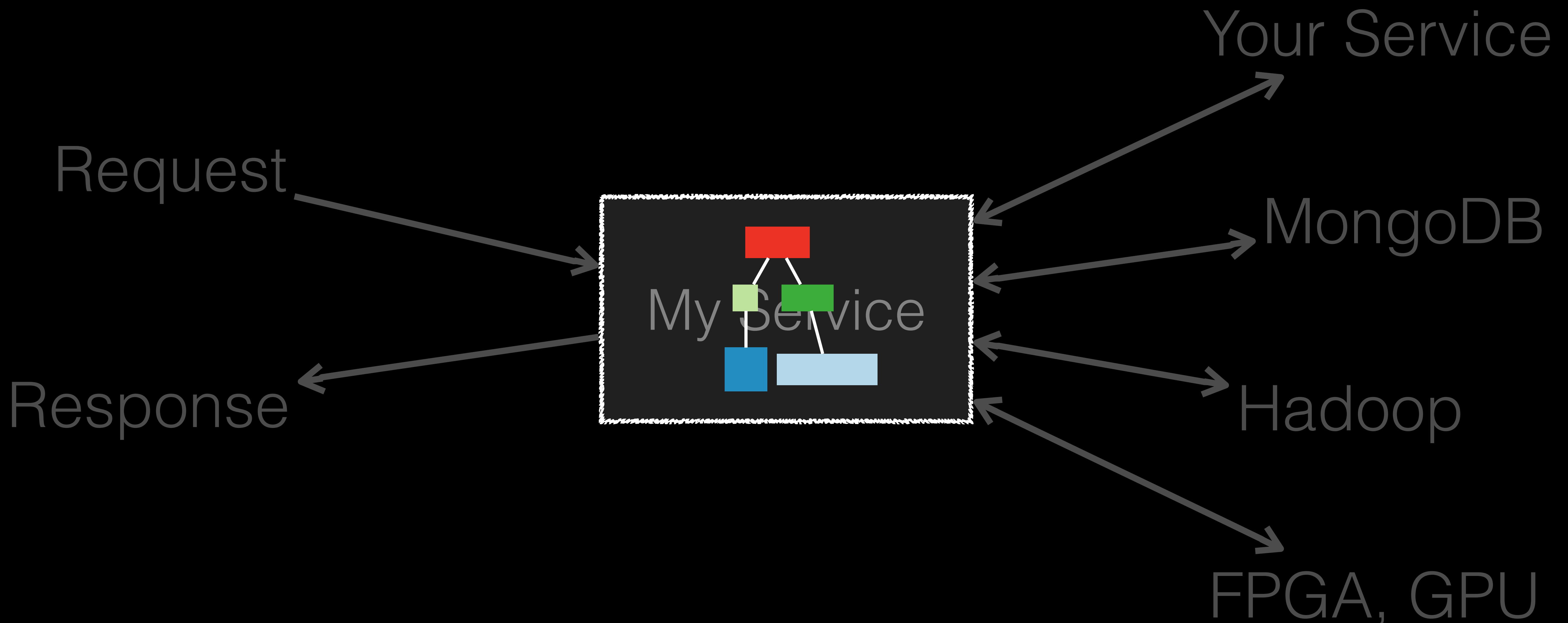
Most of Our Data Comes from Somewhere Else



Each Source Has its Own Wire Protocol



Each Service Has its Operational Form



Solutions Denied:

(but worth learning from)

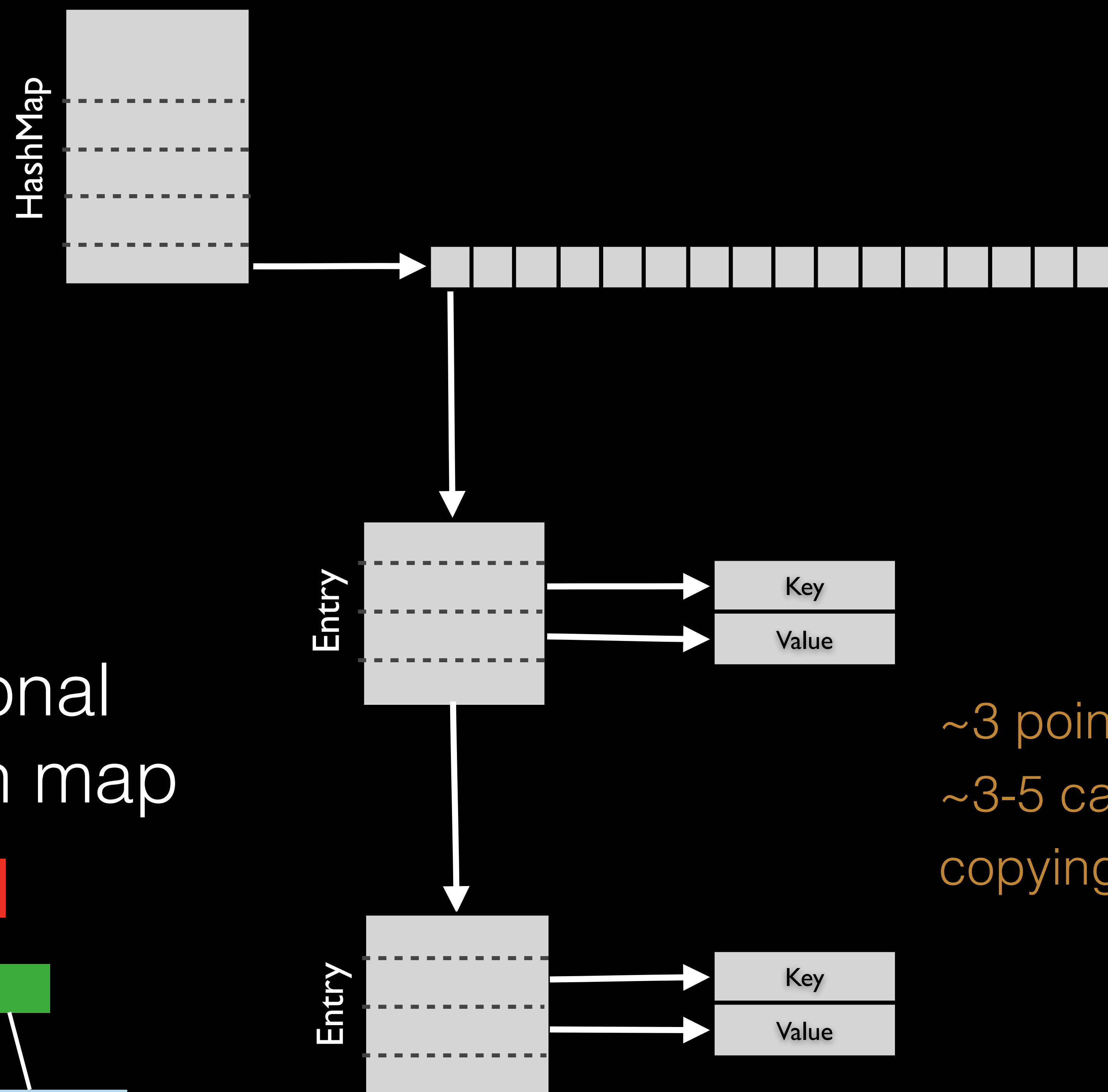
keep everything in memory
code in a systems language

Summary

- Programmers are plumbers who write software switches
- ECOOP Languages offer poor support for efficient software switches, because of the distance between operational and wire forms
- Amdahl's Law strikes again, severely limiting the use of specialized computational circuitry
- What are our options for doing better?

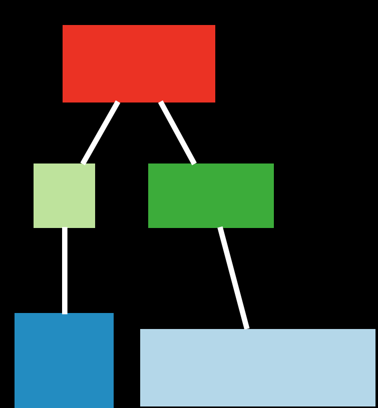
1. Initial Thought Exercises

Implement an Efficient Map



a conventional
chained hash map

c.f.



~3 pointers per entry

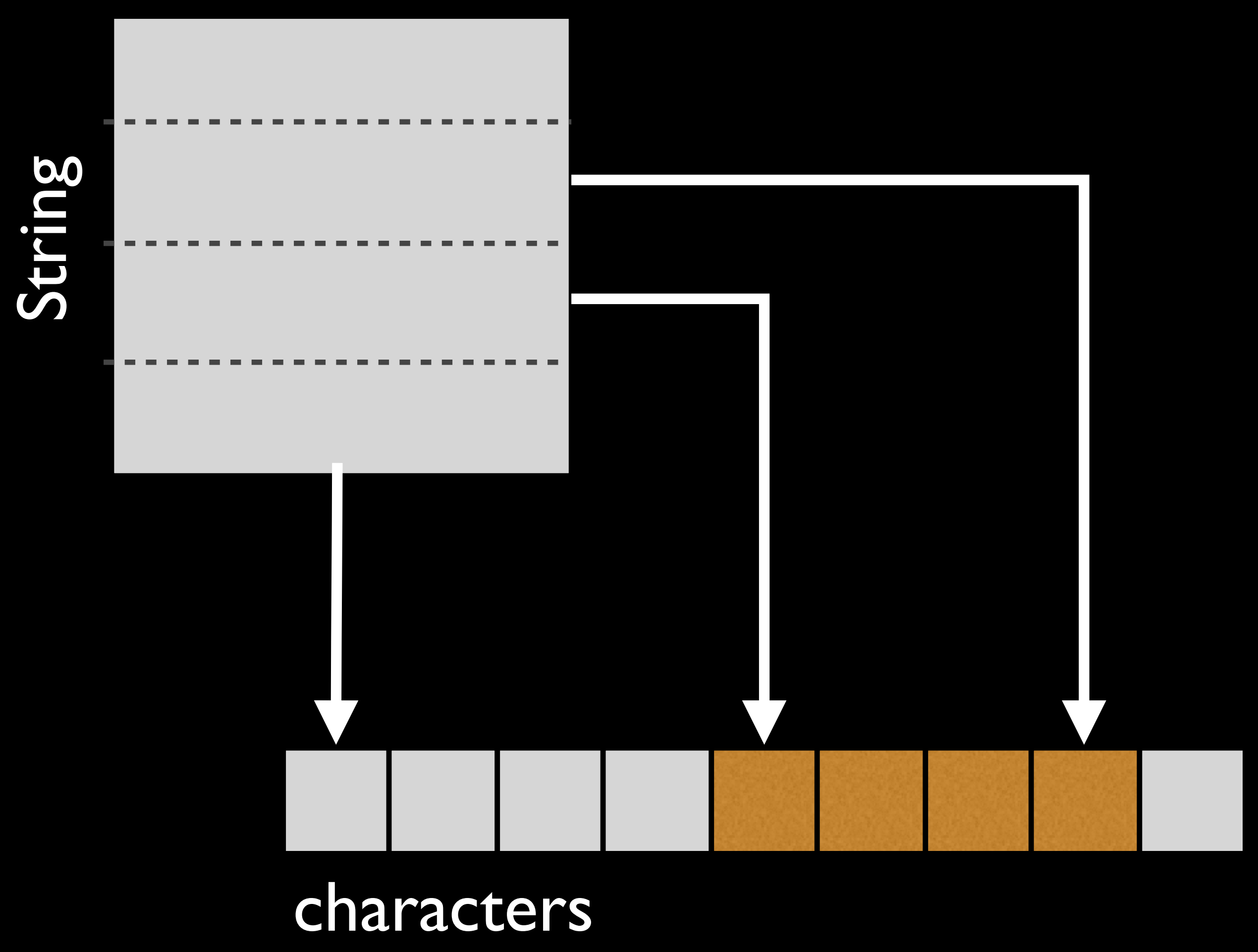
~3-5 cache misses per GET

copying required for RPC

Implement This Without Copying Any Bits Into the Heap

update this value

Implement an Efficient String



4–8 bytes of data

24–50 bytes of non-data

8–33% efficiency

2. Programmers as Plumbers

For Example...

(a JAX-RS RESTful web app)

```
@POST
@Path(“cart/add”)
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam(“session”) Cookie session,
                   @FormParam(“item”) int itemCode,
                   @FormParam(“quantity”) int quantity) {

   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

Dispatch and Routing

```
@POST
@Path("cart/add")
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam("session") Cookie session,
                   @FormParam("item") int itemCode,
                   @FormParam("quantity") int quantity) {

   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

Protocol Unwrapping

```
@POST
@Path("cart/add")
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam("session") Cookie session,
                   @FormParam("item") int itemCode,
                   @FormParam("quantity") int quantity) {

   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

Deserialization into Application Data Structures

```
@POST
@Path("cart/add")
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam("session") Cookie session,
                   @FormParam("item") int itemCode,
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   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

Application Logic!

```
@POST
@Path(“cart/add”)
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam(“session”) Cookie session,
                   @FormParam(“item”) int itemCode,
                   @FormParam(“quantity”) int quantity) {

   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

(a lonely increment operation)

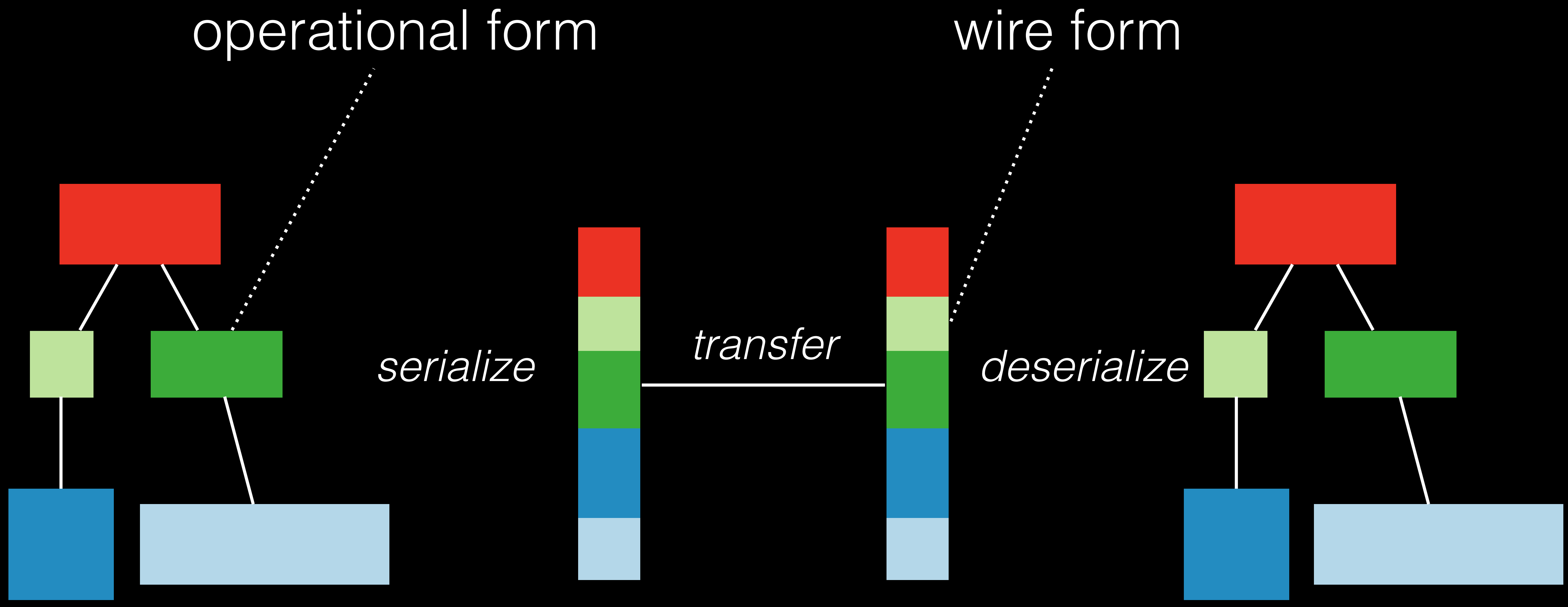
Serialize Application Data Structures Back into a Response

```
@POST
@Path("cart/add")
@Consumes(MediaType.MULTIPART_FORM_DATA)
@Produces(MediaType.APPLICATON_JSON)

Response addToCart(@CookieParam("session") Cookie session,
                   @FormParam("item") int itemCode,
                   @FormParam("quantity") int quantity) {

   ShoppingCart cart = new ShoppingCart(session);
   cart.add(itemCode, quantity);
   return Response.ok(cart.status())
                  .cookie(cart.toCookie())
                  .build();
}
```

Marshalling and Data Formats



3. The Profitability Threshold

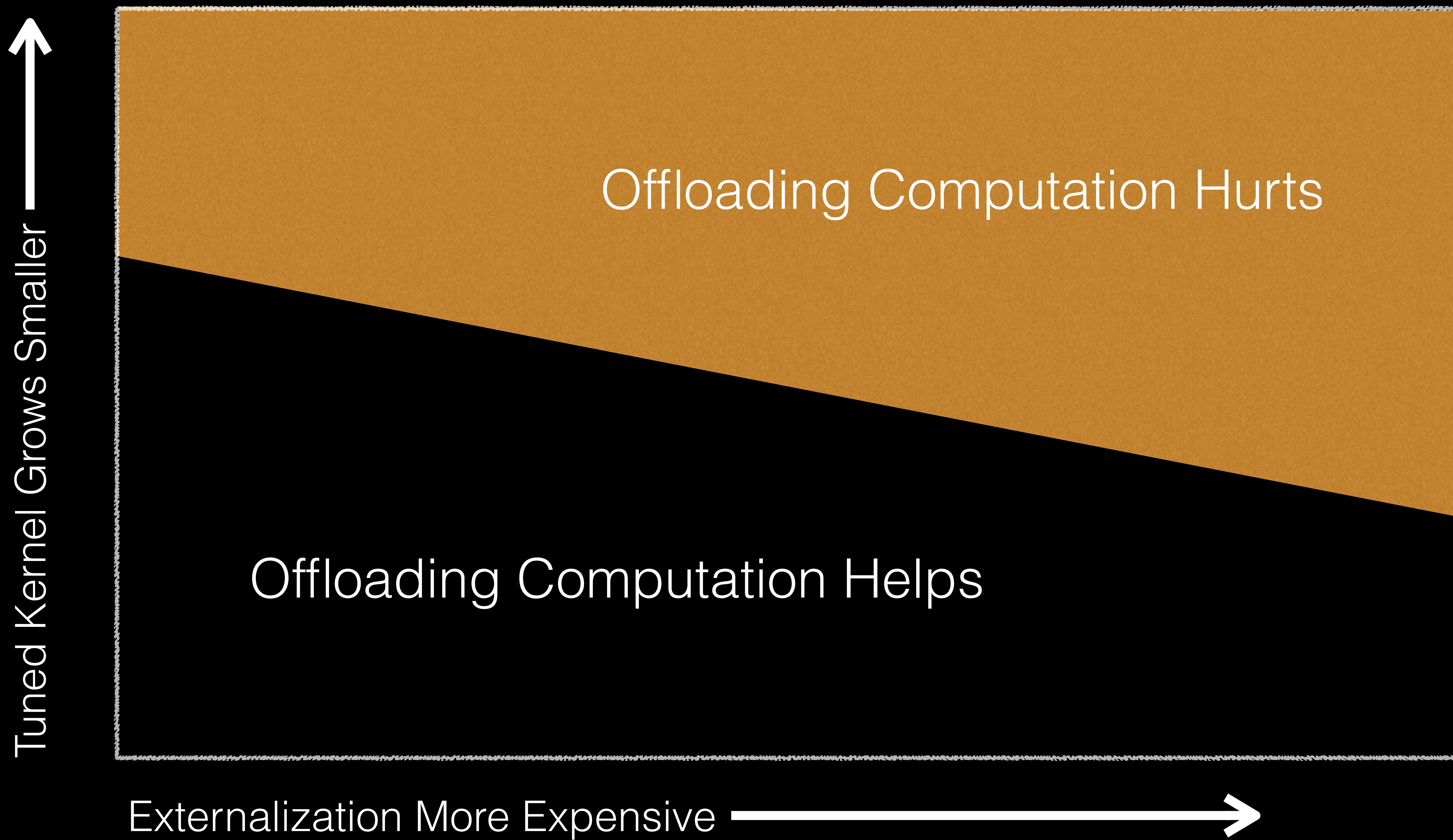
Trade-offs

- At what point does externalizing a computation become more pain than it's worth?

- granularity of kernel
- cost of externalization
- accelerator speedup

Amdahl's Law

Amdahl's Law



Tuned Kernel Grows Smaller
Offloading Computation Hurts
Offloading Computation Helps
Externalization More Expensive

Amdahl's Law

make kernel 6.25% faster

0.29%	-4.50%	-8.85%	-12.82%	-16.47%	-19.81%	-22.91%	-25.77%	-28.42%	-30.90%	-33.20%	-35.36%	-37.39%	-39.29%	-41.08%	-42.76%	-44.36%	-45.86%	-47.29%	-48.64%	-49.93%
0.58%	-4.24%	-8.61%	-12.60%	-16.26%	-19.63%	-22.73%	-25.61%	-28.28%	-30.76%	-33.08%	-35.24%	-37.27%	-39.18%	-40.98%	-42.67%	-44.27%	-45.78%	-47.21%	-48.57%	-49.86%
0.87%	-3.97%	-8.37%	-12.38%	-16.06%	-19.44%	-22.56%	-25.45%	-28.13%	-30.62%	-32.95%	-35.12%	-37.16%	-39.07%	-40.88%	-42.57%	-44.18%	-45.69%	-47.13%	-48.49%	-49.78%
1.17%	-3.70%	-8.13%	-12.16%	-15.86%	-19.25%	-22.39%	-25.29%	-27.98%	-30.48%	-32.82%	-35.00%	-37.05%	-38.97%	-40.77%	-42.48%	-44.09%	-45.61%	-47.05%	-48.41%	-49.71%
1.46%	-3.43%	-7.88%	-11.94%	-15.65%	-19.07%	-22.21%	-25.13%	-27.83%	-30.34%	-32.69%	-34.88%	-36.93%	-38.86%	-40.67%	-42.38%	-44.00%	-45.52%	-46.97%	-48.34%	-49.64%
1.76%	-3.17%	-7.64%	-11.71%	-15.45%	-18.88%	-22.04%	-24.96%	-27.68%	-30.20%	-32.55%	-34.76%	-36.82%	-38.75%	-40.57%	-42.29%	-43.90%	-45.44%	-46.88%	-48.26%	-49.56%
2.06%	-2.89%	-7.39%	-11.49%	-15.24%	-18.69%	-21.86%	-24.80%	-27.53%	-30.06%	-32.42%	-34.63%	-36.70%	-38.64%	-40.47%	-42.19%	-43.81%	-45.35%	-46.80%	-48.18%	-49.49%
2.36%	-2.62%	-7.14%	-11.26%	-15.03%	-18.49%	-21.69%	-24.64%	-27.37%	-29.92%	-32.29%	-34.51%	-36.59%	-38.53%	-40.37%	-42.09%	-43.72%	-45.26%	-46.72%	-48.10%	-49.42%
2.67%	-2.35%	-6.89%	-11.03%	-14.82%	-18.30%	-21.51%	-24.47%	-27.22%	-29.78%	-32.16%	-34.38%	-36.47%	-38.42%	-40.26%	-42.00%	-43.63%	-45.18%	-46.64%	-48.03%	-49.34%
2.97%	-2.07%	-6.64%	-10.81%	-14.61%	-18.11%	-21.33%	-24.31%	-27.07%	-29.63%	-32.03%	-34.26%	-36.35%	-38.32%	-40.16%	-41.90%	-43.54%	-45.09%	-46.56%	-47.95%	-49.27%
3.28%	-1.79%	-6.39%	-10.58%	-14.40%	-17.92%	-21.15%	-24.14%	-26.91%	-29.49%	-31.89%	-34.13%	-36.23%	-38.21%	-40.06%	-41.80%	-43.45%	-45.00%	-46.47%	-47.87%	-49.19%
3.59%	-1.51%	-6.14%	-10.34%	-14.19%	-17.72%	-20.97%	-23.98%	-26.76%	-29.35%	-31.76%	-34.01%	-36.12%	-38.09%	-39.95%	-41.70%	-43.35%	-44.91%	-46.39%	-47.79%	-49.12%
3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.52%	-20.79%	-23.81%	-26.60%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%	-41.61%	-43.26%	-44.83%	-46.31%	-47.71%	-49.04%
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4.52%	-0.67%	-5.37%	-9.64%	-13.55%	-17.13%	-20.43%	-23.47%	-26.29%	-28.91%	-31.35%	-33.63%	-35.76%	-37.76%	-39.64%	-41.41%	-43.08%	-44.65%	-46.14%	-47.55%	-48.89%
4.84%	-0.38%	-5.11%	-9.41%	-13.33%	-16.93%	-20.24%	-23.30%	-26.14%	-28.77%	-31.22%	-33.50%	-35.64%	-37.65%	-39.53%	-41.31%	-42.98%	-44.56%	-46.06%	-47.47%	-48.82%
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5.48%	0.19%	-4.59%	-8.93%	-12.90%	-16.53%	-19.88%	-22.96%	-25.82%	-28.47%	-30.94%	-33.25%	-35.40%	-37.42%	-39.32%	-41.11%	-42.79%	-44.38%	-45.89%	-47.31%	-48.67%
5.80%	0.49%	-4.32%	-8.69%	-12.68%	-16.33%	-19.69%	-22.79%	-25.66%	-28.32%	-30.80%	-33.12%	-35.28%	-37.31%	-39.22%	-41.01%	-42.70%	-44.29%	-45.80%	-47.23%	-48.59%
6.13%	0.78%	-4.06%	-8.45%	-12.46%	-16.13%	-19.50%	-22.62%	-25.50%	-28.18%	-30.67%	-32.99%	-35.16%	-37.20%	-39.11%	-40.91%	-42.60%	-44.21%	-45.72%	-47.15%	-48.51%

Externalization More Expensive →

free externalization,
kernel is 100% of overall computation

Amdahl's Law

make kernel 6.25% faster

0.29%	-4.50%	-8.85%	-12.82%	-16.47%	-19.81%	-22.91%	-25.77%	-28.42%	-30.90%	-33.20%	-35.36%	-37.39%	-39.29%	-41.08%	-42.76%	-44.36%	-45.86%	-47.29%	-48.64%	-49.93%
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0.87%	-3.97%	-8.37%	-12.38%	-16.06%	-19.44%	-22.56%	-25.45%	-28.13%	-30.62%	-32.95%	-35.12%	-37.16%	-39.07%	-40.88%	-42.57%	-44.18%	-45.69%	-47.13%	-48.49%	-49.78%
1.17%	-3.70%	-8.13%	-12.16%	-15.86%	-19.25%	-22.39%	-25.29%	-27.98%	-30.48%	-32.82%	-35.00%	-37.05%	-38.97%	-40.77%	-42.48%	-44.09%	-45.61%	-47.05%	-48.41%	-49.71%
1.46%	-3.43%	-7.88%	-11.94%	-15.65%	-19.07%	-22.21%	-25.13%	-27.83%	-30.34%	-32.69%	-34.88%	-36.93%	-38.86%	-40.67%	-42.38%	-44.00%	-45.52%	-46.97%	-48.34%	-49.64%
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2.36%	-2.62%	-7.14%	-11.26%	-15.03%	-18.49%	-21.69%	-24.64%	-27.37%	-29.92%	-32.29%	-34.51%	-36.59%	-38.53%	-40.37%	-42.09%	-43.72%	-45.26%	-46.72%	-48.10%	-49.42%
2.67%	-2.35%	-6.89%	-11.03%	-14.82%	-18.30%	-21.51%	-24.47%	-27.22%	-29.78%	-32.16%	-34.38%	-36.47%	-38.42%	-40.26%	-42.00%	-43.63%	-45.18%	-46.64%	-48.03%	-49.34%
2.97%	-2.07%	-6.64%	-10.81%	-14.61%	-18.11%	-21.33%	-24.31%	-27.07%	-29.63%	-32.03%	-34.26%	-36.35%	-38.32%	-40.16%	-41.90%	-43.54%	-45.09%	-46.56%	-47.95%	-49.27%
3.28%	-1.79%	-6.39%	-10.58%	-14.40%	-17.92%	-21.15%	-24.14%	-26.91%	-29.49%	-31.89%	-34.13%	-36.23%	-38.21%	-40.06%	-41.80%	-43.45%	-45.00%	-46.47%	-47.87%	-49.19%
3.59%	-1.51%	-6.14%	-10.34%	-14.19%	-17.72%	-20.97%	-23.98%	-26.76%	-29.35%	-31.76%	-34.01%	-36.12%	-38.09%	-39.95%	-41.70%	-43.35%	-44.91%	-46.39%	-47.79%	-49.12%
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4.52%	-0.67%	-5.37%	-9.64%	-13.55%	-17.13%	-20.43%	-23.47%	-26.29%	-28.91%	-31.35%	-33.63%	-35.76%	-37.76%	-39.64%	-41.41%	-43.08%	-44.65%	-46.14%	-47.55%	-48.89%
4.84%	-0.38%	-5.11%	-9.41%	-13.33%	-16.93%	-20.24%	-23.30%	-26.14%	-28.77%	-31.22%	-33.50%	-35.64%	-37.65%	-39.53%	-41.31%	-42.98%	-44.56%	-46.06%	-47.47%	-48.82%
5.16%	-0.09%	-4.85%	-9.17%	-13.11%	-16.73%	-20.06%	-23.13%	-25.98%	-28.62%	-31.08%	-33.38%	-35.52%	-37.54%	-39.43%	-41.21%	-42.89%	-44.47%	-45.97%	-47.39%	-48.74%
5.48%	0.19%	-4.59%	-8.93%	-12.90%	-16.53%	-19.88%	-22.96%	-25.82%	-28.47%	-30.94%	-33.25%	-35.40%	-37.42%	-39.32%	-41.11%	-42.79%	-44.38%	-45.89%	-47.31%	-48.67%
5.80%	0.49%	-4.32%	-8.69%	-12.68%	-16.33%	-19.69%	-22.79%	-25.66%	-28.32%	-30.80%	-33.12%	-35.28%	-37.31%	-39.22%	-41.01%	-42.70%	-44.29%	-45.80%	-47.23%	-48.59%
6.13%	0.78%	-4.06%	-8.45%	-12.46%	-16.13%	-19.50%	-22.62%	-25.50%	-28.18%	-30.67%	-32.99%	-35.16%	-37.20%	-39.11%	-40.91%	-42.60%	-44.21%	-45.72%	-47.15%	-48.51%

Externalization More Expensive →

externalization equivalent to 1% of overall computation,
kernel is 100% of overall computation

Amdahl’s Law

make kernel 12.5% faster

0.56%	-4.26%	-8.63%	-12.62%	-16.28%	-19.64%	-22.75%	-25.62%	-28.29%	-30.77%	-33.09%	-35.25%	-37.28%	-39.19%	-40.98%	-42.68%	-44.27%	-45.78%	-47.21%	-48.57%	-49.86%
1.12%	-3.74%	-8.16%	-12.20%	-15.89%	-19.28%	-22.41%	-25.31%	-28.00%	-30.50%	-32.84%	-35.02%	-37.06%	-38.98%	-40.79%	-42.49%	-44.10%	-45.62%	-47.06%	-48.42%	-49.72%
1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%	-46.90%	-48.28%	-49.58%
2.27%	-2.70%	-7.22%	-11.33%	-15.09%	-18.55%	-21.74%	-24.69%	-27.42%	-29.96%	-32.33%	-34.55%	-36.62%	-38.57%	-40.40%	-42.12%	-43.75%	-45.29%	-46.75%	-48.13%	-49.44%
2.86%	-2.17%	-6.74%	-10.89%	-14.69%	-18.18%	-21.40%	-24.37%	-27.13%	-29.69%	-32.08%	-34.31%	-36.40%	-38.36%	-40.20%	-41.94%	-43.57%	-45.12%	-46.59%	-47.98%	-49.30%
3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%	-46.43%	-47.83%	-49.15%
4.05%	-1.10%	-5.76%	-10.00%	-13.88%	-17.43%	-20.70%	-23.73%	-26.53%	-29.13%	-31.56%	-33.82%	-35.94%	-37.93%	-39.80%	-41.56%	-43.22%	-44.79%	-46.27%	-47.67%	-49.01%
4.65%	-0.55%	-5.26%	-9.55%	-13.46%	-17.05%	-20.35%	-23.40%	-26.23%	-28.85%	-31.30%	-33.58%	-35.71%	-37.72%	-39.60%	-41.37%	-43.04%	-44.62%	-46.11%	-47.52%	-48.86%
5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%	-48.72%
5.88%	0.56%	-4.26%	-8.63%	-12.62%	-16.28%	-19.64%	-22.75%	-25.62%	-28.29%	-30.77%	-33.09%	-35.25%	-37.28%	-39.19%	-40.98%	-42.68%	-44.27%	-45.78%	-47.21%	-48.57%
6.51%	1.12%	-3.74%	-8.16%	-12.20%	-15.89%	-19.28%	-22.41%	-25.31%	-28.00%	-30.50%	-32.84%	-35.02%	-37.06%	-38.98%	-40.79%	-42.49%	-44.10%	-45.62%	-47.06%	-48.42%
7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%	-46.90%	-48.28%
7.78%	2.27%	-2.70%	-7.22%	-11.33%	-15.09%	-18.55%	-21.74%	-24.69%	-27.42%	-29.96%	-32.33%	-34.55%	-36.62%	-38.57%	-40.40%	-42.12%	-43.75%	-45.29%	-46.75%	-48.13%
8.43%	2.86%	-2.17%	-6.74%	-10.89%	-14.69%	-18.18%	-21.40%	-24.37%	-27.13%	-29.69%	-32.08%	-34.31%	-36.40%	-38.36%	-40.20%	-41.94%	-43.57%	-45.12%	-46.59%	-47.98%
9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%	-46.43%	-47.83%
9.76%	4.05%	-1.10%	-5.76%	-10.00%	-13.88%	-17.43%	-20.70%	-23.73%	-26.53%	-29.13%	-31.56%	-33.82%	-35.94%	-37.93%	-39.80%	-41.56%	-43.22%	-44.79%	-46.27%	-47.67%
10.43%	4.65%	-0.55%	-5.26%	-9.55%	-13.46%	-17.05%	-20.35%	-23.40%	-26.23%	-28.85%	-31.30%	-33.58%	-35.71%	-37.72%	-39.60%	-41.37%	-43.04%	-44.62%	-46.11%	-47.52%
11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%
11.80%	5.88%	0.56%	-4.26%	-8.63%	-12.62%	-16.28%	-19.64%	-22.75%	-25.62%	-28.29%	-30.77%	-33.09%	-35.25%	-37.28%	-39.19%	-40.98%	-42.68%	-44.27%	-45.78%	-47.21%
12.50%	6.51%	1.12%	-3.74%	-8.16%	-12.20%	-15.89%	-19.28%	-22.41%	-25.31%	-28.00%	-30.50%	-32.84%	-35.02%	-37.06%	-38.98%	-40.79%	-42.49%	-44.10%	-45.62%	-47.06%

Amdahl’s Law

make kernel 25% faster

1.01%	-3.85%	-8.26%	-12.28%	-15.97%	-19.35%	-22.48%	-25.37%	-28.06%	-30.56%	-32.89%	-35.06%	-37.11%	-39.02%	-40.83%	-42.53%	-44.13%	-45.65%	-47.09%	-48.45%	-49.75%
2.04%	-2.91%	-7.41%	-11.50%	-15.25%	-18.70%	-21.88%	-24.81%	-27.54%	-30.07%	-32.43%	-34.64%	-36.71%	-38.65%	-40.48%	-42.20%	-43.82%	-45.36%	-46.81%	-48.19%	-49.49%
3.09%	-1.96%	-6.54%	-10.71%	-14.53%	-18.03%	-21.26%	-24.24%	-27.01%	-29.58%	-31.97%	-34.21%	-36.31%	-38.27%	-40.12%	-41.86%	-43.50%	-45.05%	-46.52%	-47.92%	-49.24%
4.17%	-0.99%	-5.66%	-9.91%	-13.79%	-17.36%	-20.63%	-23.66%	-26.47%	-29.08%	-31.51%	-33.77%	-35.90%	-37.89%	-39.76%	-41.52%	-43.18%	-44.75%	-46.24%	-47.64%	-48.98%
5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%	-48.72%
6.38%	1.01%	-3.85%	-8.26%	-12.28%	-15.97%	-19.35%	-22.48%	-25.37%	-28.06%	-30.56%	-32.89%	-35.06%	-37.11%	-39.02%	-40.83%	-42.53%	-44.13%	-45.65%	-47.09%	-48.45%
7.53%	2.04%	-2.91%	-7.41%	-11.50%	-15.25%	-18.70%	-21.88%	-24.81%	-27.54%	-30.07%	-32.43%	-34.64%	-36.71%	-38.65%	-40.48%	-42.20%	-43.82%	-45.36%	-46.81%	-48.19%
8.70%	3.09%	-1.96%	-6.54%	-10.71%	-14.53%	-18.03%	-21.26%	-24.24%	-27.01%	-29.58%	-31.97%	-34.21%	-36.31%	-38.27%	-40.12%	-41.86%	-43.50%	-45.05%	-46.52%	-47.92%
9.89%	4.17%	-0.99%	-5.66%	-9.91%	-13.79%	-17.36%	-20.63%	-23.66%	-26.47%	-29.08%	-31.51%	-33.77%	-35.90%	-37.89%	-39.76%	-41.52%	-43.18%	-44.75%	-46.24%	-47.64%
11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%
12.36%	6.38%	1.01%	-3.85%	-8.26%	-12.28%	-15.97%	-19.35%	-22.48%	-25.37%	-28.06%	-30.56%	-32.89%	-35.06%	-37.11%	-39.02%	-40.83%	-42.53%	-44.13%	-45.65%	-47.09%
13.64%	7.53%	2.04%	-2.91%	-7.41%	-11.50%	-15.25%	-18.70%	-21.88%	-24.81%	-27.54%	-30.07%	-32.43%	-34.64%	-36.71%	-38.65%	-40.48%	-42.20%	-43.82%	-45.36%	-46.81%
14.94%	8.70%	3.09%	-1.96%	-6.54%	-10.71%	-14.53%	-18.03%	-21.26%	-24.24%	-27.01%	-29.58%	-31.97%	-34.21%	-36.31%	-38.27%	-40.12%	-41.86%	-43.50%	-45.05%	-46.52%
16.28%	9.89%	4.17%	-0.99%	-5.66%	-9.91%	-13.79%	-17.36%	-20.63%	-23.66%	-26.47%	-29.08%	-31.51%	-33.77%	-35.90%	-37.89%	-39.76%	-41.52%	-43.18%	-44.75%	-46.24%
17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%
19.05%	12.36%	6.38%	1.01%	-3.85%	-8.26%	-12.28%	-15.97%	-19.35%	-22.48%	-25.37%	-28.06%	-30.56%	-32.89%	-35.06%	-37.11%	-39.02%	-40.83%	-42.53%	-44.13%	-45.65%
20.48%	13.64%	7.53%	2.04%	-2.91%	-7.41%	-11.50%	-15.25%	-18.70%	-21.88%	-24.81%	-27.54%	-30.07%	-32.43%	-34.64%	-36.71%	-38.65%	-40.48%	-42.20%	-43.82%	-45.36%
21.95%	14.94%	8.70%	3.09%	-1.96%	-6.54%	-10.71%	-14.53%	-18.03%	-21.26%	-24.24%	-27.01%	-29.58%	-31.97%	-34.21%	-36.31%	-38.27%	-40.12%	-41.86%	-43.50%	-45.05%
23.46%	16.28%	9.89%	4.17%	-0.99%	-5.66%	-9.91%	-13.79%	-17.36%	-20.63%	-23.66%	-26.47%	-29.08%	-31.51%	-33.77%	-35.90%	-37.89%	-39.76%	-41.52%	-43.18%	-44.75%
25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%

Amdahl's Law

make kernel 50% faster

1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%	-46.90%	-48.28%	-49.58%
3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%	-46.43%	-47.83%	-49.15%
5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%	-48.72%
7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%	-46.90%	-48.28%
9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%	-46.43%	-47.83%
11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%
13.21%	7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%	-46.90%
15.38%	9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%	-46.43%
17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%
20.00%	13.21%	7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%	-45.45%
22.45%	15.38%	9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%	-44.95%
25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%
27.66%	20.00%	13.21%	7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%	-43.93%
30.43%	22.45%	15.38%	9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%	-43.40%
33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%
36.36%	27.66%	20.00%	13.21%	7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%	-42.31%
39.53%	30.43%	22.45%	15.38%	9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%	-41.75%
42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%
46.34%	36.36%	27.66%	20.00%	13.21%	7.14%	1.69%	-3.23%	-7.69%	-11.76%	-15.49%	-18.92%	-22.08%	-25.00%	-27.71%	-30.23%	-32.58%	-34.78%	-36.84%	-38.78%	-40.59%
50.00%	39.53%	30.43%	22.45%	15.38%	9.09%	3.45%	-1.64%	-6.25%	-10.45%	-14.29%	-17.81%	-21.05%	-24.05%	-26.83%	-29.41%	-31.82%	-34.07%	-36.17%	-38.14%	-40.00%

Amdahl's Law

make kernel 2x faster

2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%	-46.67%	-48.05%	-49.37%
5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%	-48.72%
8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%	-46.67%	-48.05%
11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%	-47.37%
14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%	-46.67%
17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%
21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%
25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%
29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%
33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%
37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%
42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%
48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%
53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%
60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%
66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%
73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%
81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%
90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%
100.00%	81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%

Amdahl’s Law

make kernel 4x faster

3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%	-41.61%	-43.26%	-44.83%	-46.31%	-47.71%	-49.04%
8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%	-46.67%	-48.05%
12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%	-32.77%	-34.96%	-37.01%	-38.93%	-40.74%	-42.45%	-44.06%	-45.58%	-47.02%
17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%	-42.86%	-44.44%	-45.95%
23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%	-41.61%	-43.26%	-44.83%
29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%
35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%	-32.77%	-34.96%	-37.01%	-38.93%	-40.74%	-42.45%
42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%	-41.18%
50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%
60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%
70.21%	56.86%	45.45%	35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%	-32.77%	-34.96%	-37.01%
81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%
95.12%	77.78%	63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%
110.53%	90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%
128.57%	105.13%	86.05%	70.21%	56.86%	45.45%	35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%
150.00%	122.22%	100.00%	81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%
175.86%	142.42%	116.22%	95.12%	77.78%	63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%
207.69%	166.67%	135.29%	110.53%	90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%
247.83%	196.30%	158.06%	128.57%	105.13%	86.05%	70.21%	56.86%	45.45%	35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%
300.00%	233.33%	185.71%	150.00%	122.22%	100.00%	81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%

Amdahl’s Law

make kernel 8x faster

4.58%	-0.62%	-5.33%	-9.60%	-13.51%	-17.10%	-20.40%	-23.44%	-26.27%	-28.89%	-31.33%	-33.61%	-35.74%	-37.74%	-39.62%	-41.39%	-43.06%	-44.64%	-46.13%	-47.54%	-48.88%
9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%	-41.61%	-43.26%	-44.83%	-46.31%	-47.71%
15.11%	8.84%	3.23%	-1.84%	-6.43%	-10.61%	-14.44%	-17.95%	-21.18%	-24.17%	-26.94%	-29.52%	-31.91%	-34.16%	-36.25%	-38.22%	-40.07%	-41.82%	-43.46%	-45.02%	-46.49%
21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%	-40.30%	-42.03%	-43.66%	-45.21%
28.00%	20.30%	13.48%	7.38%	1.91%	-3.03%	-7.51%	-11.60%	-15.34%	-18.78%	-21.95%	-24.88%	-27.60%	-30.13%	-32.49%	-34.69%	-36.76%	-38.70%	-40.52%	-42.24%	-43.86%
35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%	-32.77%	-34.96%	-37.01%	-38.93%	-40.74%	-42.45%
44.14%	34.45%	25.98%	18.52%	11.89%	5.96%	0.63%	-4.19%	-8.57%	-12.57%	-16.23%	-19.60%	-22.71%	-25.58%	-28.25%	-30.74%	-33.05%	-35.22%	-37.25%	-39.16%	-40.96%
53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%	-25.93%	-28.57%	-31.03%	-33.33%	-35.48%	-37.50%	-39.39%
64.95%	52.38%	41.59%	32.23%	24.03%	16.79%	10.34%	4.58%	-0.62%	-5.33%	-9.60%	-13.51%	-17.10%	-20.40%	-23.44%	-26.27%	-28.89%	-31.33%	-33.61%	-35.74%	-37.74%
77.78%	63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%
92.77%	75.82%	61.62%	49.53%	39.13%	30.08%	22.14%	15.11%	8.84%	3.23%	-1.84%	-6.43%	-10.61%	-14.44%	-17.95%	-21.18%	-24.17%	-26.94%	-29.52%	-31.91%	-34.16%
110.53%	90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%
131.88%	107.79%	88.24%	72.04%	58.42%	46.79%	36.75%	28.00%	20.30%	13.48%	7.38%	1.91%	-3.03%	-7.51%	-11.60%	-15.34%	-18.78%	-21.95%	-24.88%	-27.60%	-30.13%
158.06%	128.57%	105.13%	86.05%	70.21%	56.86%	45.45%	35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%
190.91%	153.97%	125.35%	102.53%	83.91%	68.42%	55.34%	44.14%	34.45%	25.98%	18.52%	11.89%	5.96%	0.63%	-4.19%	-8.57%	-12.57%	-16.23%	-19.60%	-22.71%	-25.58%
233.33%	185.71%	150.00%	122.22%	100.00%	81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%	-23.08%
290.24%	226.53%	180.70%	146.15%	119.18%	97.53%	79.78%	64.95%	52.38%	41.59%	32.23%	24.03%	16.79%	10.34%	4.58%	-0.62%	-5.33%	-9.60%	-13.51%	-17.10%	-20.40%
370.59%	280.95%	220.00%	175.86%	142.42%	116.22%	95.12%	77.78%	63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%
492.59%	357.14%	272.09%	213.73%	171.19%	138.81%	113.33%	92.77%	75.82%	61.62%	49.53%	39.13%	30.08%	22.14%	15.11%	8.84%	3.23%	-1.84%	-6.43%	-10.61%	-14.44%
700.00%	471.43%	344.44%	263.64%	207.69%	166.67%	135.29%	110.53%	90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%

Amdahl’s Law

make kernel 16x faster

4.92%	-0.31%	-5.04%	-9.35%	-13.28%	-16.88%	-20.20%	-23.26%	-26.10%	-28.73%	-31.18%	-33.47%	-35.61%	-37.62%	-39.51%	-41.28%	-42.96%	-44.54%	-46.04%	-47.45%	-48.80%
10.34%	4.58%	-0.62%	-5.33%	-9.60%	-13.51%	-17.10%	-20.40%	-23.44%	-26.27%	-28.89%	-31.33%	-33.61%	-35.74%	-37.74%	-39.62%	-41.39%	-43.06%	-44.64%	-46.13%	-47.54%
16.36%	9.97%	4.23%	-0.93%	-5.60%	-9.86%	-13.75%	-17.31%	-20.60%	-23.63%	-26.44%	-29.05%	-31.48%	-33.75%	-35.87%	-37.86%	-39.74%	-41.50%	-43.16%	-44.73%	-46.22%
23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%	-39.85%	-41.61%	-43.26%	-44.83%
30.61%	22.61%	15.52%	9.22%	3.56%	-1.54%	-6.16%	-10.36%	-14.21%	-17.74%	-20.99%	-23.99%	-26.77%	-29.36%	-31.77%	-34.02%	-36.13%	-38.10%	-39.96%	-41.71%	-43.36%
39.13%	30.08%	22.14%	15.11%	8.84%	3.23%	-1.84%	-6.43%	-10.61%	-14.44%	-17.95%	-21.18%	-24.17%	-26.94%	-29.52%	-31.91%	-34.16%	-36.25%	-38.22%	-40.07%	-41.82%
48.84%	38.53%	29.55%	21.67%	14.70%	8.47%	2.89%	-2.14%	-6.71%	-10.86%	-14.67%	-18.16%	-21.38%	-24.35%	-27.11%	-29.67%	-32.06%	-34.29%	-36.38%	-38.34%	-40.19%
60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%	-21.57%	-24.53%	-27.27%	-29.82%	-32.20%	-34.43%	-36.51%	-38.46%
72.97%	59.20%	47.47%	37.34%	28.51%	20.75%	13.88%	7.74%	2.24%	-2.74%	-7.25%	-11.36%	-15.12%	-18.58%	-21.76%	-24.71%	-27.44%	-29.98%	-32.35%	-34.56%	-36.63%
88.24%	72.04%	58.42%	46.79%	36.75%	28.00%	20.30%	13.48%	7.38%	1.91%	-3.03%	-7.51%	-11.60%	-15.34%	-18.78%	-21.95%	-24.88%	-27.60%	-30.13%	-32.49%	-34.69%
106.45%	87.13%	71.12%	57.64%	46.12%	36.17%	27.49%	19.85%	13.07%	7.02%	1.59%	-3.32%	-7.78%	-11.85%	-15.57%	-18.99%	-22.14%	-25.06%	-27.77%	-30.28%	-32.63%
128.57%	105.13%	86.05%	70.21%	56.86%	45.45%	35.59%	26.98%	19.40%	12.68%	6.67%	1.27%	-3.61%	-8.05%	-12.09%	-15.79%	-19.19%	-22.33%	-25.23%	-27.93%	-30.43%
156.00%	126.95%	103.82%	84.97%	69.31%	56.10%	44.80%	35.02%	26.48%	18.96%	12.28%	6.31%	0.95%	-3.90%	-8.31%	-12.33%	-16.01%	-19.40%	-22.52%	-25.41%	-28.09%
190.91%	153.97%	125.35%	102.53%	83.91%	68.42%	55.34%	44.14%	34.45%	25.98%	18.52%	11.89%	5.96%	0.63%	-4.19%	-8.57%	-12.57%	-16.23%	-19.60%	-22.71%	-25.58%
236.84%	188.29%	151.97%	123.78%	101.26%	82.86%	67.54%	54.59%	43.50%	33.89%	25.49%	18.08%	11.50%	5.61%	0.31%	-4.48%	-8.83%	-12.81%	-16.45%	-19.80%	-22.89%
300.00%	233.33%	185.71%	150.00%	122.22%	100.00%	81.82%	66.67%	53.85%	42.86%	33.33%	25.00%	17.65%	11.11%	5.26%	0.00%	-4.76%	-9.09%	-13.04%	-16.67%	-20.00%
392.31%	295.06%	229.90%	183.19%	148.06%	120.69%	98.76%	80.79%	65.80%	53.11%	42.22%	32.78%	24.51%	17.22%	10.73%	4.92%	-0.31%	-5.04%	-9.35%	-13.28%	-16.88%
540.00%	384.85%	290.24%	226.53%	180.70%	146.15%	119.18%	97.53%	79.78%	64.95%	52.38%	41.59%	32.23%	24.03%	16.79%	10.34%	4.58%	-0.62%	-5.33%	-9.60%	-13.51%
814.29%	527.45%	377.61%	285.54%	223.23%	178.26%	144.27%	117.69%	96.32%	78.77%	64.10%	51.66%	40.97%	31.69%	23.55%	16.36%	9.97%	4.23%	-0.93%	-5.60%	-9.86%
1500.00%	788.89%	515.38%	370.59%	280.95%	220.00%	175.86%	142.42%	116.22%	95.12%	77.78%	63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%

Amdahl’s Law

make kernel 32x faster

5.09%	-0.16%	-4.90%	-9.22%	-13.16%	-16.78%	-20.10%	-23.17%	-26.01%	-28.65%	-31.11%	-33.40%	-35.55%	-37.56%	-39.45%	-41.23%	-42.91%	-44.49%	-45.99%	-47.41%	-48.76%
10.73%	4.92%	-0.31%	-5.04%	-9.35%	-13.28%	-16.88%	-20.20%	-23.26%	-26.10%	-28.73%	-31.18%	-33.47%	-35.61%	-37.62%	-39.51%	-41.28%	-42.96%	-44.54%	-46.04%	-47.45%
17.00%	10.54%	4.75%	-0.47%	-5.19%	-9.48%	-13.40%	-16.99%	-20.30%	-23.35%	-26.18%	-28.81%	-31.26%	-33.54%	-35.68%	-37.68%	-39.57%	-41.34%	-43.01%	-44.59%	-46.08%
24.03%	16.79%	10.34%	4.58%	-0.62%	-5.33%	-9.60%	-13.51%	-17.10%	-20.40%	-23.44%	-26.27%	-28.89%	-31.33%	-33.61%	-35.74%	-37.74%	-39.62%	-41.39%	-43.06%	-44.64%
31.96%	23.79%	16.58%	10.15%	4.40%	-0.78%	-5.47%	-9.73%	-13.63%	-17.21%	-20.50%	-23.54%	-26.35%	-28.97%	-31.40%	-33.68%	-35.81%	-37.80%	-39.68%	-41.45%	-43.11%
40.97%	31.69%	23.55%	16.36%	9.97%	4.23%	-0.93%	-5.60%	-9.86%	-13.75%	-17.31%	-20.60%	-23.63%	-26.44%	-29.05%	-31.48%	-33.75%	-35.87%	-37.86%	-39.74%	-41.50%
51.30%	40.66%	31.42%	23.31%	16.15%	9.78%	4.07%	-1.08%	-5.74%	-9.99%	-13.86%	-17.42%	-20.69%	-23.72%	-26.52%	-29.13%	-31.55%	-33.82%	-35.94%	-37.92%	-39.79%
63.27%	50.94%	40.35%	31.15%	23.08%	15.94%	9.59%	3.90%	-1.23%	-5.88%	-10.11%	-13.98%	-17.53%	-20.79%	-23.81%	-26.61%	-29.20%	-31.62%	-33.88%	-36.00%	-37.98%
77.29%	62.85%	50.59%	40.04%	30.88%	22.84%	15.73%	9.40%	3.73%	-1.39%	-6.02%	-10.24%	-14.09%	-17.63%	-20.89%	-23.90%	-26.69%	-29.28%	-31.70%	-33.95%	-36.06%
93.94%	76.80%	62.44%	50.23%	39.74%	30.61%	22.61%	15.52%	9.22%	3.56%	-1.54%	-6.16%	-10.36%	-14.21%	-17.74%	-20.99%	-23.99%	-26.77%	-29.36%	-31.77%	-34.02%
114.05%	93.35%	76.31%	62.03%	49.88%	39.43%	30.35%	22.37%	15.32%	9.03%	3.39%	-1.69%	-6.30%	-10.49%	-14.32%	-17.84%	-21.09%	-24.08%	-26.86%	-29.44%	-31.84%
138.81%	113.33%	92.77%	75.82%	61.62%	49.53%	39.13%	30.08%	22.14%	15.11%	8.84%	3.23%	-1.84%	-6.43%	-10.61%	-14.44%	-17.95%	-21.18%	-24.17%	-26.94%	-29.52%
170.04%	137.92%	112.62%	92.19%	75.34%	61.21%	49.18%	38.83%	29.82%	21.90%	14.90%	8.66%	3.06%	-1.99%	-6.57%	-10.74%	-14.55%	-18.05%	-21.28%	-24.26%	-27.02%
210.68%	168.91%	137.04%	111.92%	91.62%	74.86%	60.80%	48.84%	38.53%	29.55%	21.67%	14.70%	8.47%	2.89%	-2.14%	-6.71%	-10.86%	-14.67%	-18.16%	-21.38%	-24.35%
265.71%	209.18%	167.78%	136.16%	111.22%	91.04%	74.39%	60.40%	48.49%	38.23%	29.29%	21.44%	14.49%	8.29%	2.73%	-2.29%	-6.84%	-10.99%	-14.78%	-18.26%	-21.47%
344.44%	263.64%	207.69%	166.67%	135.29%	110.53%	90.48%	73.91%	60.00%	48.15%	37.93%	29.03%	21.21%	14.29%	8.11%	2.56%	-2.44%	-6.98%	-11.11%	-14.89%	-18.37%
466.37%	341.38%	261.58%	206.22%	165.56%	134.43%	109.84%	89.91%	73.44%	59.60%	47.81%	37.63%	28.77%	20.98%	14.08%	7.93%	2.40%	-2.59%	-7.11%	-11.23%	-15.01%
680.49%	461.40%	338.36%	259.55%	204.76%	164.46%	133.58%	109.15%	89.35%	72.97%	59.20%	47.47%	37.34%	28.51%	20.75%	13.88%	7.74%	2.24%	-2.74%	-7.25%	-11.36%
1154.90%	671.08%	456.52%	335.37%	257.54%	203.32%	163.37%	132.73%	108.47%	88.79%	72.51%	58.81%	47.13%	37.04%	28.26%	20.53%	13.68%	7.56%	2.07%	-2.88%	-7.38%
3100.00%	1130.77%	661.90%	451.72%	332.43%	255.56%	201.89%	162.30%	131.88%	107.79%	88.24%	72.04%	58.42%	46.79%	36.75%	28.00%	20.30%	13.48%	7.38%	1.91%	-3.03%

4. The Costs of Externalization

Rough Measurements

Object Churn

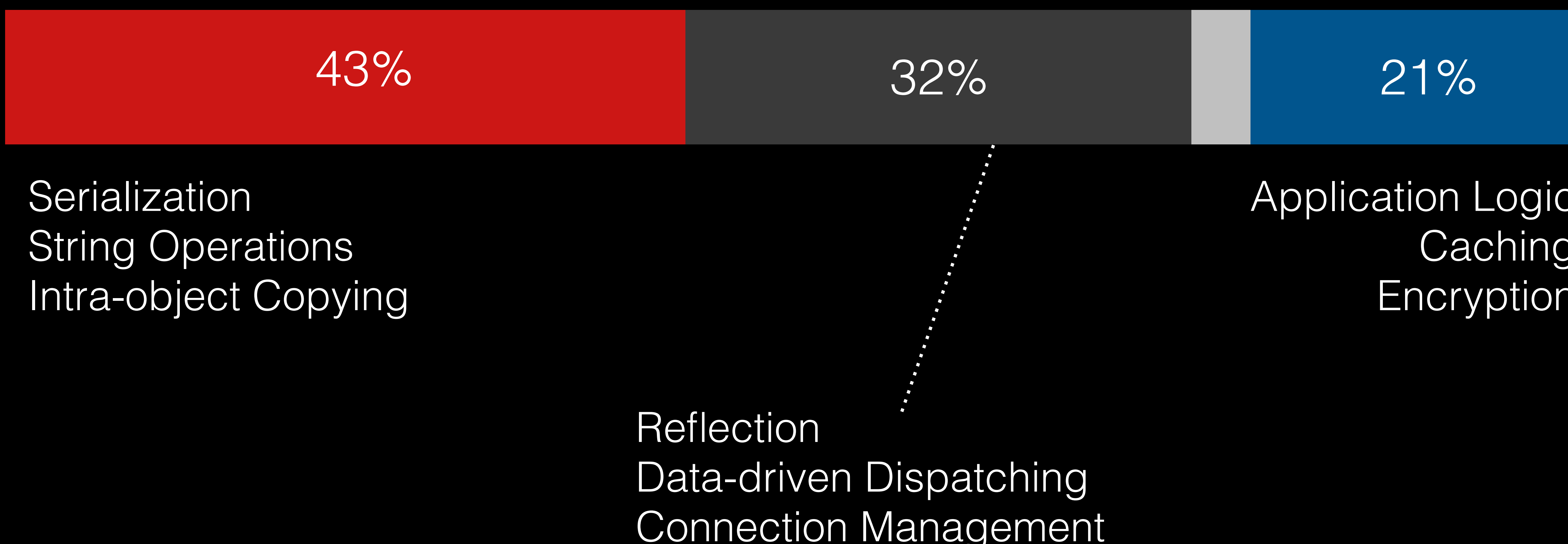
- 3000 temps to ingest one document
- 70 temps to turn a SOAP date (as bytes) into a Java Calendar
- 6 temps to turn month into int

Fractal Webs of Invocations

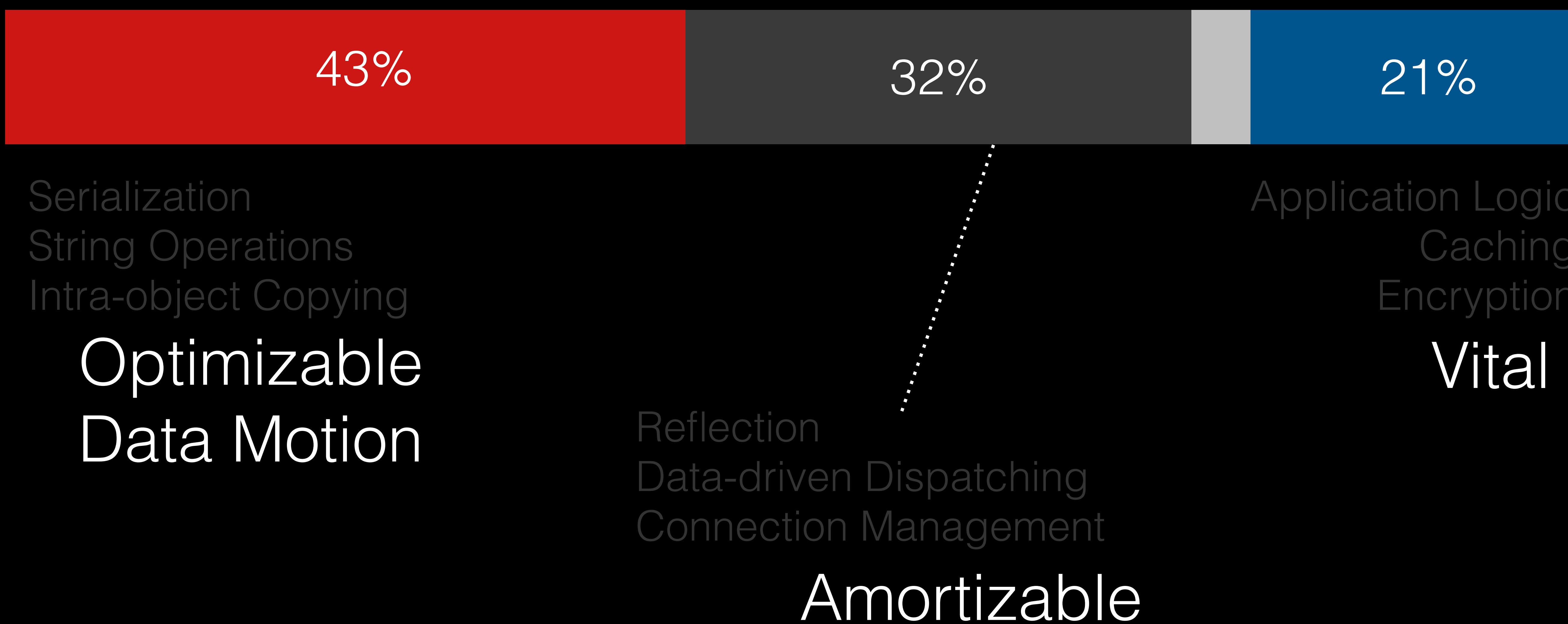
- 200k calls to ingest that document
- 2000 calls to turn an XML timecard into a Java data structure

(Sevitsky 2006)

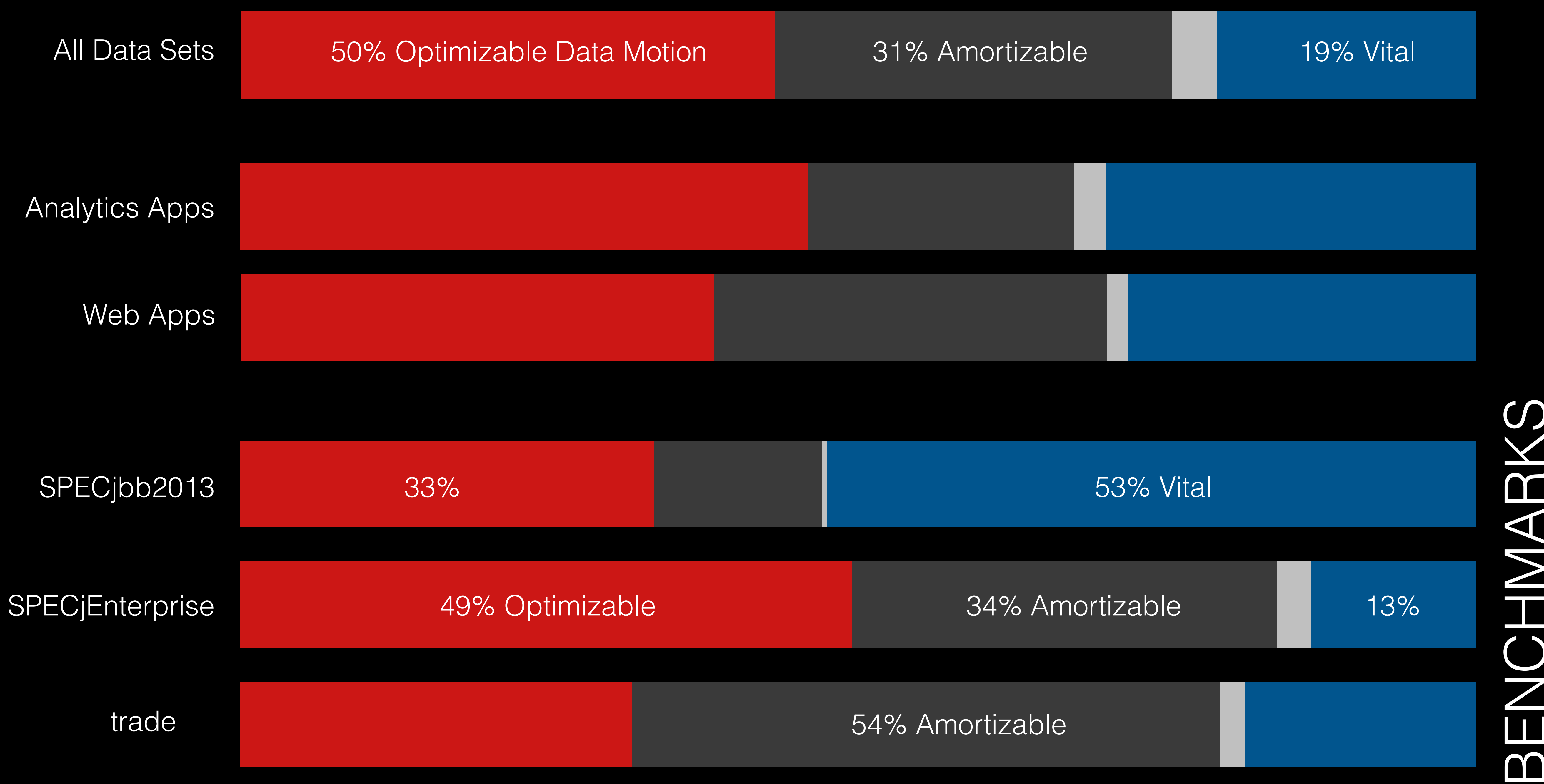
Spending CPU Cycles



Three Kinds of Expenses

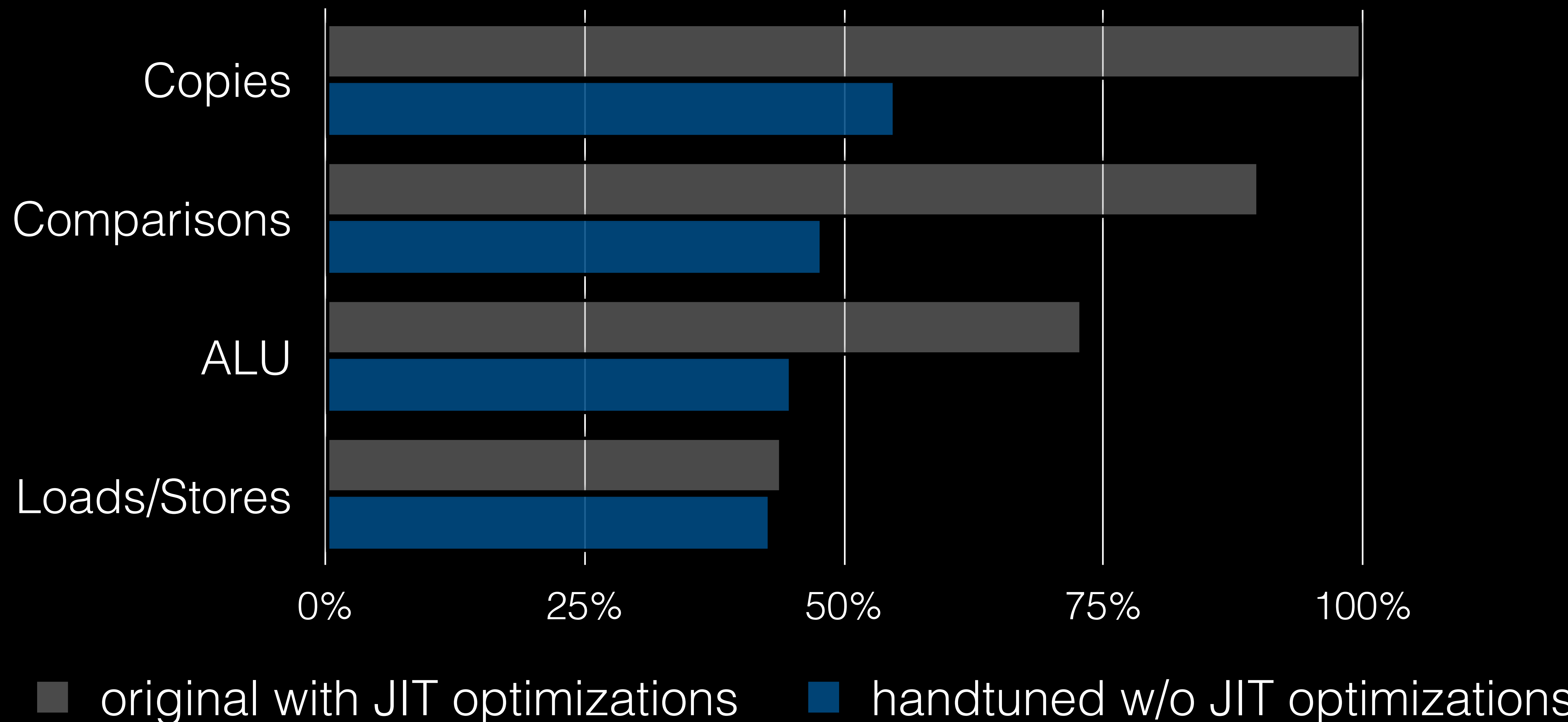


Does the Story Vary?



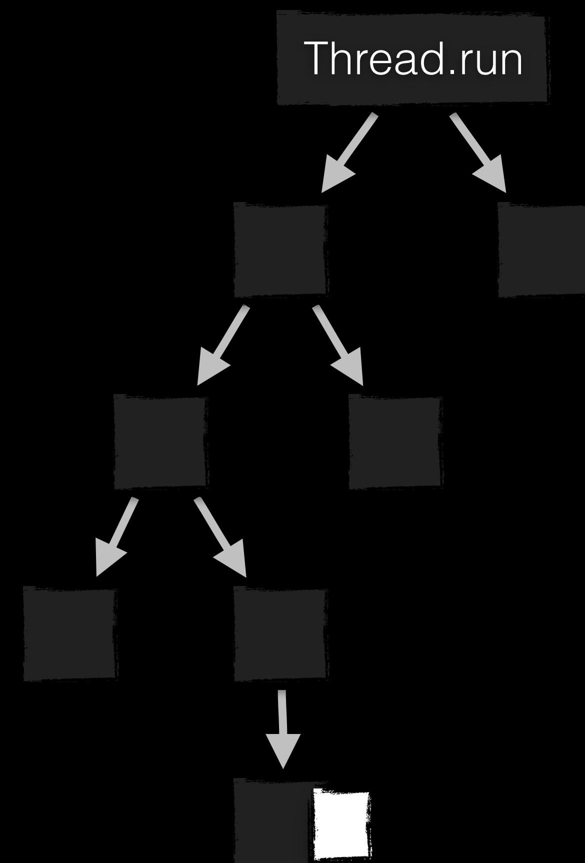
What the JIT Doesn't Catch

(numbers relative to original w/o JIT optimizations)



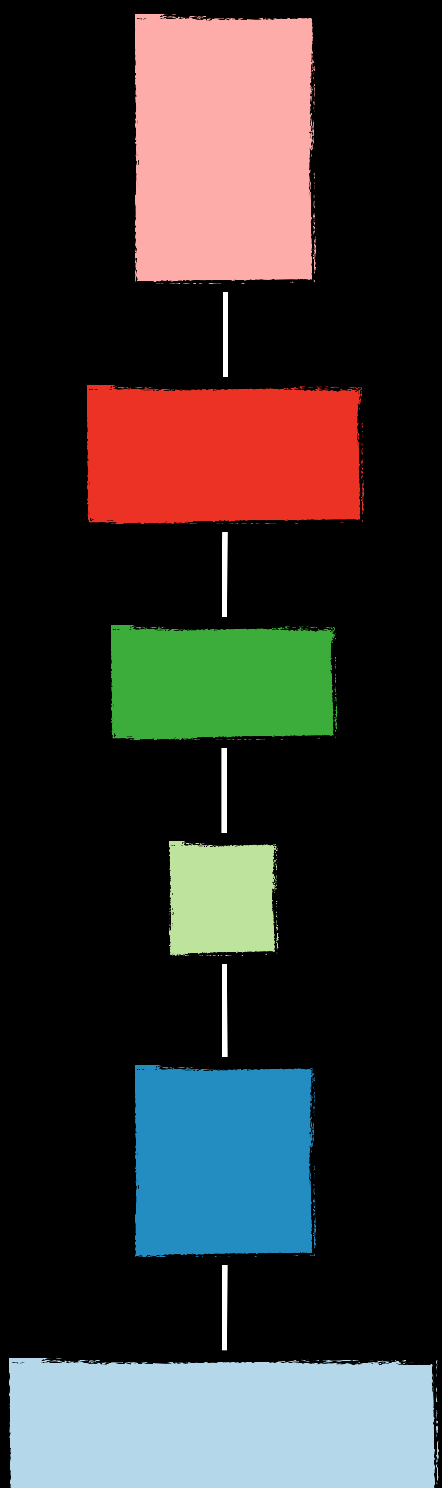
(Xu 2009)

Allocate-Use Separation



How much do we have to inline to have a chance of removing temps and copies?

Method Inlining



	% temps eliminated	
	base J9 inliner	JOLT inliner
Eclipse	0.4%	1.9%
JPetStore on Spring	0.7%	2.5%
TPCW on JBoss	0%	4.3%
DaCapo	3.4%	13.3%

Inlining is hard!

Small benchmarks don't reflect difficulties

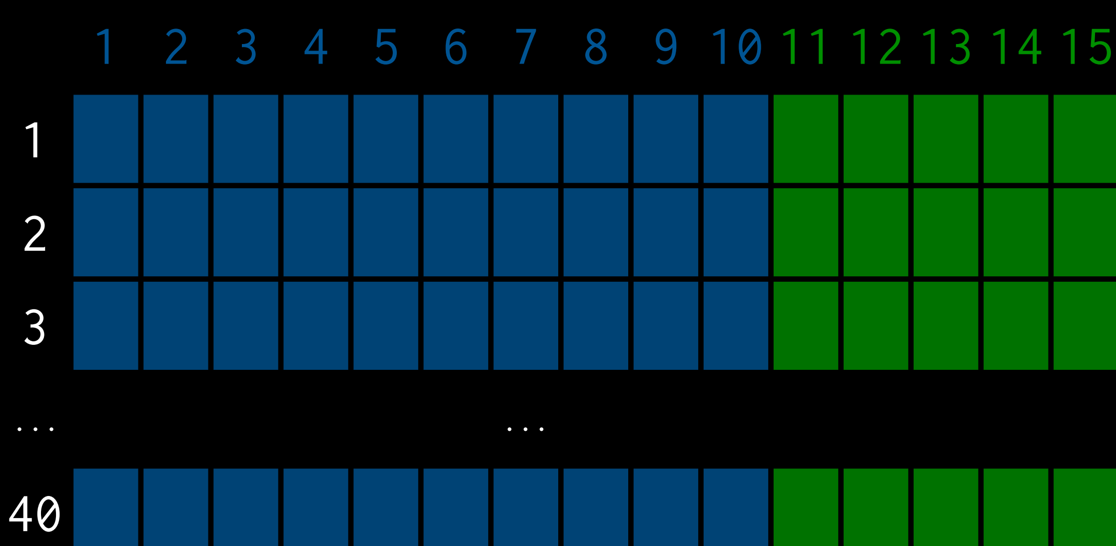
(Shankar 2008)

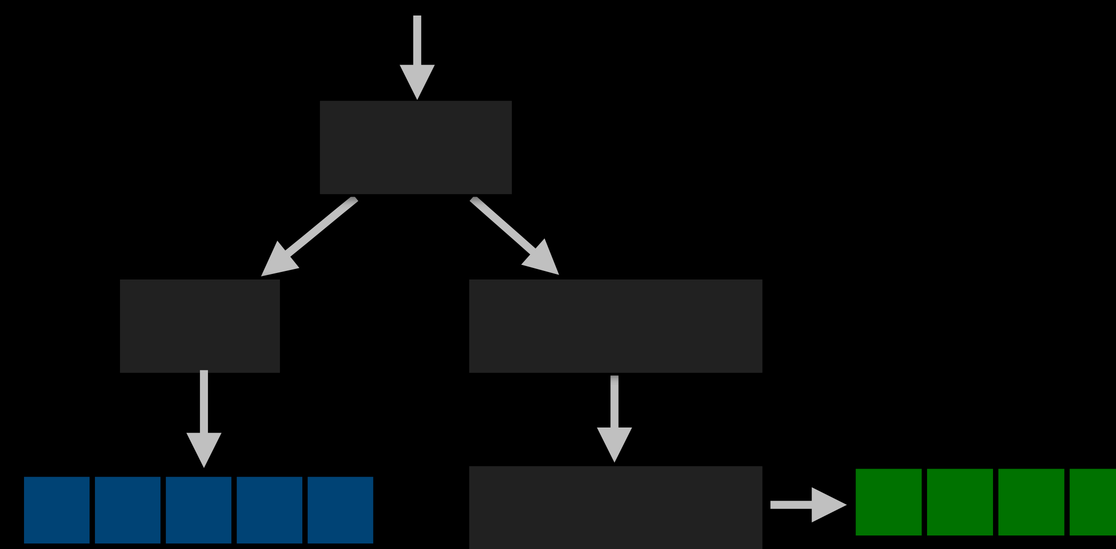
Spending Memory

COBOL vs Java

```
01 Student occurs 40
     02 Name      PIC X(10)
     02 Score     PIC 999V99
```

```
class Student {
    String name;
    BigDecimal score;
}
Student[] data = new Student[40];
```



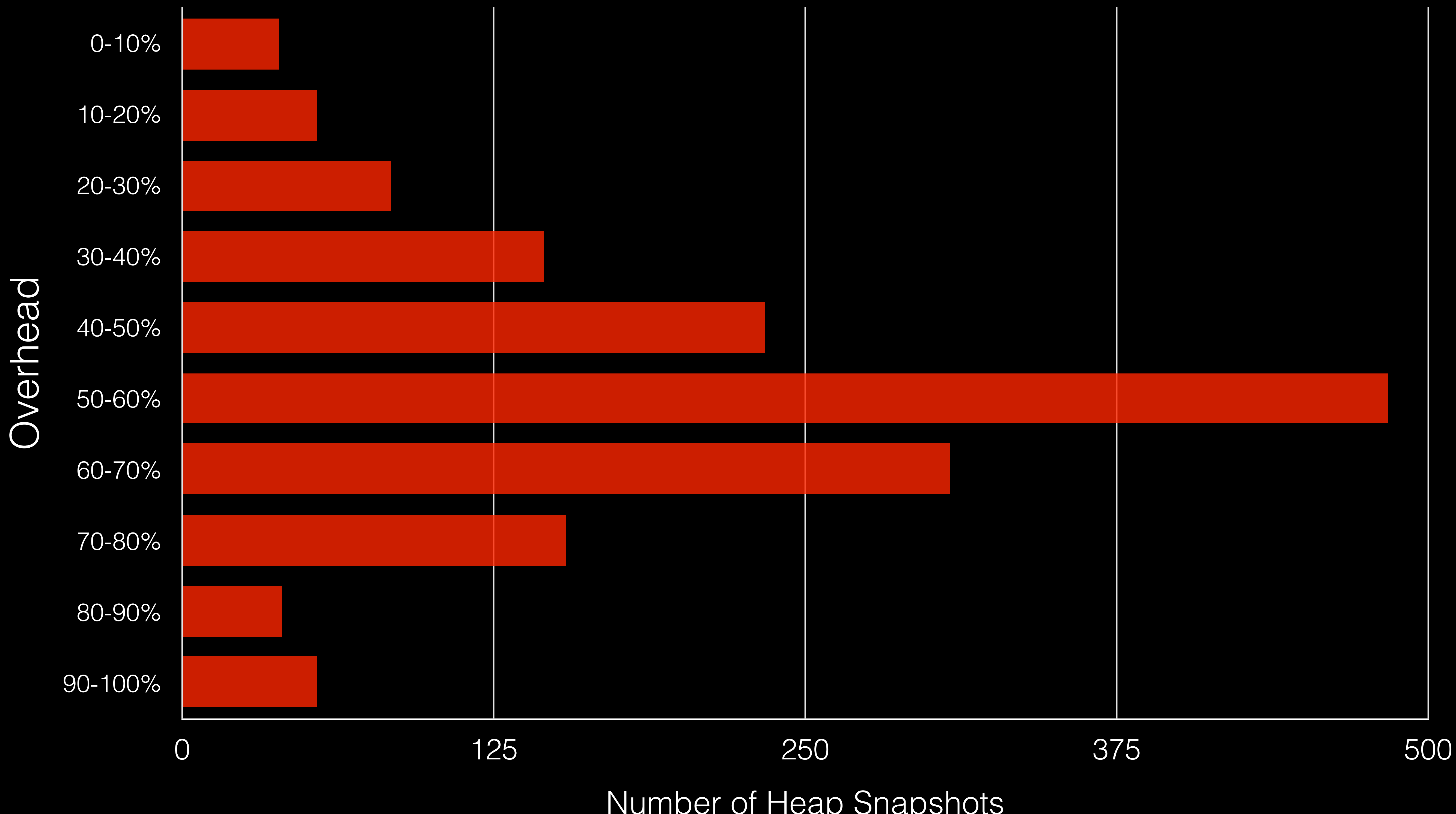


600 bytes

4492 bytes

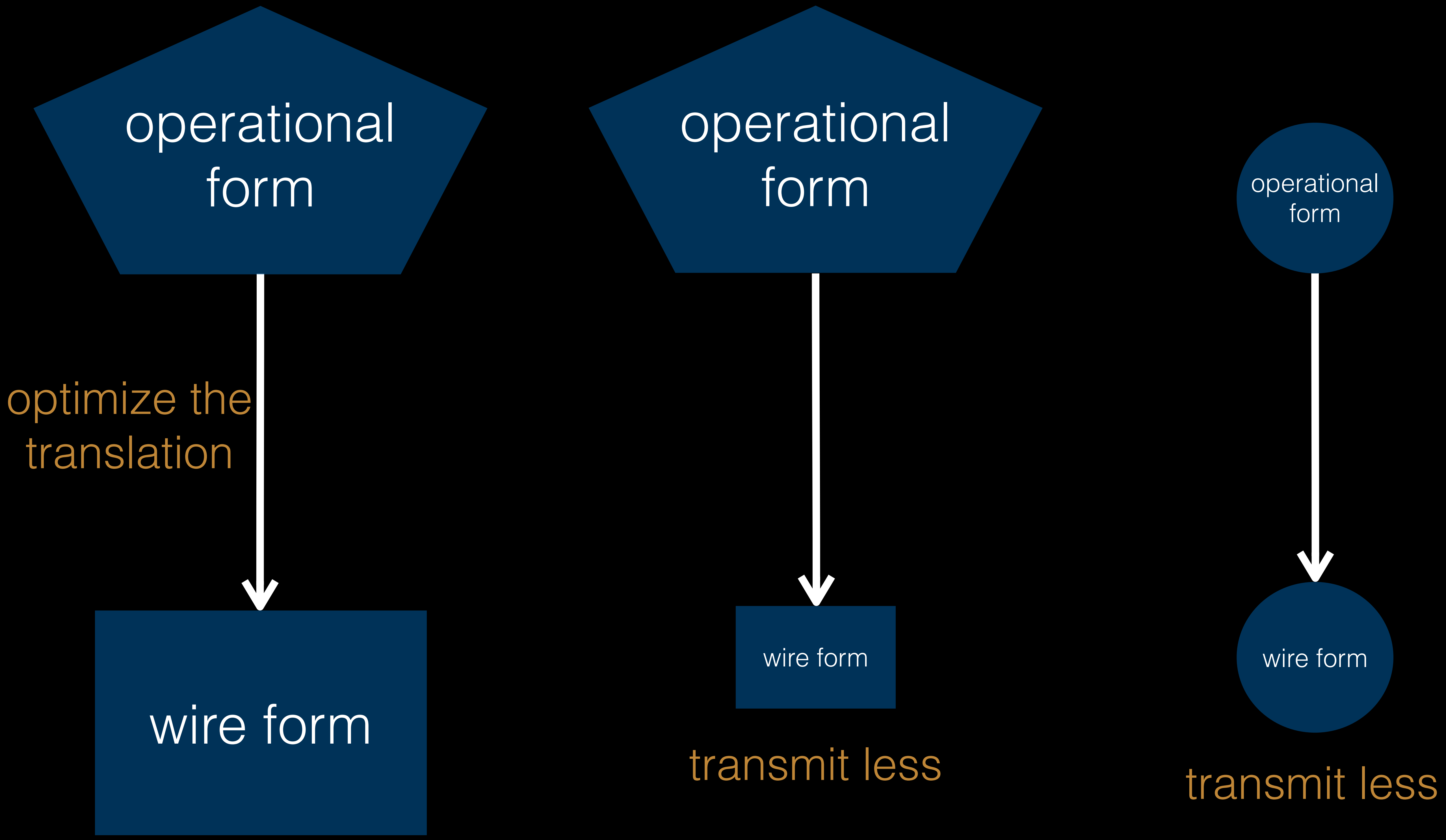
(Suganuma 2008)

Memory Overhead

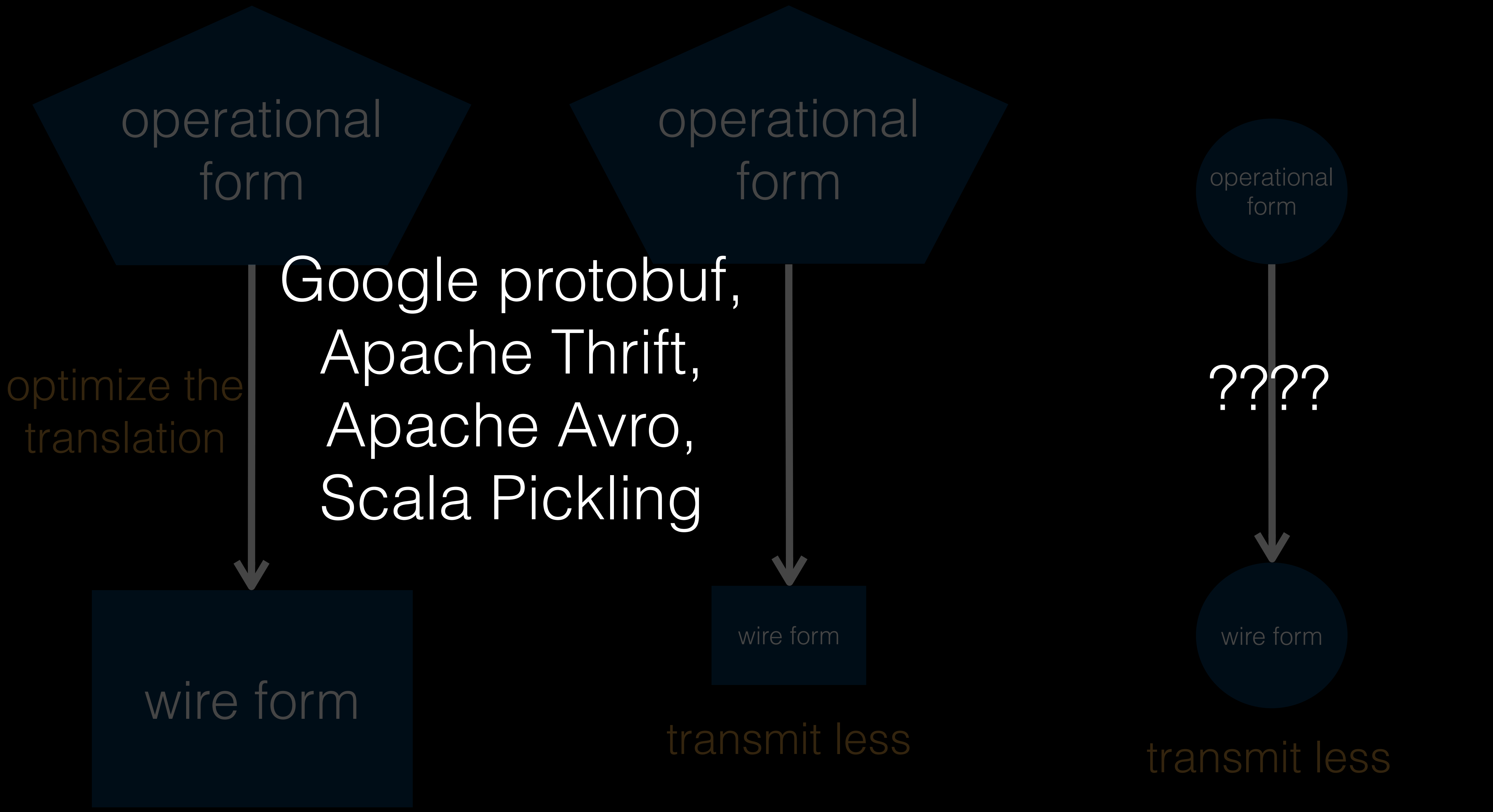


5. Alternative Marshalling Schemes

Options


operational form
optimize the translation
wire form
operational form
wire form
transmit less
operational form
wire form
transmit less

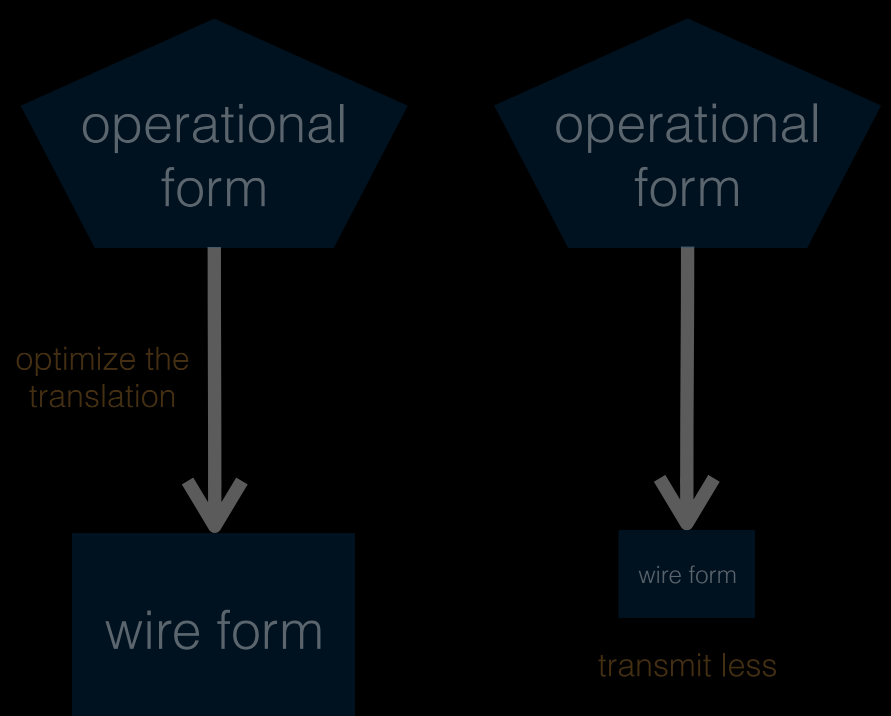
Options


operational form
optimize the translation
wire form
Google protobuf,
Apache Thrift,
Apache Avro,
Scala Pickling
operational form
wire form
transmit less
operational form
????
wire form
transmit less

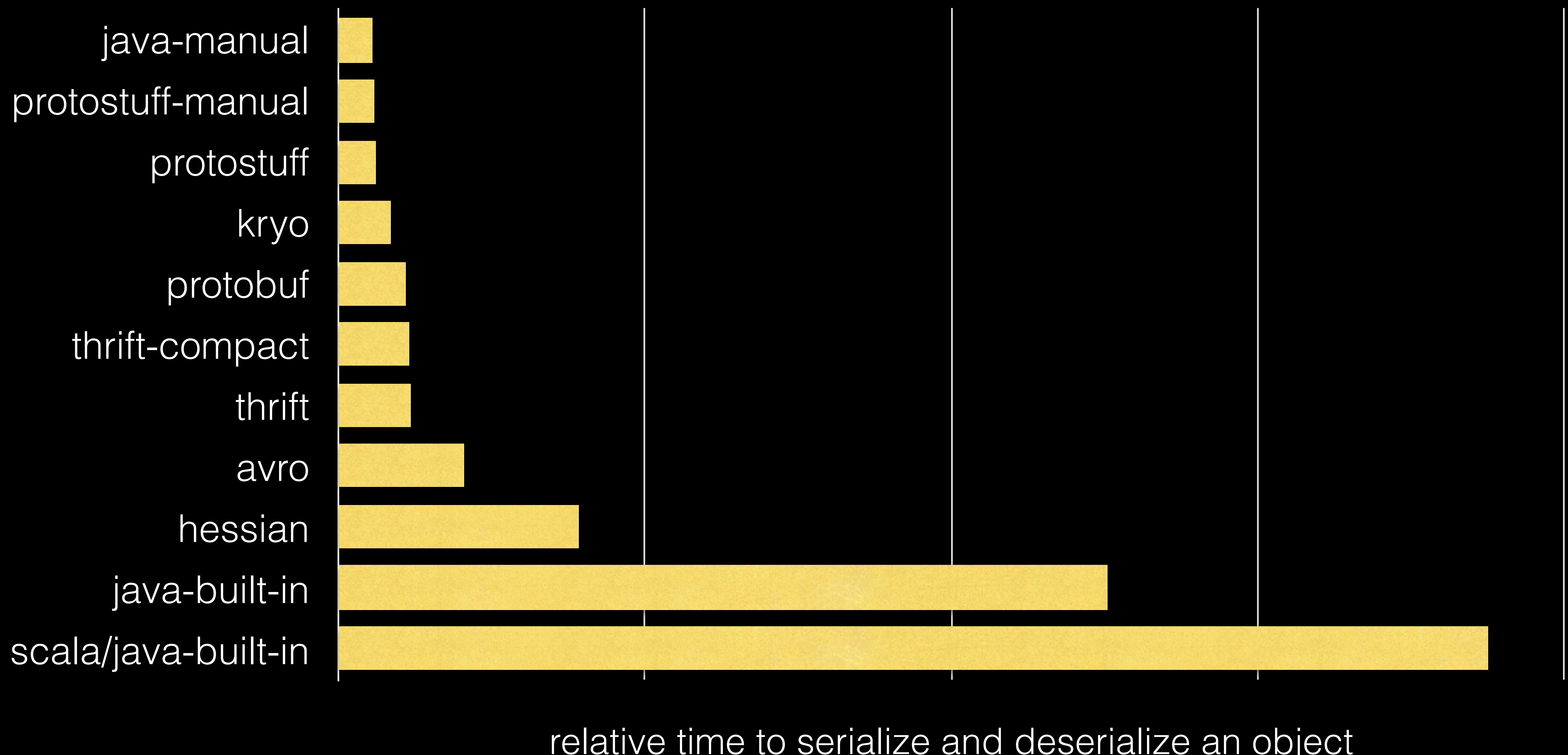
protobuf, avro, thrift

- declaratively specify schema of data
- automatically generate marshallers

```
struct Work {
  1: i32 num1 = 0,
  2: i32 num2,
  3: Operation op,
  4: optional string comment,
}
```

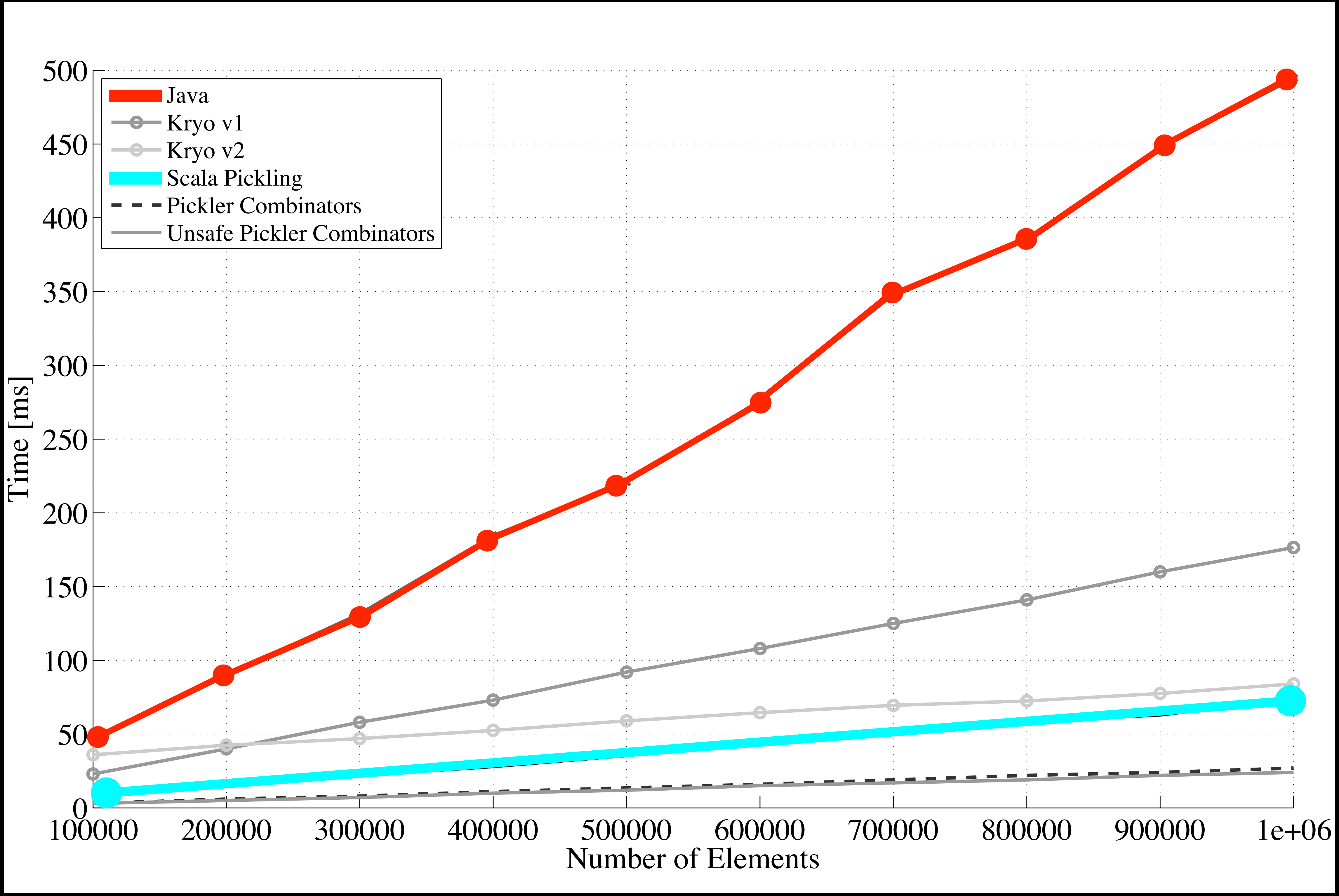


Does it Matter?



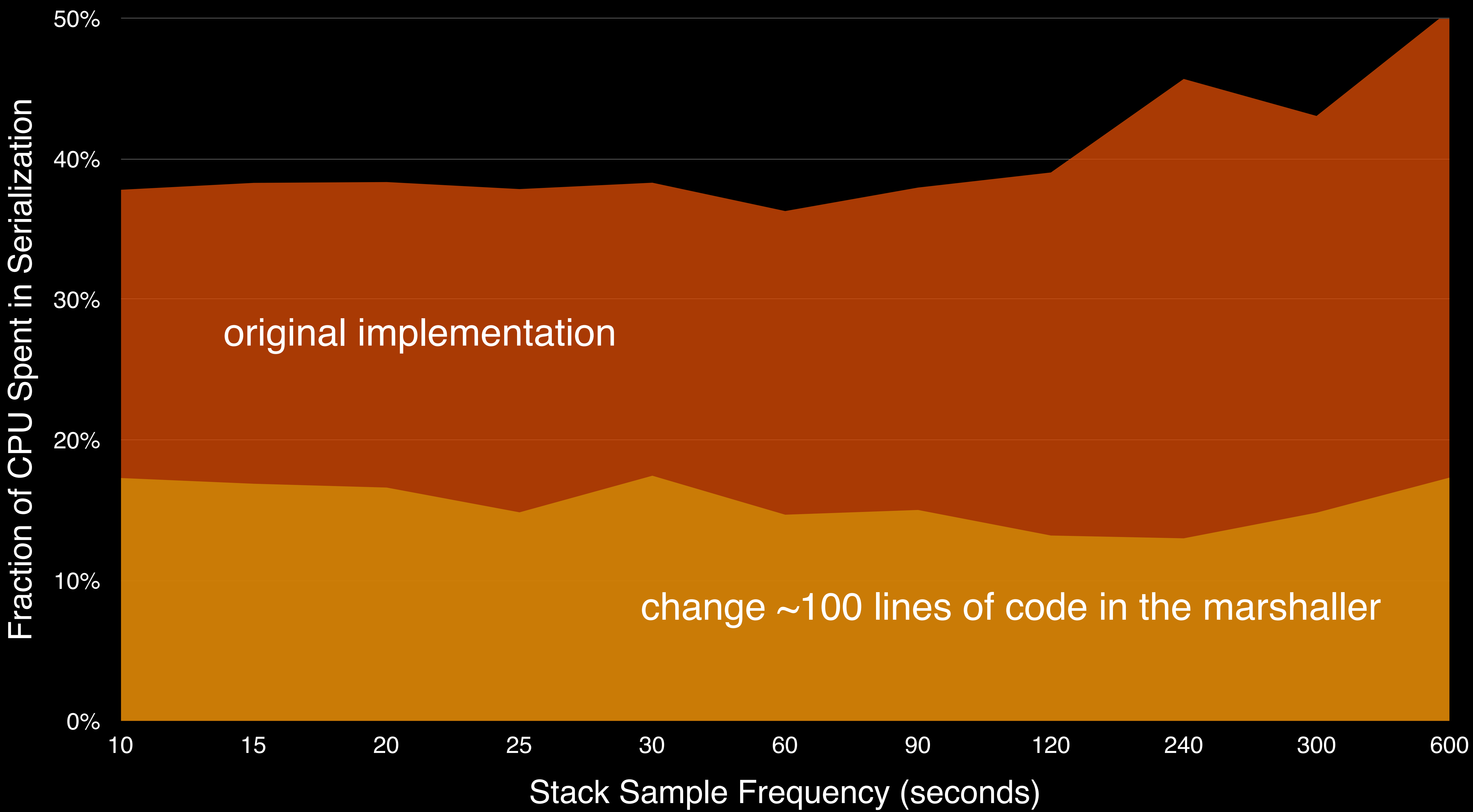
(http://ganges.usc.edu/pgroupW/images/a/a9/Serializarion_Framework.pdf)

Does it Matter?



(Miller 2013)

Experiment: specjbb2013



6. Alternative Storage Schemes

Value Types and Structs

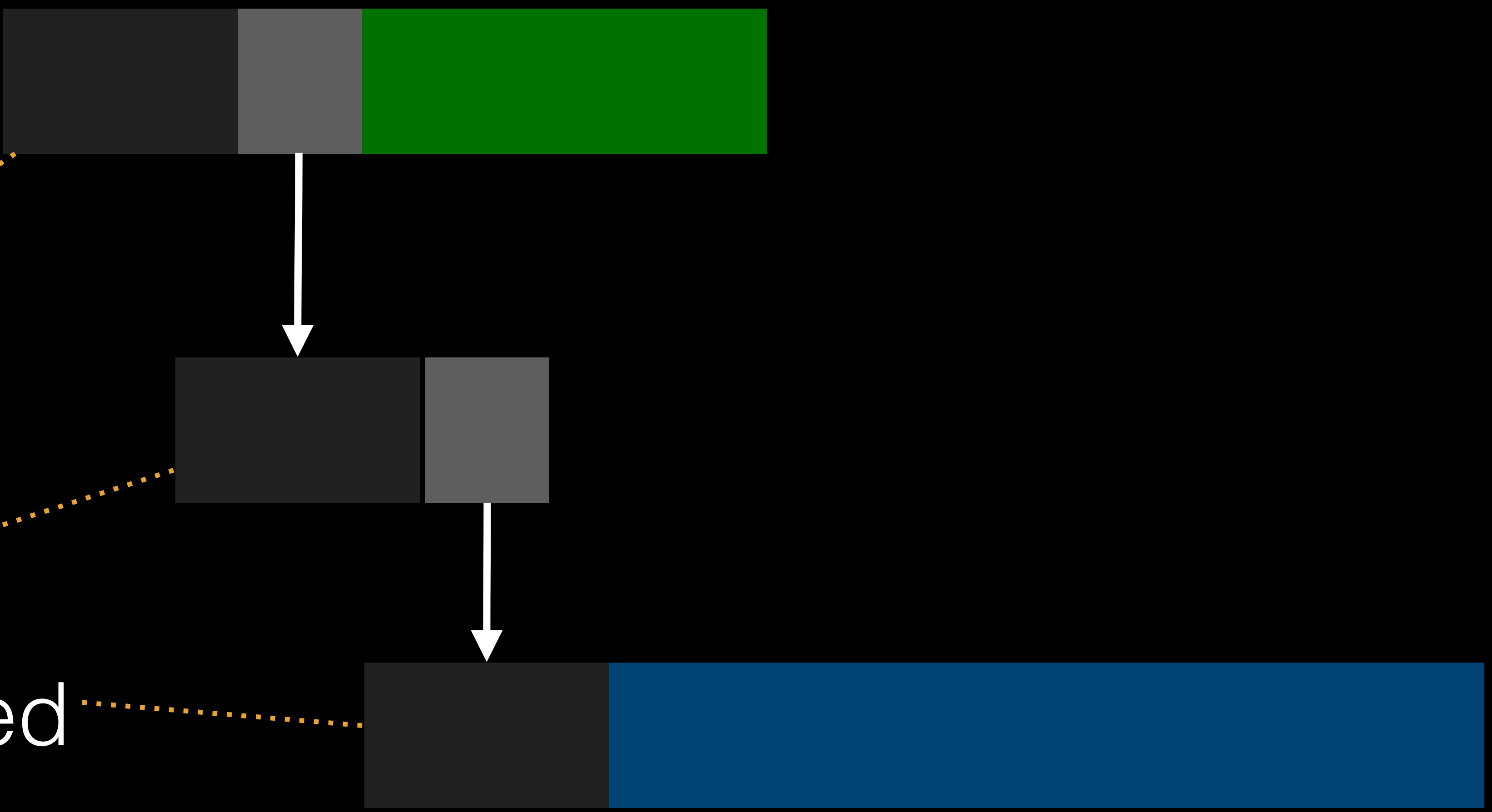
```
struct Student {
    char[] name;
    int score;
}
```

pay the header cost once per **record**

Ref Poisoning

```
struct Student {
    String name;
    int score;
}
```

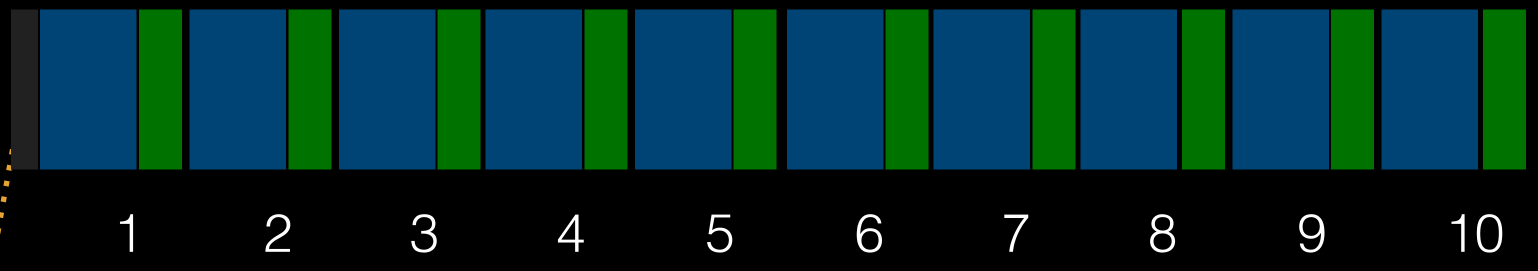
…. unless we use a reference type



in which case, we're
back to where we started

Arrays of Records

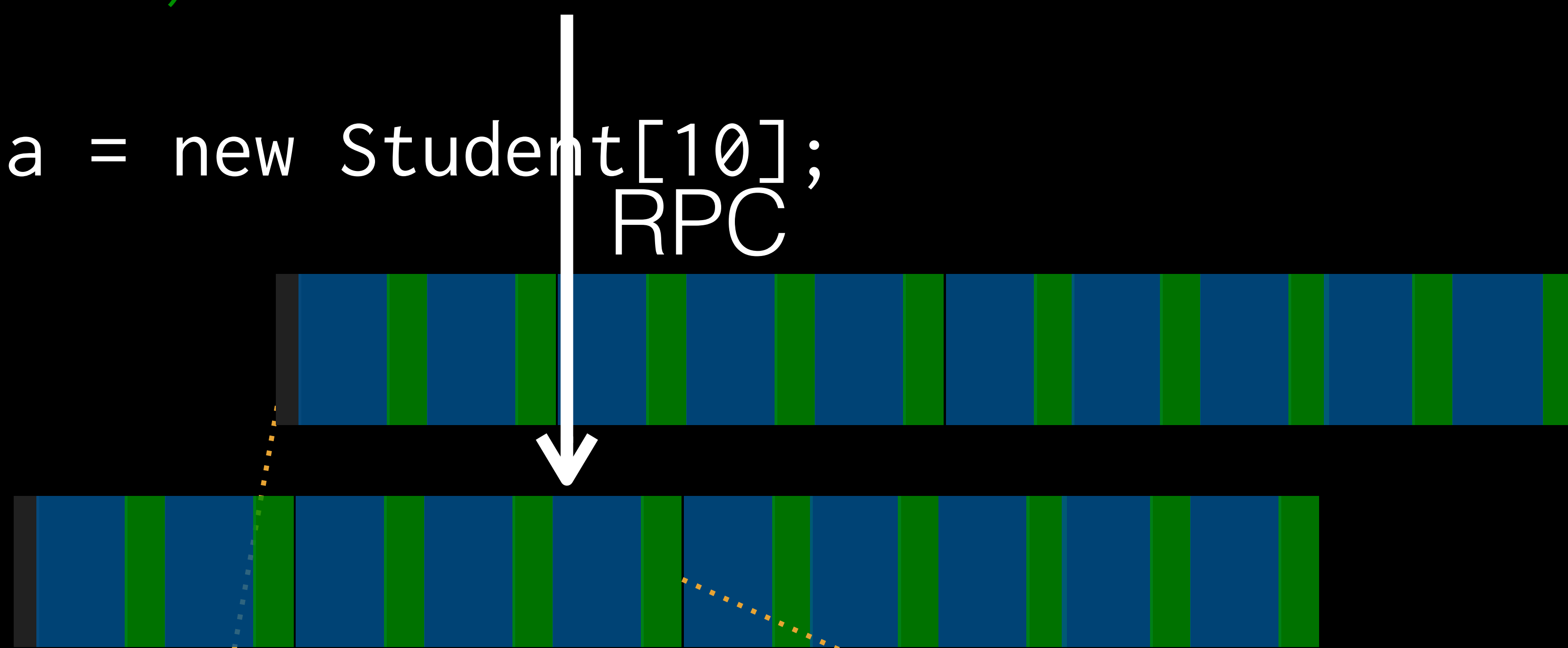
```
struct Student {
    chart[] name;
    int score;
}
Student[] data = new Student[10];
```



pay the header cost once per **array**

Marshalling Arrays of Records

```
struct Student {
    string name;
    decimal score;
}
Student[] data = new Student[10];
```

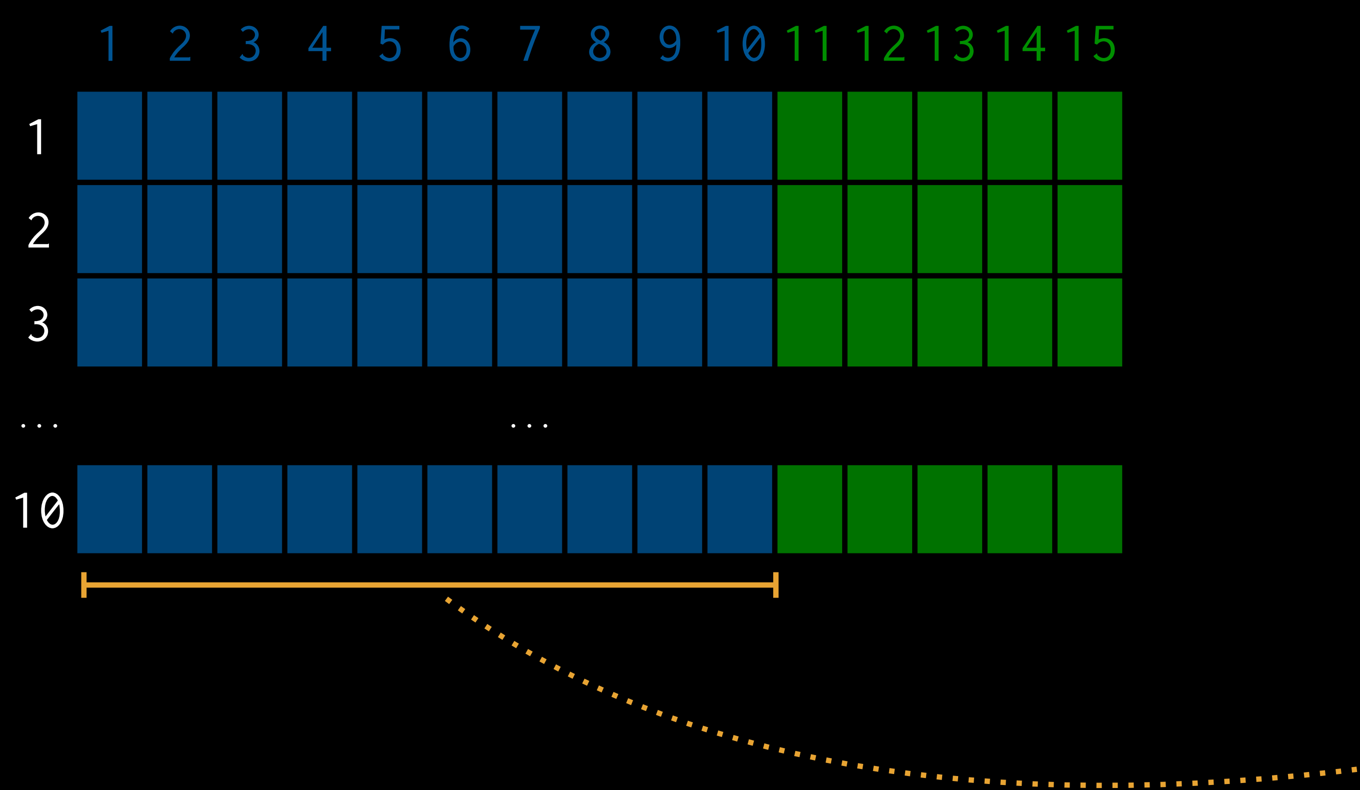


pay the header cost once per **array**

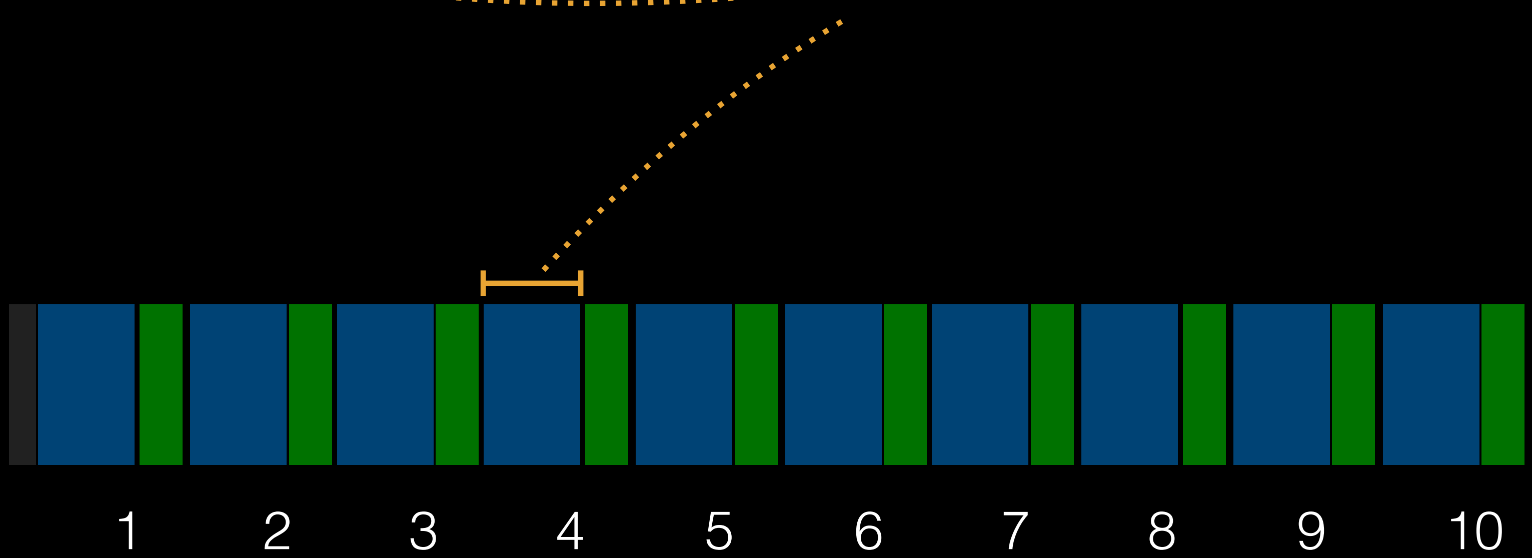
data[3].name.charAt(5)

operational form
and wire form

c.f. Cobol

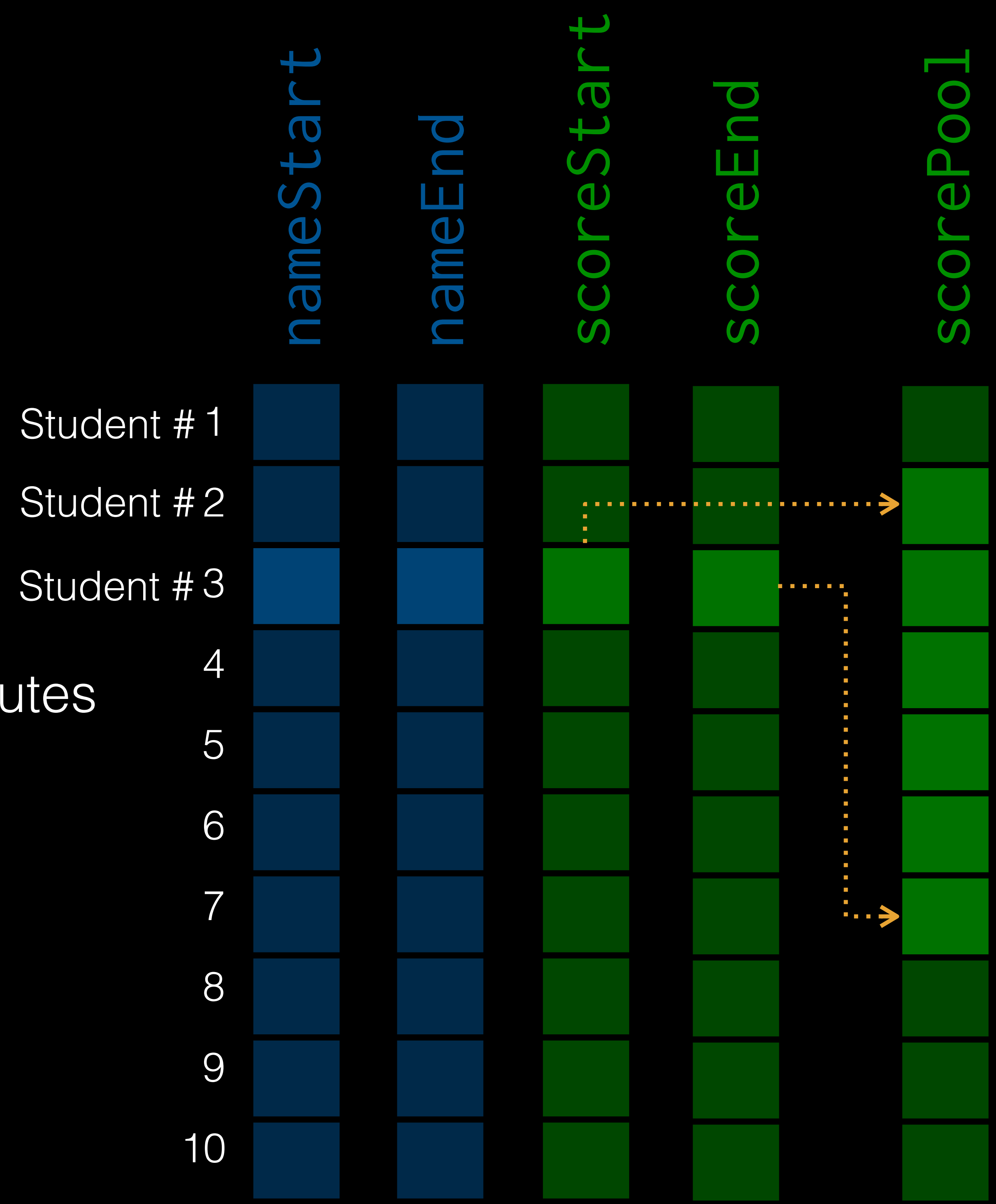


both are fine… until we need to store non-scalar data, i.e. variable-length data



Column Stores

```
class Student {
    String name;
    BigDecimal score;
}
```



PROS

maintains easily serializability

allows for mix-and-match use of attributes

CONS

added overhead (start and end pointers)

unspeakably horrible code

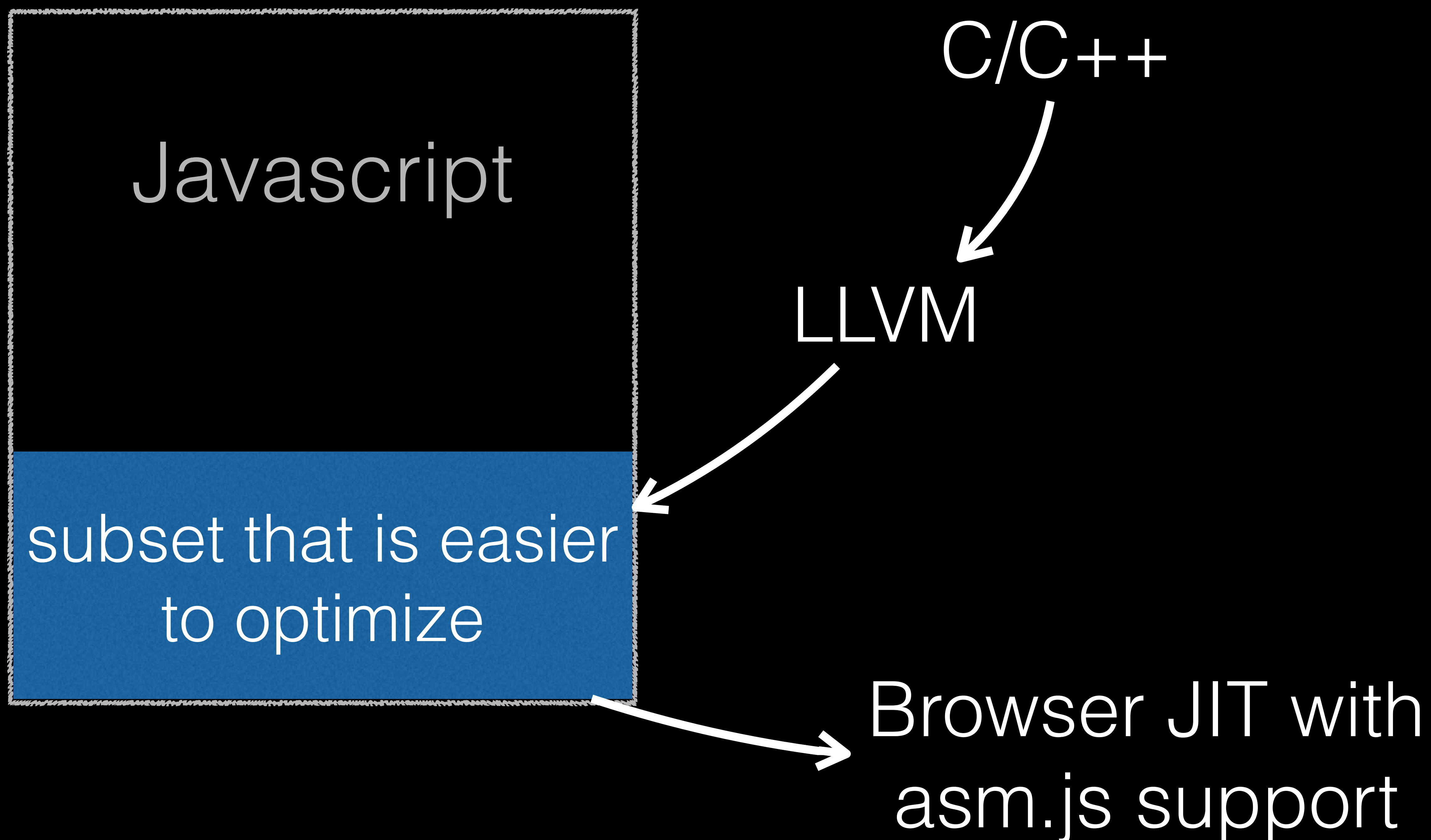
7. Alternative Compilation Schemes
and
Optimizable Language Kernels

High-level Languages for Targeting FPGAs

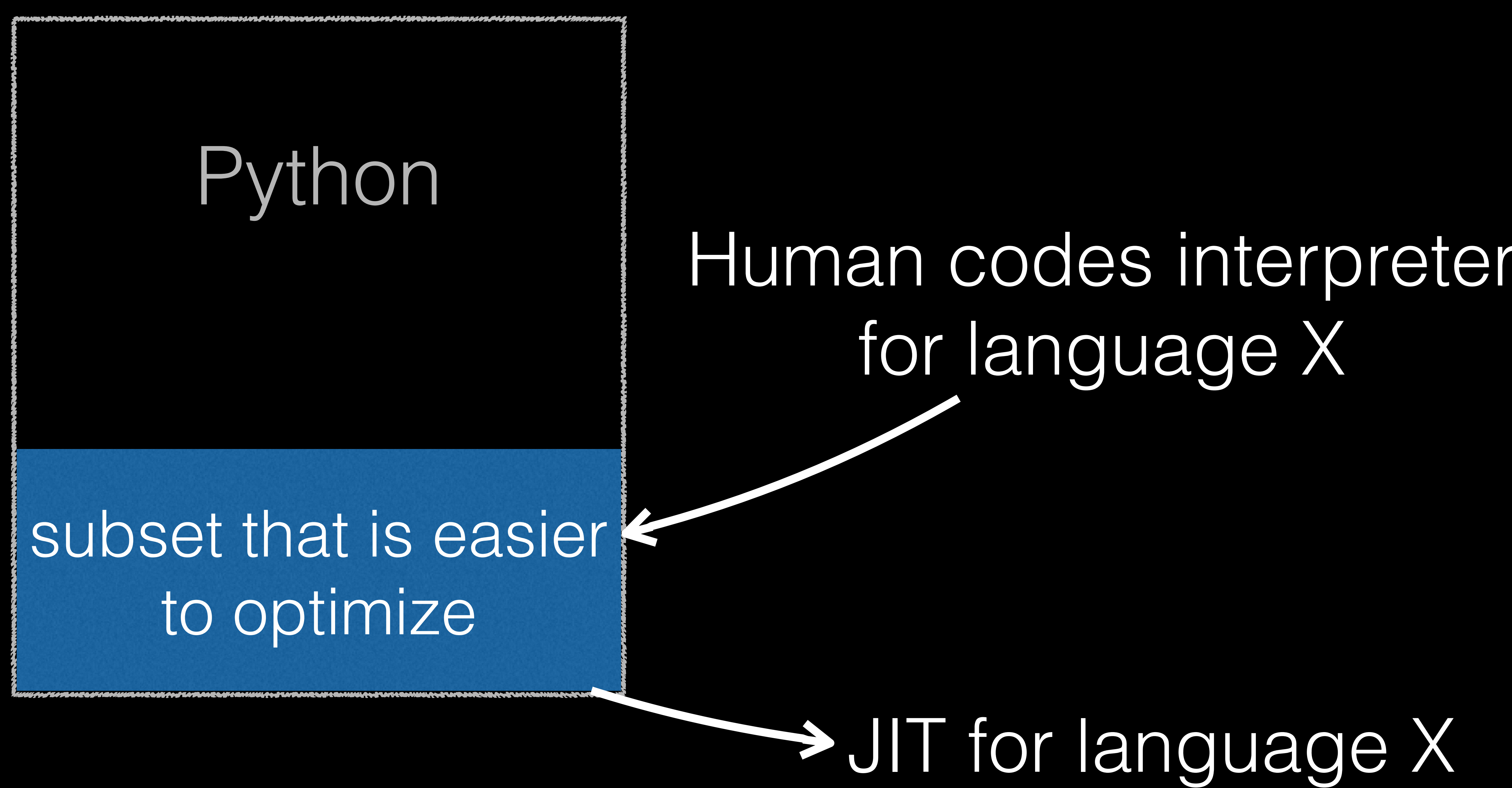
- LegUp (U. Toronto)
- Kiwi (Microsoft Research)
- Bluespec (MIT)
- Lime (IBM Research)

make it easier to write computational kernels

asm.js

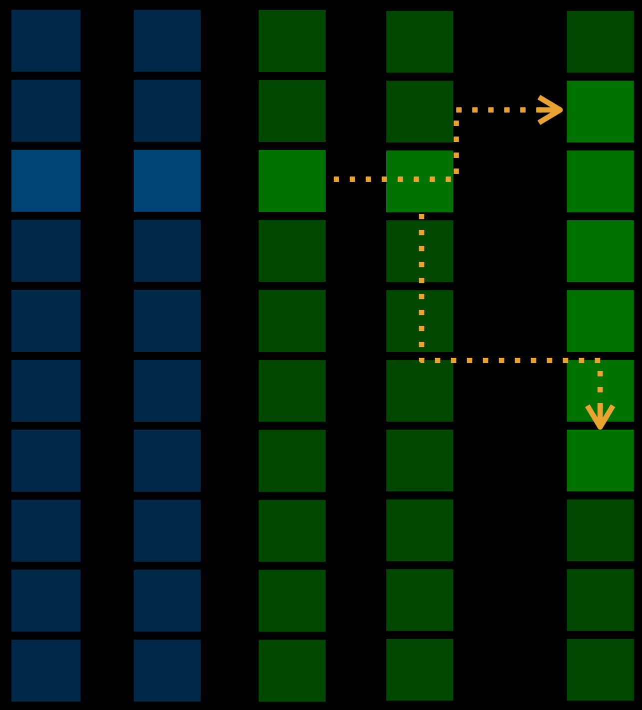

Javascript
subset that is easier to optimize
C/C++
LLVM
Browser JIT with asm.js support

RPython (c.f. Truffle)

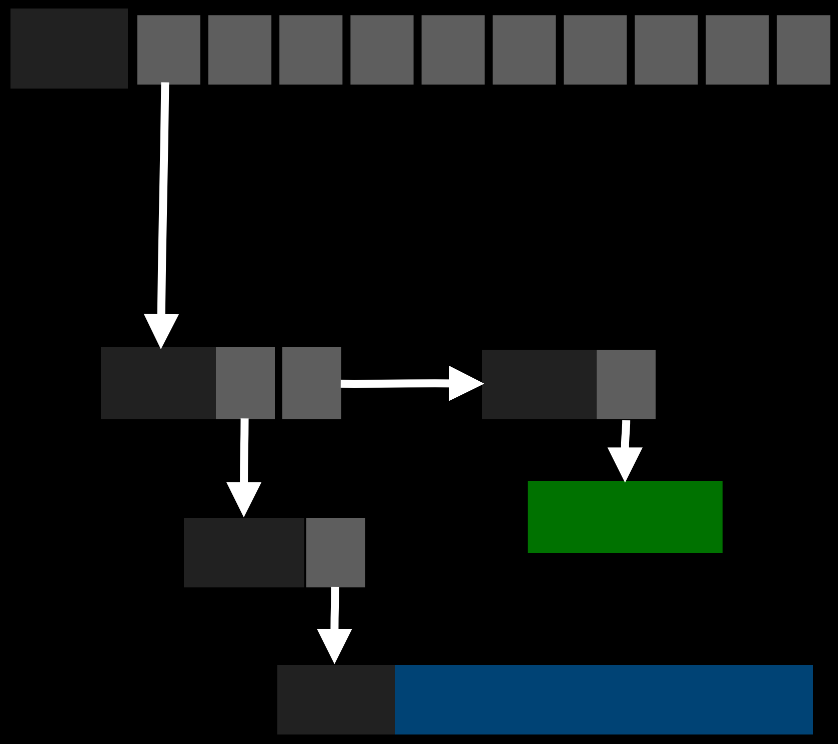


Models vs Storage

```
class Student {
    String name;
    BigDecimal score;
}
```



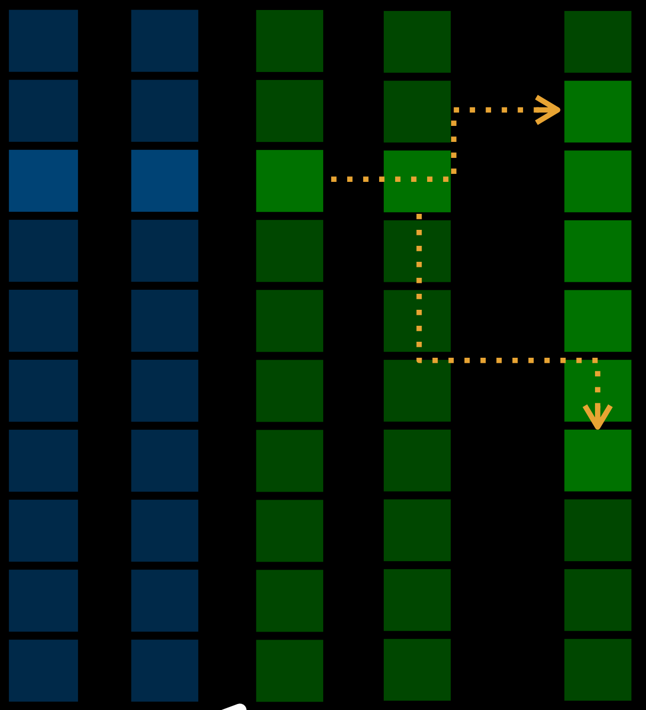
code is hard to maintain, or impossible to express in the language, but performance is great

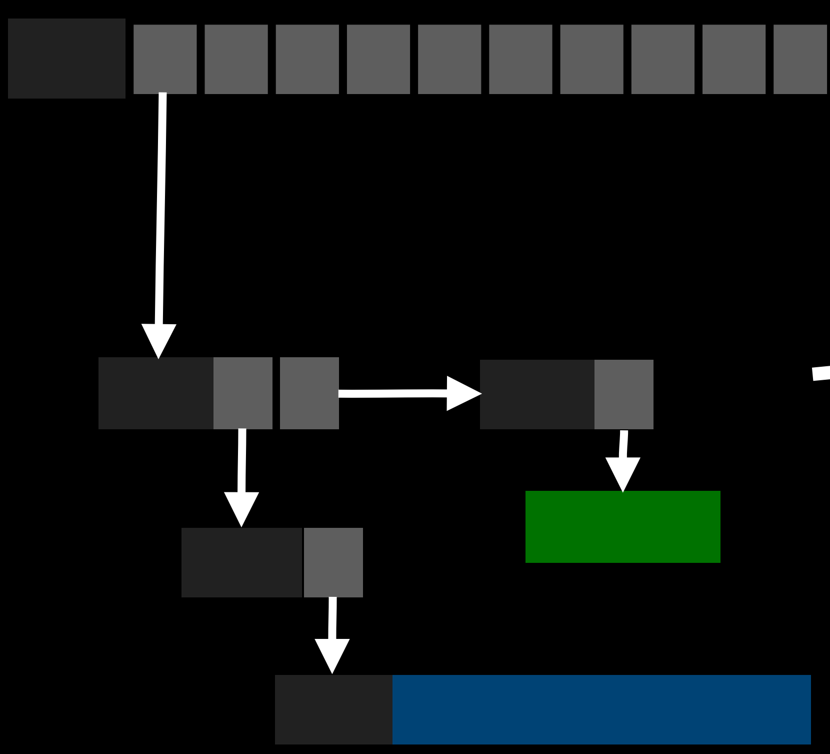


code is easy to maintain, but performance sucks

Lowering...

```
class Student {
    String name;
    BigDecimal score;
}
```

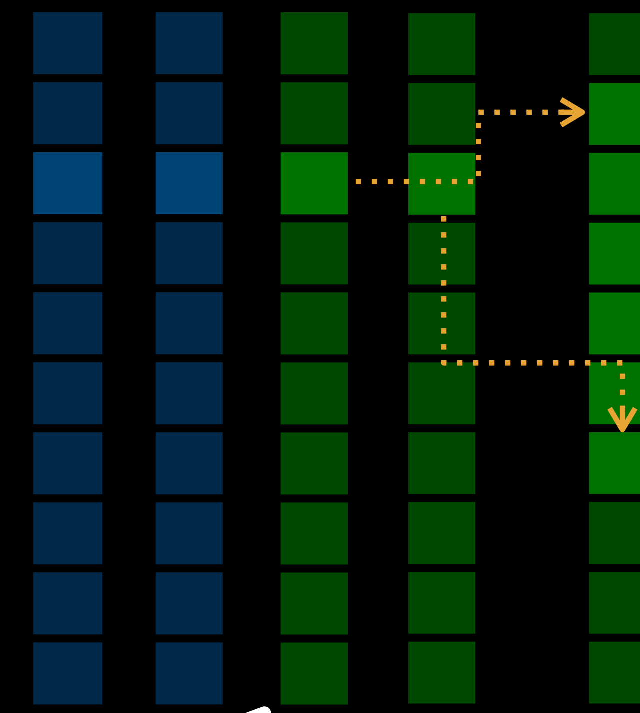


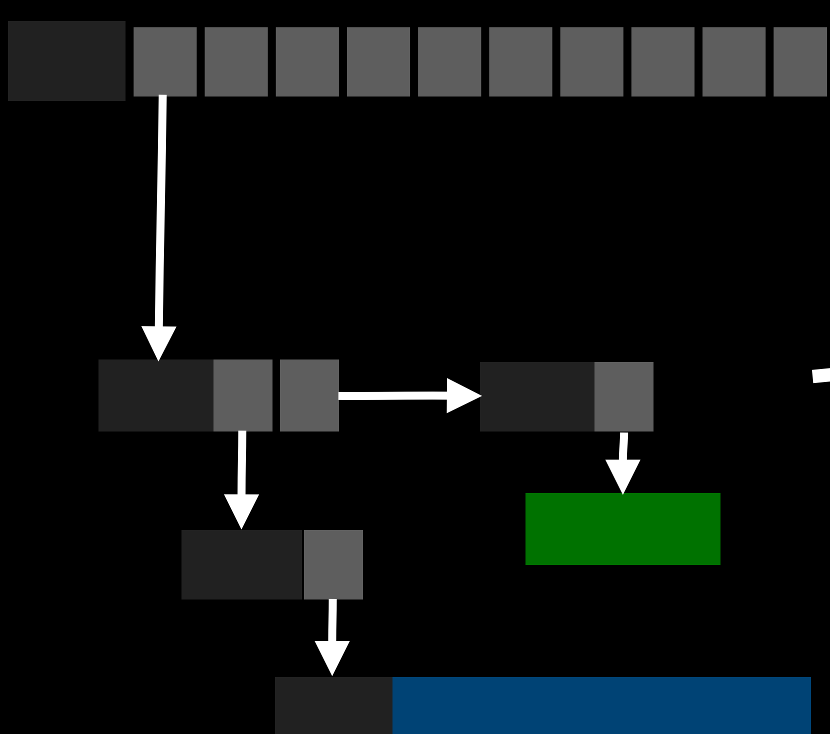


Can we lower from one to the other?

Lowering…

```
class Student {
    String name;
    BigDecimal score;
}
```





What is lowering other than… a partial evaluation of serialization?

Partial Marshal

```
class Student {
    String name;
    BigDecimal score;
}
```

transformer??

```
class StudentTable {
    CharTable names;
    int[] nameStart;
    int[] nameEnd;
    IntTable scores;
    int[] scoreStart;
    int[] scoreEnd;
}
```

```
student.getName();
```

transformer??

```
students.getName(i);
```

```
names.splice(students.nameStart[i],
              students.nameEnd([i]);
```

Partial Marshal

```
class Student {
    String name;
    BigDecimal score;
}
```

```
student.getName();
```

data model

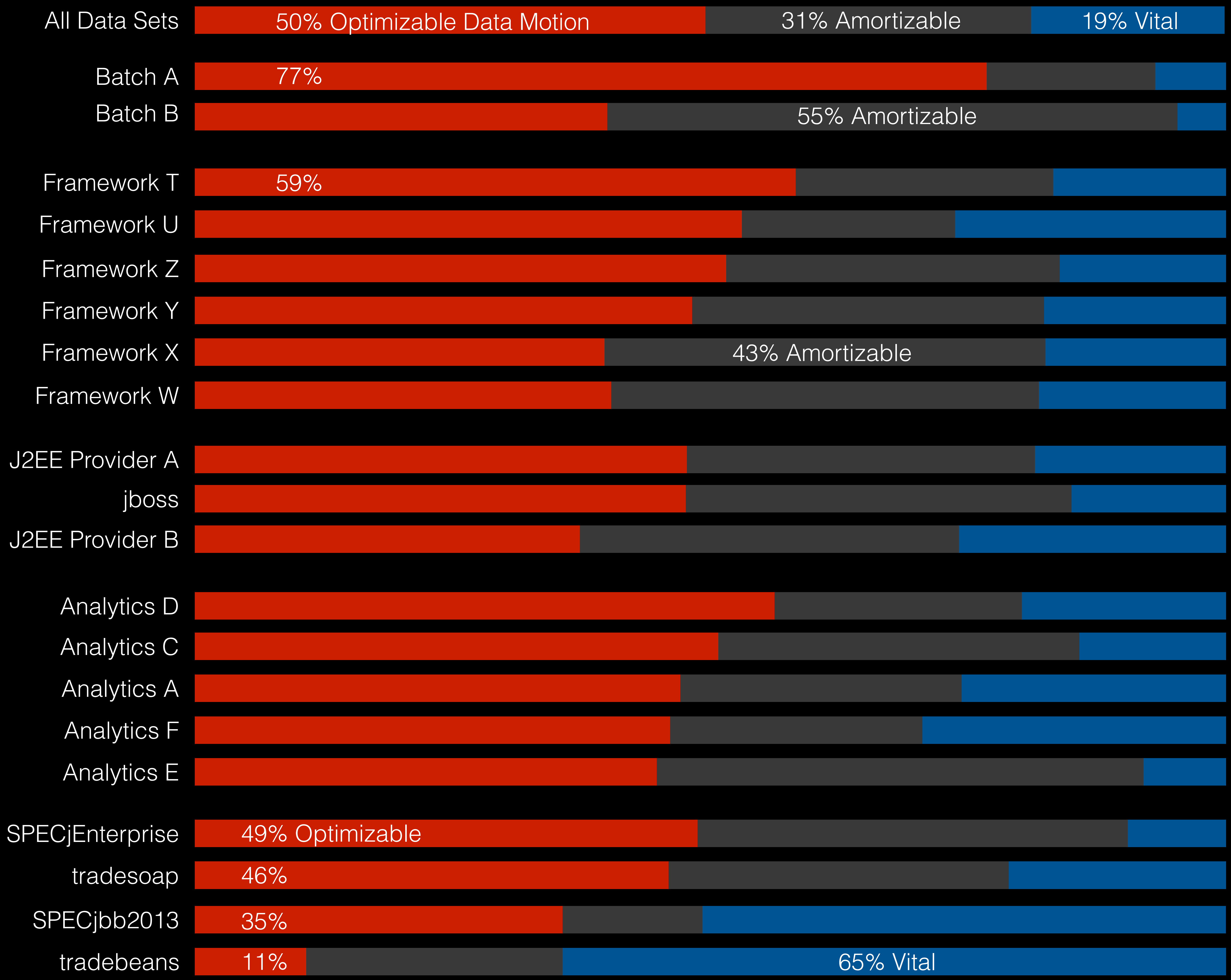
data access

```
class StudentTable
    CharTable names;
    int[] nameStart;
    int[] nameEnd;
    IntTable scores;
    int[] scoreStart;
    int[] scoreEnd;
}
```

```
students.getName(i);
```

```
names.splice(students.nameStart[i],
              students.nameEnd([i]);
```

Attic


All Data Sets
50% Optimizable Data Motion
31% Amortizable
19% Vital
Batch A
77%
Batch B
55% Amortizable
Framework T
59%
Framework U
Framework Z
Framework Y
Framework X
43% Amortizable
Framework W
J2EE Provider A
jboss
J2EE Provider B
Analytics D
Analytics C
Analytics A
Analytics F
Analytics E
SPECjEnterprise
49% Optimizable
tradesoap
46%
SPECjbb2013
35%
tradebeans
11%
65% Vital