Watching for Software Inefficiencies with Witch 

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Classical Performance Analysis

- Identify hotspots — high resource utilization
  - time / CPU cycles
  - cache misses on different levels
  - floating point operations, SIMD
  - derived metrics such as instruction per cycle (IPC)
- Improve code in hot spots
- Hotspot analysis is indispensable, but
  - cannot tell if resources were “**well spent**”
  - hotspots may be symptoms of performance problems
  - need significant manual efforts to investigate root causes

Pinpoint resource wastage instead of usage

Software Inefficiency — Redundant Operations

Dead write

```
x = 0;
x = 20;
```

Silent write

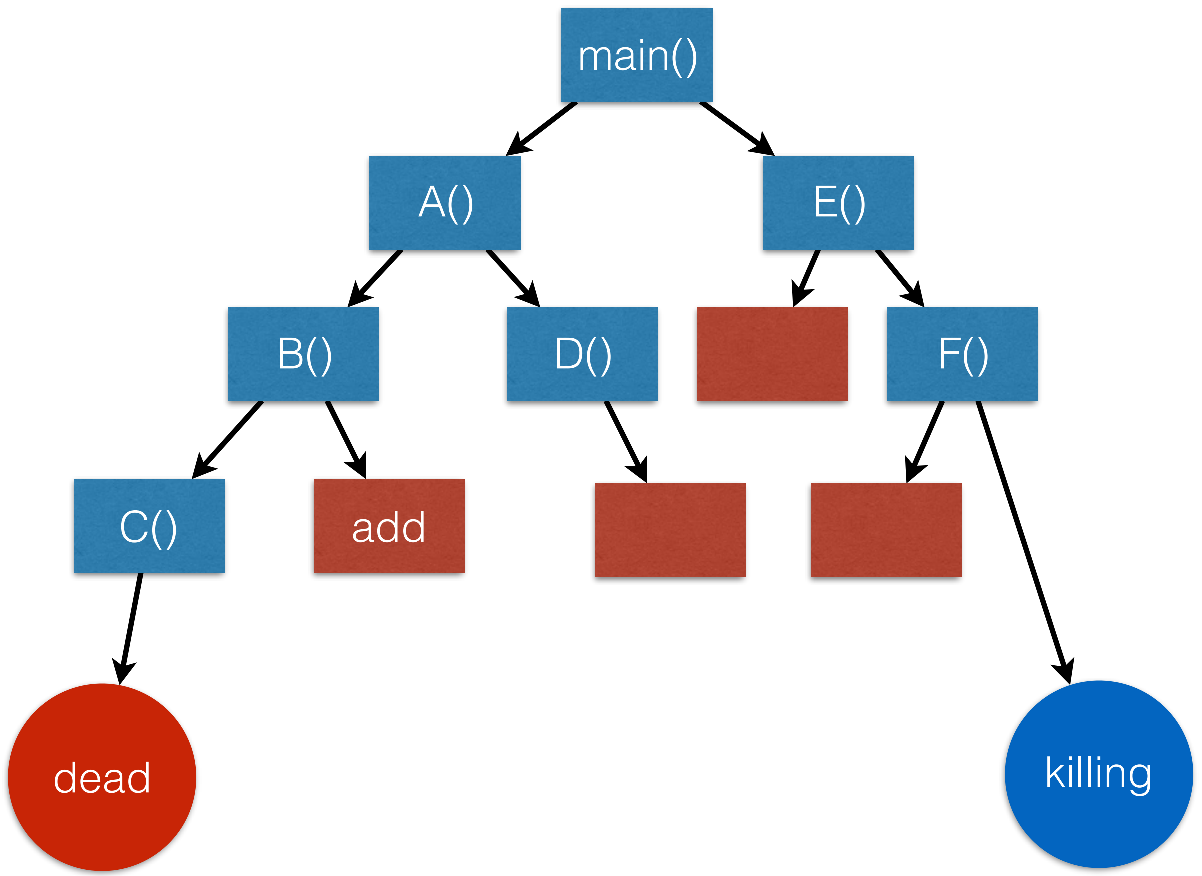
```
x = 20;
y=func(x);
x = 20;
```

Silent load

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

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

Software Inefficiency — Redundant Operations



Need fine-grained binary analysis + call path analysis

HMMER: An Example for Resource Wastage

Unoptimized

```
for (i = 1; i <= L; i++) {
 for (k = 1; k <= M; k++) {
     mc[k] = mpp[k-1] + tpmm[k-1];
     if ((sc = ip[k-1] + tpim[k-1]) > mc[k])
         mc[k] = sc;
```

-O3 optimized

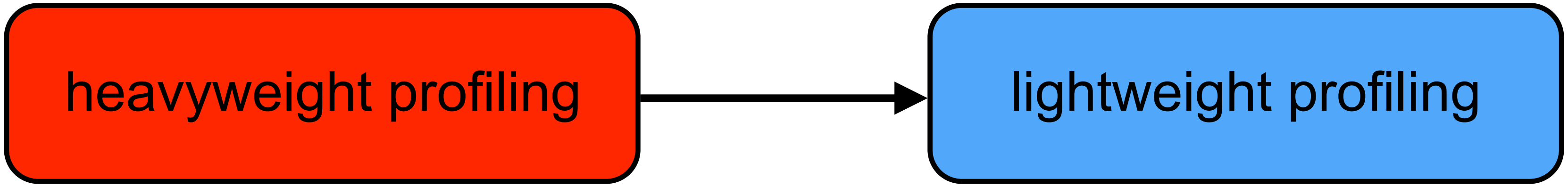
```
for (i = 1; i <= L; i++) {
   for (k = 1; k <= M; k++) {
       R1= mpp[k-1] + tpmm[k-1];
       mc[k] = R1;
       if ((sc = ip[k-1] + tpim[k-1]) > R1)
          mc[k] = sc;

       else
          mc[k] = R1;
```

Never Alias.
Declare as “restrict” pointers.
Can vectorize.

> 16% running time improvement
> 40% with vectorization

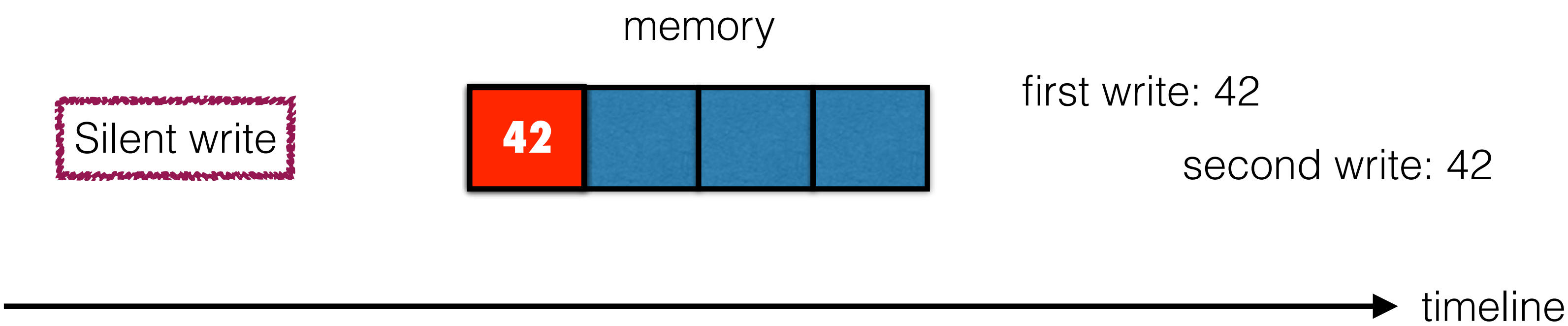
Straightforward Measurement for Inefficiencies

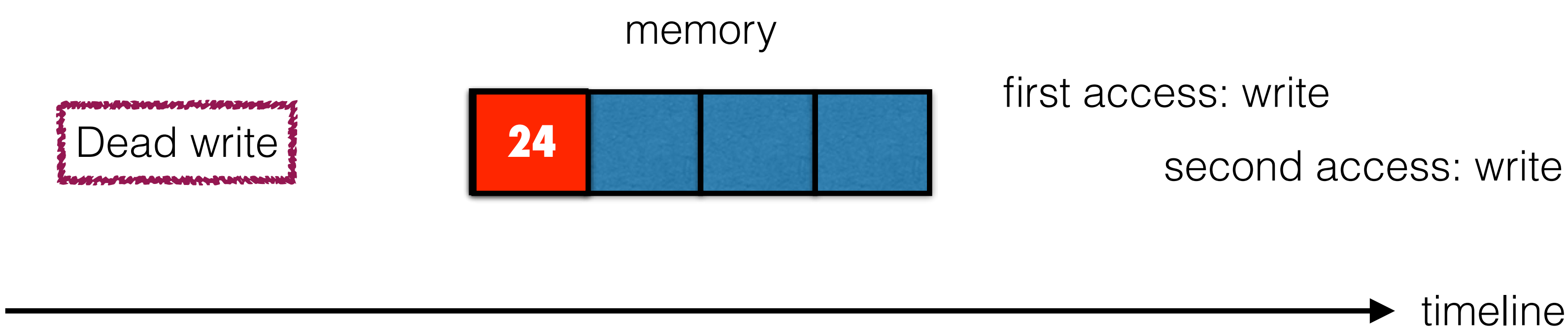
- Fine-grained analysis
  - Instrument every memory load and store
  - RedSpy (ASPLOS’17), LoadSpy, RVN (PACT’15), DeadSpy (CGO’12)
- Advantages
  - do not miss anything
  - serve as a proof-of-concept and upper-bound of other analyses
- Disadvantages
  - high time and space overhead



A Key Observation

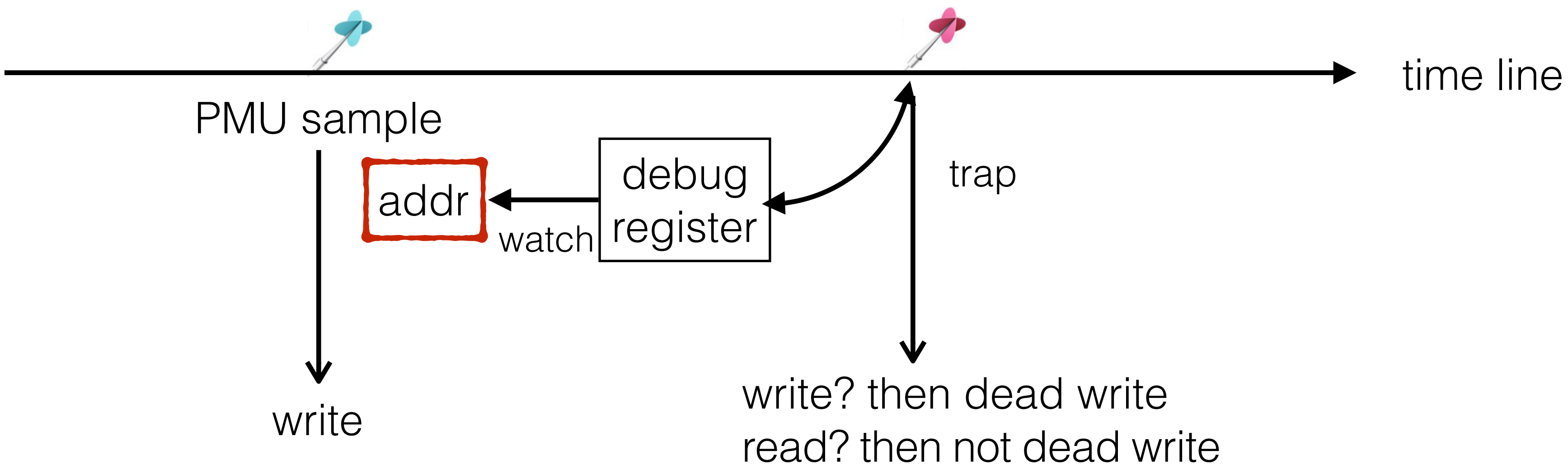
Detecting a variety of inefficiencies requires monitoring *consecutive accesses to the same memory location*





Witch: Lightweight Inefficiency Analysis

- Methodology: sample pair of consecutive accesses to the same memory address
  - hardware performance monitoring units (PMU)
    - event-based sampling → profiling memory addresses
    - first access in the pair
  - hardware debug registers
    - watch for the next access of sampled memory address
    - second access in the pair



Witch Advantages

- No source code or binary instrumentation / recompilation
- Work for fully optimized binary, independent from programming languages and models
- Capture statistically significant inefficiencies
- Low runtime and memory overhead

Challenge 1

- Limited number of debug registers
  - 4 on x86
  - 1 on PowerPC

Assume: PMU samples one in 10k memory stores

loop 1

```
for ( int i = 1; i <= 100K; i++){
    arrayA[i] = 0;
}
```

loop 2

```
for ( int k = 1; k <= 100K; k++){
    arrayB[k] = 0;
}
```

loop 3

```
for ( int j = 1; j <= 100K; j++){
    arrayA[j] = 0;
}
```

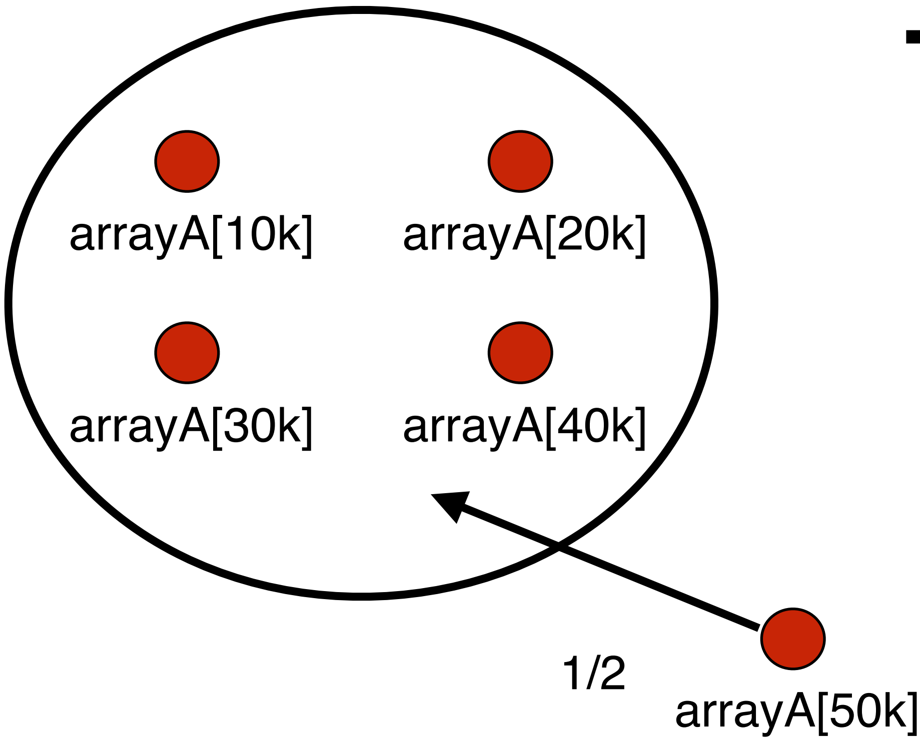
watchpoints set in loop 1 should remain till loop 3

To detect dead store between loop 1 and loop 3

20 sampled addresses to monitor but have only 4 debug registers!

Temporally Unbiased Sampling

- Monitoring addresses with equal probability
  - have a free debug register → monitor the next sample
  - no free debug register → probabilistically replace the address from monitoring



PMU samples 10k memory stores

```
for ( int i = 1; i <= 100K; i++){
    arrayA[i] = 0;
}

for ( int k = 1; k <= 100K; k++){
    arrayB[k] = 0;
}

for ( int j = 1; j <= 100K; j++){
    arrayA[j] = 0;
}
```

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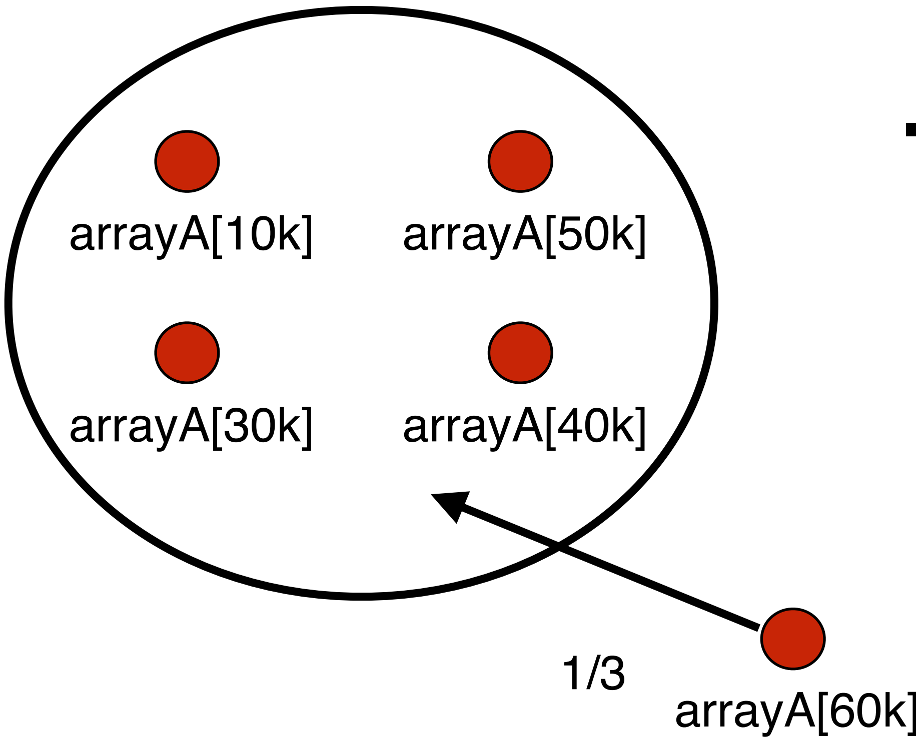

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}
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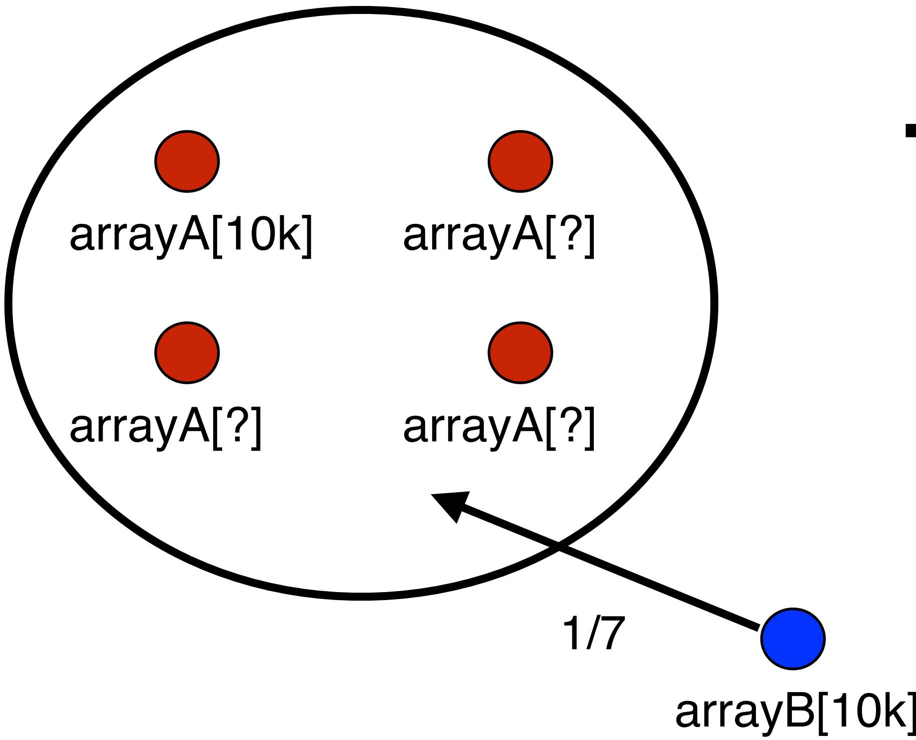

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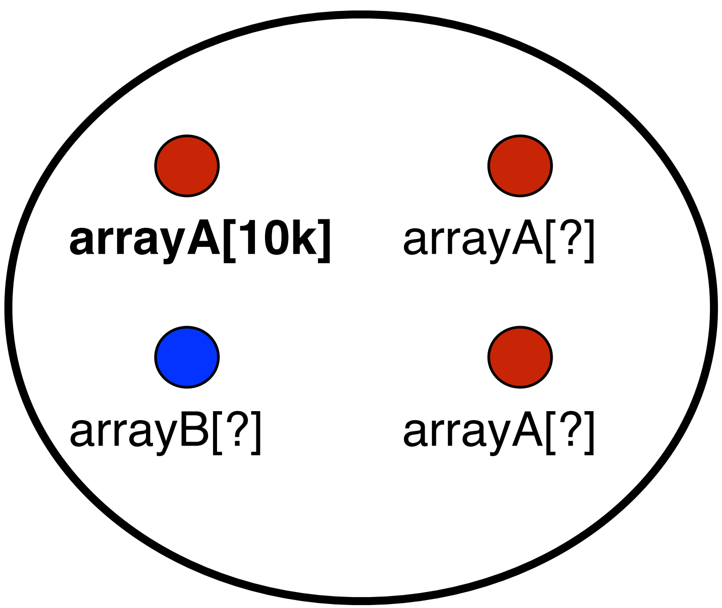

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}
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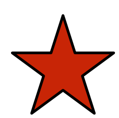


arrayA[10k]

Challenge 2

- Biased results

100k
dead stores

100k
dead stores

ideal

```
for ( int i = 1; i <= 100K; i++){
    arrayA[i] = 0;
}
for ( int k = 1; k <= 100K; k++){
    x = func();
    x = func();
}
for ( int j = 1; j <= 100K; j++){
    arrayA[j] = 0;
}
```

10k
dead stores

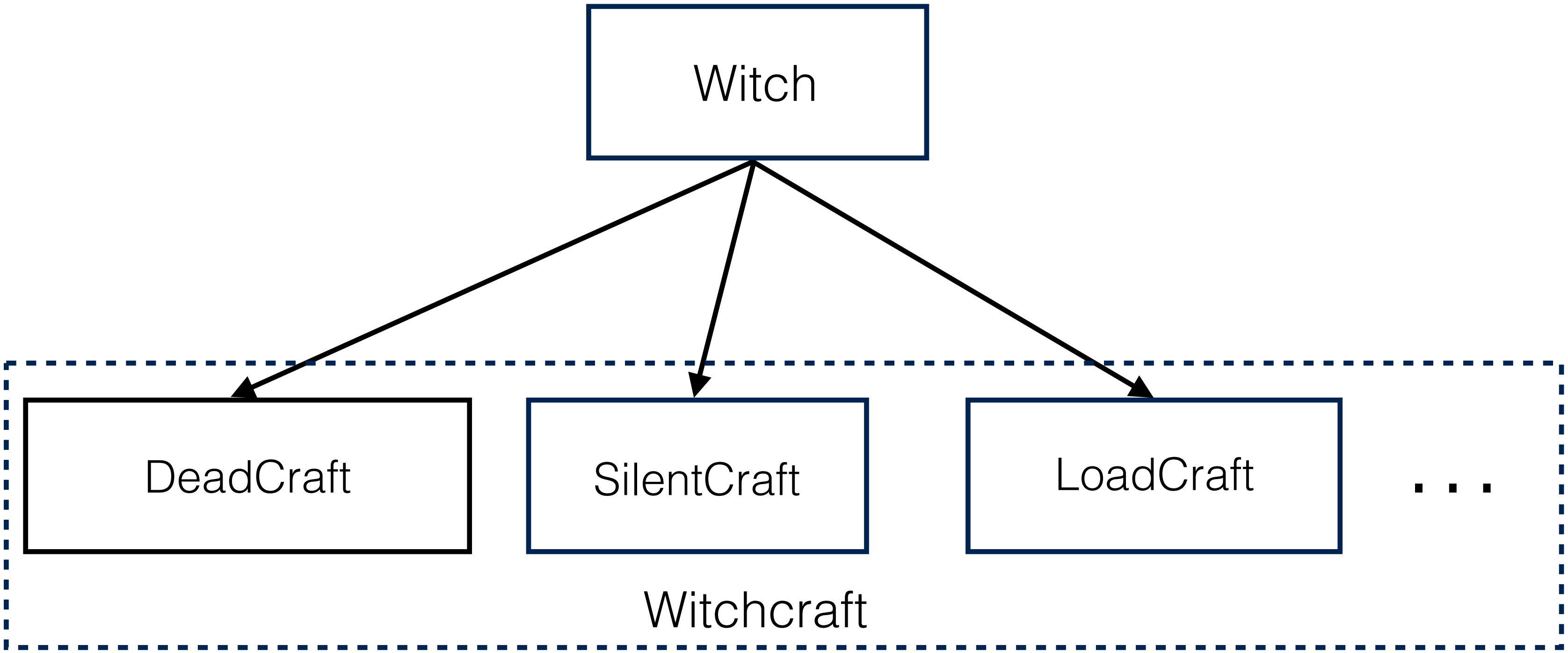
100k
dead stores

biased

10 samples but 1 monitored → 10k*10 = 100k

Solution: proportional attribution — code in the same context has similar behaviors

Witchcraft: Tools Built atop Witch



Witch Has High Accuracy

- Witch identifies all significant inefficiencies found by exhaustive tools

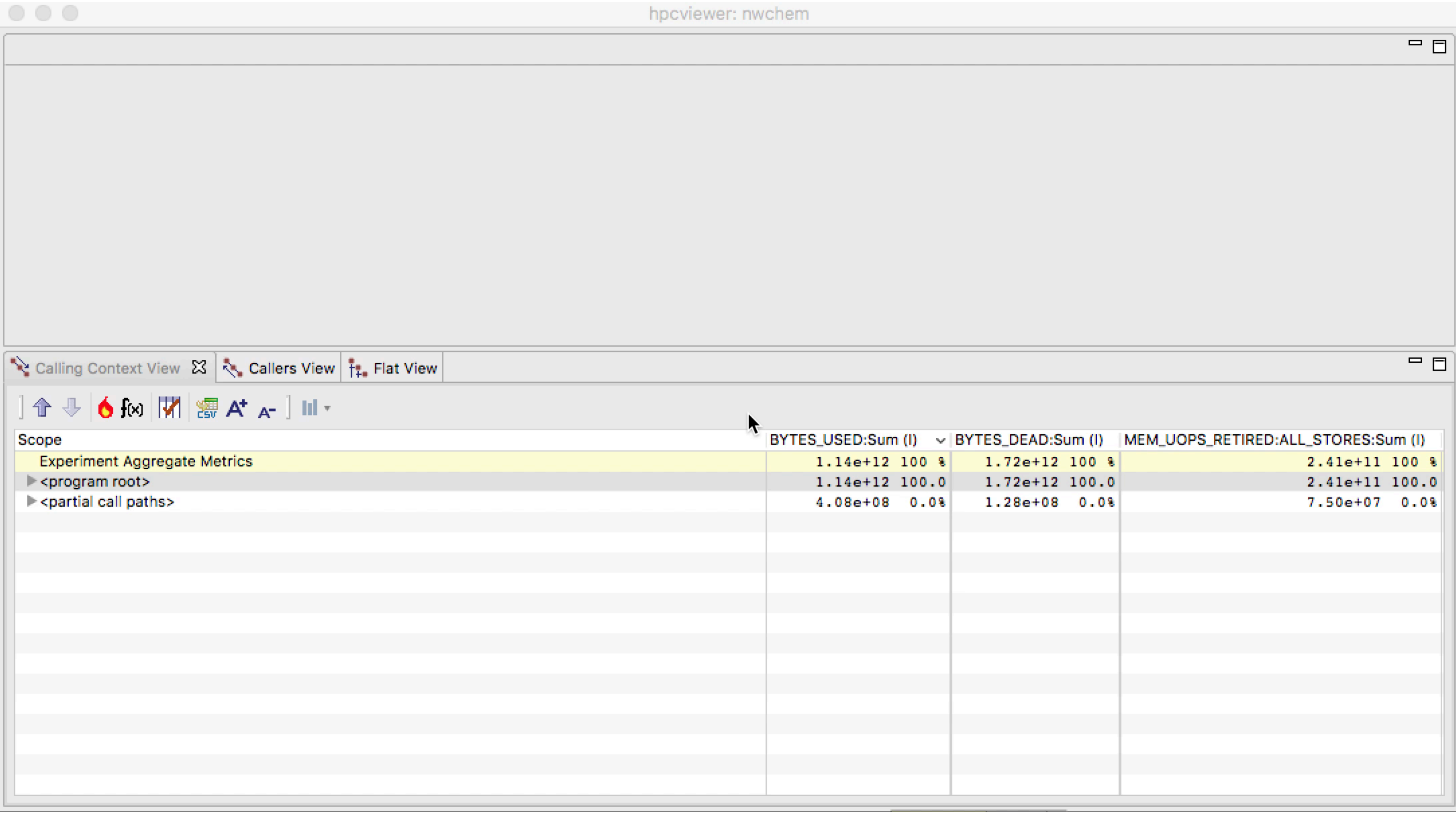
Application	Inefficiencies
gcc	DeadStore
bzip2	DeadStore
hmmer	DeadStore, SilentStore
h264ref	SilentLoad
backprop	SilentStore
lavaMD	SilentLoad
NWChem-6.3	DeadStore, SilentStore

Witch's Runtime and Memory Overheads

Sampling rates	DeadCraft		SilentCraft		LoadCraft	
	slowdown	memory bloat	slowdown	memory bloat	slowdown	memory bloat
10M	1.01x	1.05x	1.00x	1.04x	1.04x	1.05x
1M	1.03x	1.05x	1.03x	1.04x	1.27x	1.07x
500K	1.03x	1.06x	1.04x	1.05x	1.53x	1.07x
Instr	30.8x	7.16x	26.4x	6.16x	57.1x	8.35x

Case Study

NWChem is a DoE flagship computational chemistry application with 6 million lines of code. We run it with 8 MPI processes.



New Inefficiencies Reported by Witch

App	Problem	Speedup
povray	DeadStore	1.08X
Caffe-1.0	SilentStore	1.06X
Binutils-2.27	SilentLoad	10X
botsspar	SilentLoad	1.15X
imagick	SilentLoad	1.6X
Kallisto-0.43	SilentLoad	4.1X
lbm	SilentLoad	1.25X
SMB	SilentLoad	1.47X
vacation	SilentLoad	1.31X

Witch Supports Multithreading

- PMU and debug register are per-thread
- Signal delivery is per-thread
- Witch tools for multi-threaded cases — false sharing
  - thread A populates memory addresses to a shared location
  - thread B grabs a memory address in the shared location to monitor its adjacent addresses

A lightweight false sharing detector
PPoPP'18 best paper

Speedups after False-sharing Elimination

Benchmark		2-socket Haswell				16-socket Haswell						
		Num threads				Num threads						
		4	**8**	**16**	**32**	**4**	**8**	**18**	**36**	**72**	**144**	**288**
Synchro-bench	Fuzzy-KMeans	1.22	1.25	1.13	**1.75**	1.17	1.22	1.15	1.67	**2.15**	1.13	1.26
	SPIN-lazy-list	2.06	1.96	2.02	**2.71**	5.29	5.76	5.5	6.48	**16.06**	4.35	2.81
	SPIN-hashtable	1.19	1.35	1.41	**1.77**	1.33	1.44	1.45	**2.47**	1.26	2.49	1.99
	MUTEX-lazy-list	2.04	1.99	2.11	**2.23**	4.66	4.8	4.54	**7.19**	6.47	1.54	2.06
	MUTEX-hashtable	1.01	1.03	1.03	**1.44**	1.12	1.09	1.14	2.29	**2.65**	2.32	1.87
	lockfree-fraser-skiplist	1	1	**1.18**	1.05	1.05	1.06	1.1	1.43	1.56	**1.79**	1.65
	ESTM-specfriendly-tree	2.14	2.67	2.97	**5.52**	1.83	2.53	3.86	4.23	**9.43**	7.08	1.88
	ESTM-rbtree	1.01	1.19	**1.25**	1.03	1.08	1.23	1.32	1.19	1.25	**1.73**	1.27
Discrete event simulator	Libdes	3.97	5.37	**8.45**	1.39	4.27	6.51	9.25	4.81	**10.4**	8.58	7.19
Formal verification	Spin6.4.4	1.23	1.21	1.28	**2**	1.38	1.35	1.23	2.21	2.31	**3.93**	NA

On-going Work

- Lightweight reuse distance measurement
  - plot reuse histogram with >90% accuracy for program characterization
  - provide call paths for use and reuse to guide code optimization
- Lightweight inefficiency detection in Java programs
  - PMU + debug regster + JVMTI
- Lightweight inefficiency detection in Linux kernel

Conclusions

- Potential to pinpoint software inefficiencies in production codes
  - redundant computation
  - redundant memory accesses
  - useless operations
  - …
- Potential to deeper program analysis
  - access pattern analysis
  - inter-thread analysis (e.g., contention, false sharing)
- Witch is a unique framework to pinpoint software inefficiencies
  - lightweight measurement
  - extensible interfaces to other client tools
  - available at htttps://github.com/WitchTools/