Chainsaw: Using Binary Matching for Relative Instruction Mix Comparison

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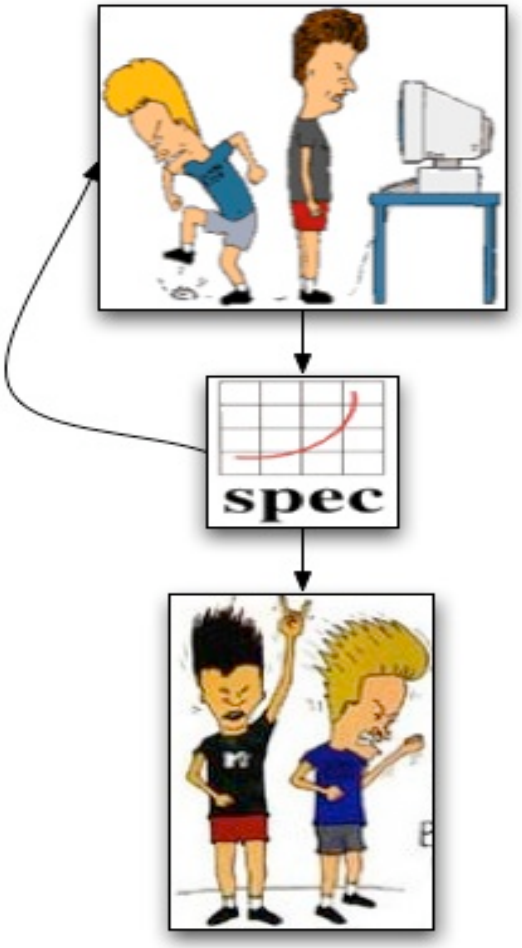
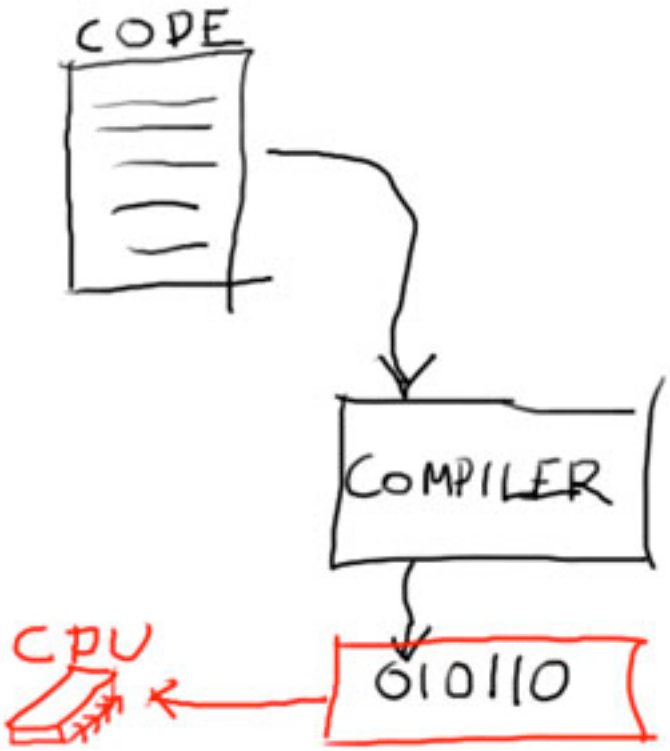
Primitive Development Cycle for Compilers

1. Come up with an idea
2. Test it
3. If nothing improved, go to 1
4. Celebrate

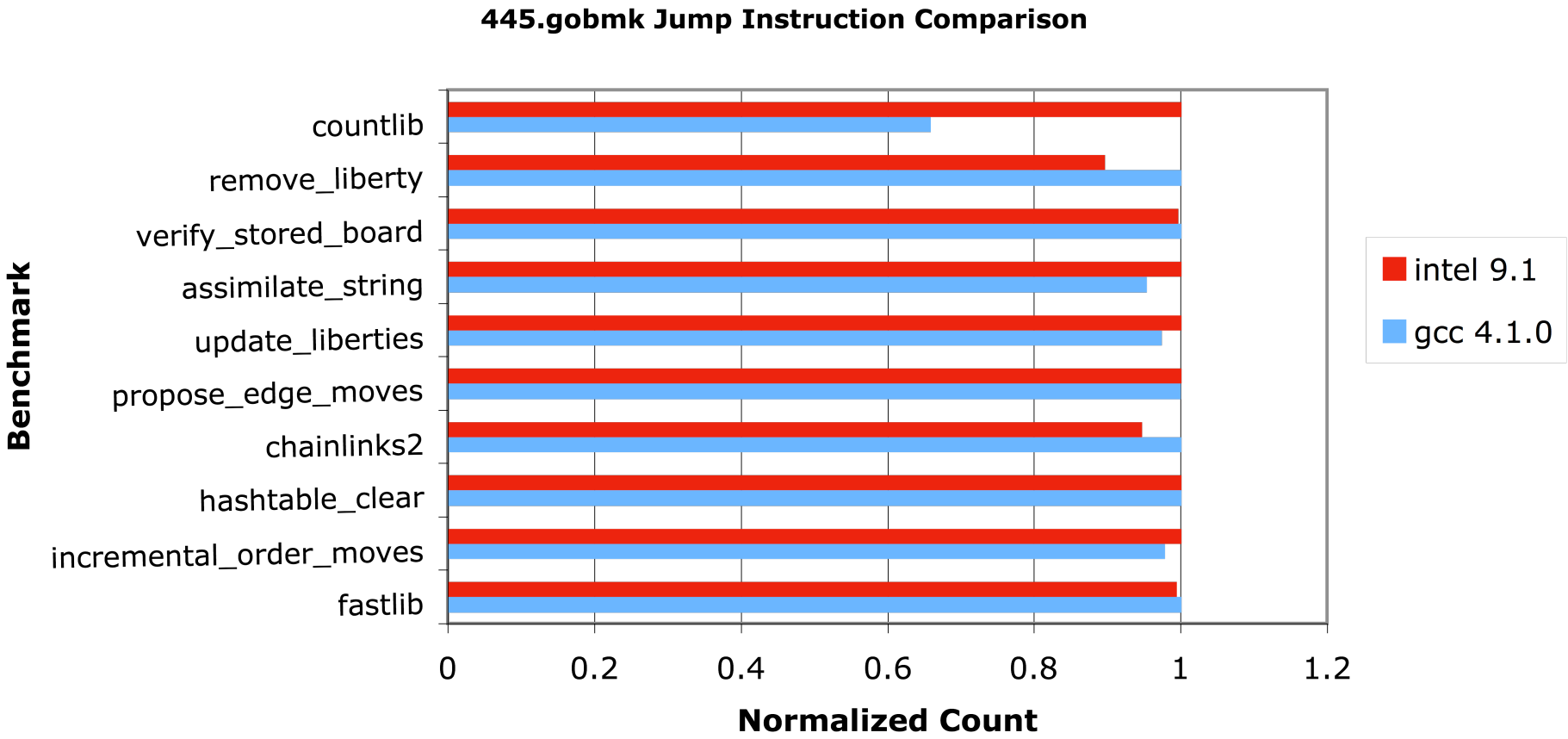


Understanding Transformations Is Hard



- Code size vs. control flow
  - Inlining, loop transformations, superblocks, if-conversion
- Architectural Features
  - Alignment, speculation, instruction selection, multilevel memory hierarchy, prefetching

Unpredictable Results



Motivating Example

```
assert(x == 1 || x == 2);
return array[x];
```

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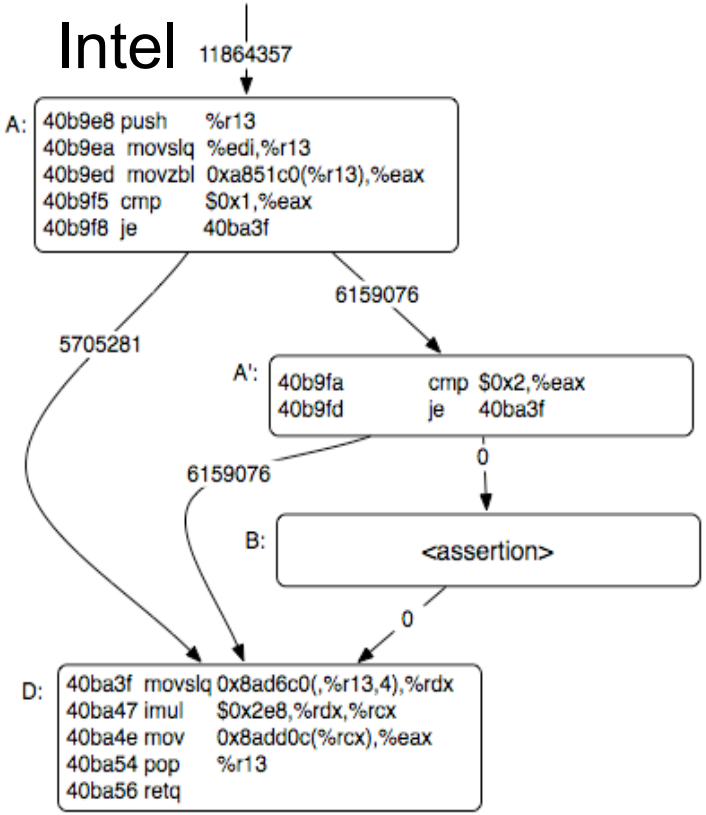
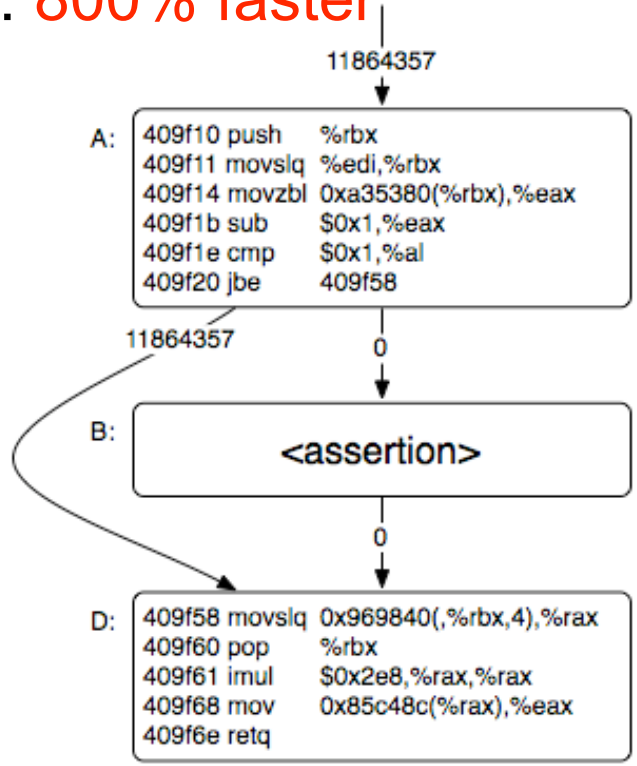


GCC: 800% faster



What if…

…this case is insignificant in the compiler vendor's regression suite?

…it is in the kernel of an important customer's application?

We need better tools!

Chainsaw Approach

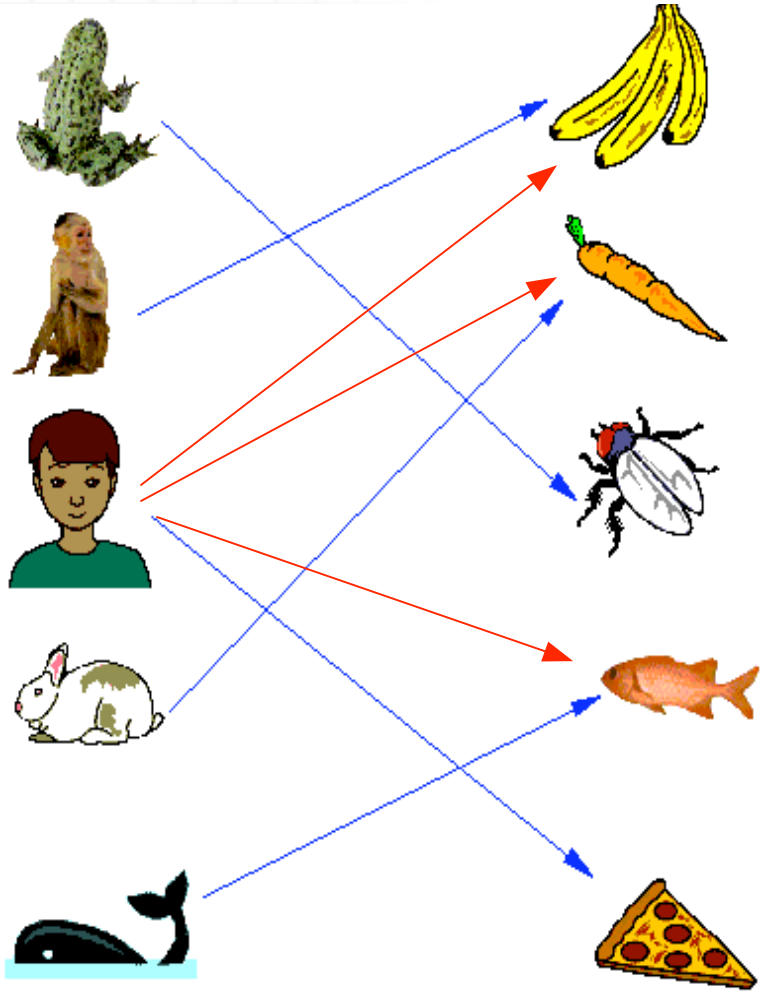
- Chainsaw offers high resolution relative performance comparison for arbitrarily compiled binaries (including IPO)
- Match a log of execution events from two differently compiled programs
  - Use BASE as reference point
- Compare profiles of matched intervals to identify outliers

Matching Resolution

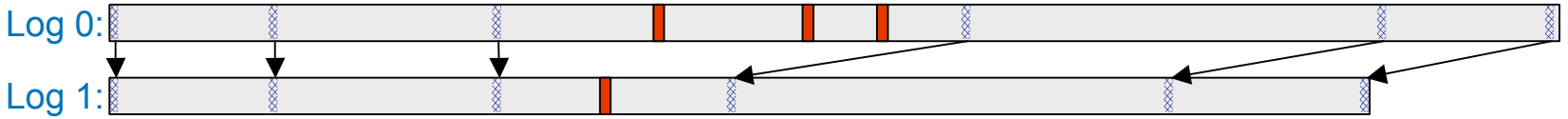
- Program- and function-level
  - Too big; miss opportunities
- Instructions and basic blocks
  - Too small; automatic comparisons are too noisy
- Loops
  - Just right; corresponds well with source
  - Be conservative; match innermost loop that makes sense

Challenges to Binary Matching

- Compiler can perform very aggressive optimization
  - Unrolling, peeling, splitting, merging, multiple entrypoints, versioning, …
- Larger functions can have many loops that look identical



Log-based Event Matching



- ***Event***: call, return, or backedge
- ***Anchor***: a pair of events that
  - Occurs the same number of times in both logs
  - Is semantically similar in both logs (e.g., same symbol names)
  - Has the same respective ordering to all other anchors in both logs
- ***Interval***: execution history between two anchored events

- Similar to sequence alignment, but much simpler
  - Don't deal with insertions/deletions; only align tokens that occur same number of times

Log-based Event Matching

Compilers can sometimes order function calls arbitrarily, so semantics and count alone are insufficient

- x = f() + g();
- LOG 0: CALL f, RET, CALL g, RET
- LOG 1: CALL g, RET, CALL f, RET

Ordering Signature

- Two anchors have the same ordering signature (OrdSig) **iff** they occur the same number of time and in the same order in both logs
- For each log, an ordering table (OrdTable) is filled with the OrdSig for every pair of events in the log

Computing Ordering Signatures

Traverse the log and maintain a stack-like structure ordering events

1. If the event, *i*, is not on the stack, run Update(*i, j*) for every *j* residing on the stack. Place i on the stack.
2. If the event, *i*, is on the stack, run Update(*i, j*) for every event *j* that has been seen since the last time *i* was seen. Move *i* to the back of the stack.
3. When the end of an interval is reached, run Update(*i, j*) for every event pair where *i* has been seen more recently than *j* on the stack.

Computing Ordering Signatures

Update function:

Modify ordtable[i, j] and ordtable[j, i] by xor with event count, circular shift, and multiply with large prime seed.

Ordering Signatures Example

Log: ABCBBA

	A	B	C
A	2	0x21	0x67
B	0x11	3	0x03
C	0xeb	0x75	1

Log: AXYBCXXBYBYAX

	A	B	C	X	Y
A	2	0x21	0x67	0x9a	0x1b
B	0x11	3	0x03	0xd	0x9f
C	0xeb	0x75	1	0x81	0x8c
X	0xb2	0x86	0x63	4	0x47
Y	0x19	0xfe	0x88	0x5e	3

Ordering Signatures Example

Initial state:

Sequence: ABCBBA

stack = []

	A	B	C
A	0	0	0
B	0	0	0
C	0	0	0

Ordering Signatures Example

Step 1:
Sequence: **A**BCBBA
Actions: OrdTable[A, A]++
stack = [A]

	A	B	C
A	1	0	0
B	0	0	0
C	0	0	0

Ordering Signatures Example

Step 2:

Sequence: A**B**CBBA

Actions: OrdTable[B, B]++, Update(B, A)

stack = [A, B]

	A	B	C
A	1	0xa1	0
B	0xb7	1	0
C	0	0	0

Ordering Signatures Example

Step 3:
Sequence: AB**C**BBA
Actions: OrdTable[C, C]++, Update(C, B),
Update(C, A)
stack = [A, B, C]

	A	B	C
A	1	0xa1	0xa1
B	0xb7	1	0xa1
C	0xb7	0xb7	1

Ordering Signatures Example

Step 4:

Sequence: ABC**B**BA

Actions: OrdTable[B, B]++, Update(B, C)

stack = [A, C, B]

	A	B	C
A	1	0xa1	0xa1
B	0xb7	2	0x5a
C	0xb7	0x13	1

Ordering Signatures Example

Step 5:
Sequence: ABCB**B**A
Actions: OrdTable[B, B]++
stack = [A, C, B]

	A	B	C
A	1	0xa1	0xa1
B	0xb7	3	0x5a
C	0xb7	0x13	1

Ordering Signatures Example

Step 6:

Sequence: ABCBB**A**

Actions: OrdTable[A, A]++, Update(A, B)

Update(A, C)

stack = [C, B, A]

	A	B	C
A	2	0x12	0x4e
B	0x61	3	0x5a
C	0x9f	0x13	1

Ordering Signatures Example

End of interval:

Sequence: <>

Actions: Update(A, B), Update(A, C),
Update(B, C)

stack = [C, B, A]

	A	B	C
A	2	0x21	0x67
B	0x11	3	0x03
C	0xeb	0x75	1

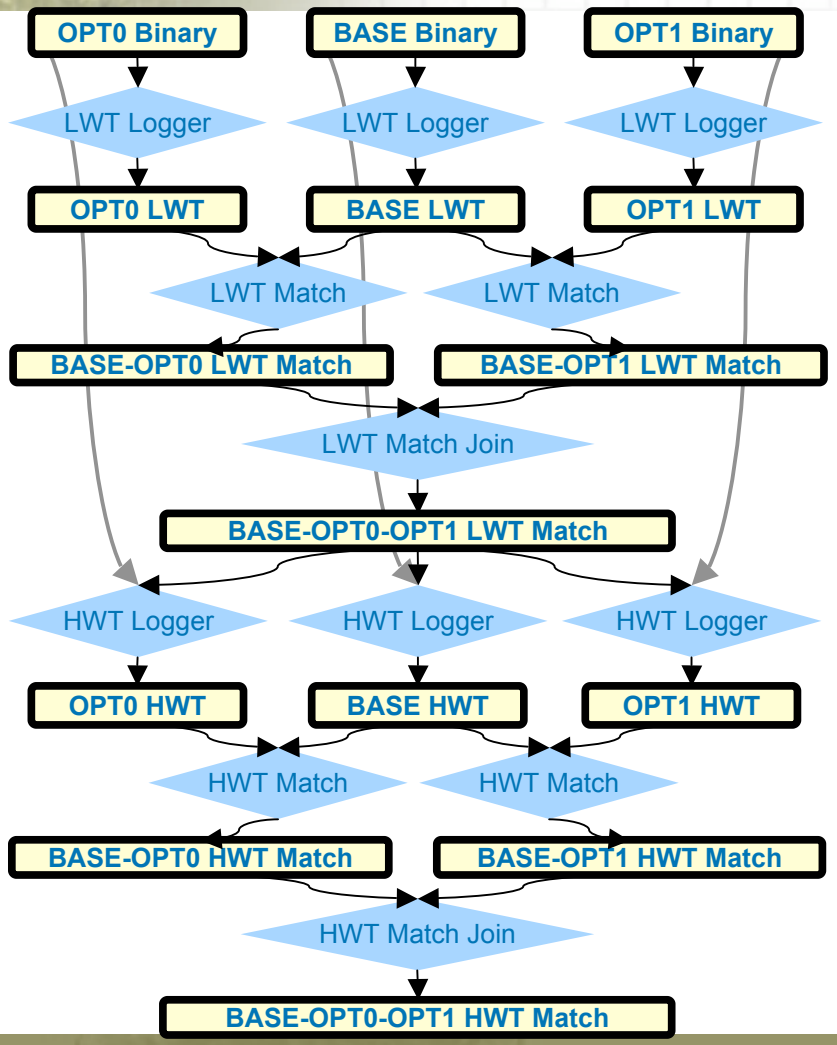
Selecting Matches

- Score potential anchors
  - Sort by number of common OrdSigs in each log
  - Event counts must be equal
  - Events must be semantically similar
- Select first match with highest score
- Subsequent matches must be legally ordered with respect to previous matches

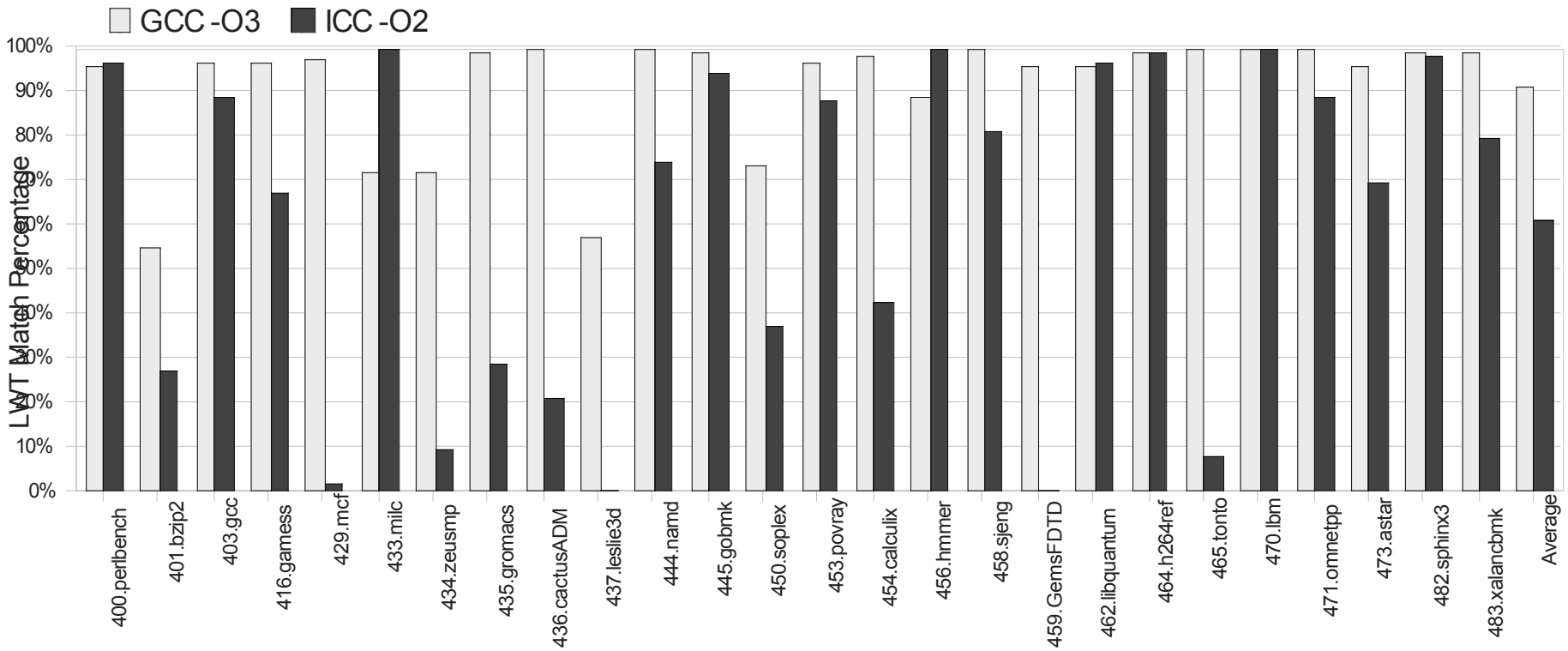
Real-world Challenges

- Event logs are enormous and slow to collect
  - Two-pass algorithm
    - Lightweight log (LWT)
      - Only CALL, RET, and non-inner loop BACKEDGE
    - Heavyweight log (HWT) – inner loops too
- Comparing optimized (OPT) binaries leads to ambiguity
  - Compare each log to unoptimized (BASE) and infer mapping

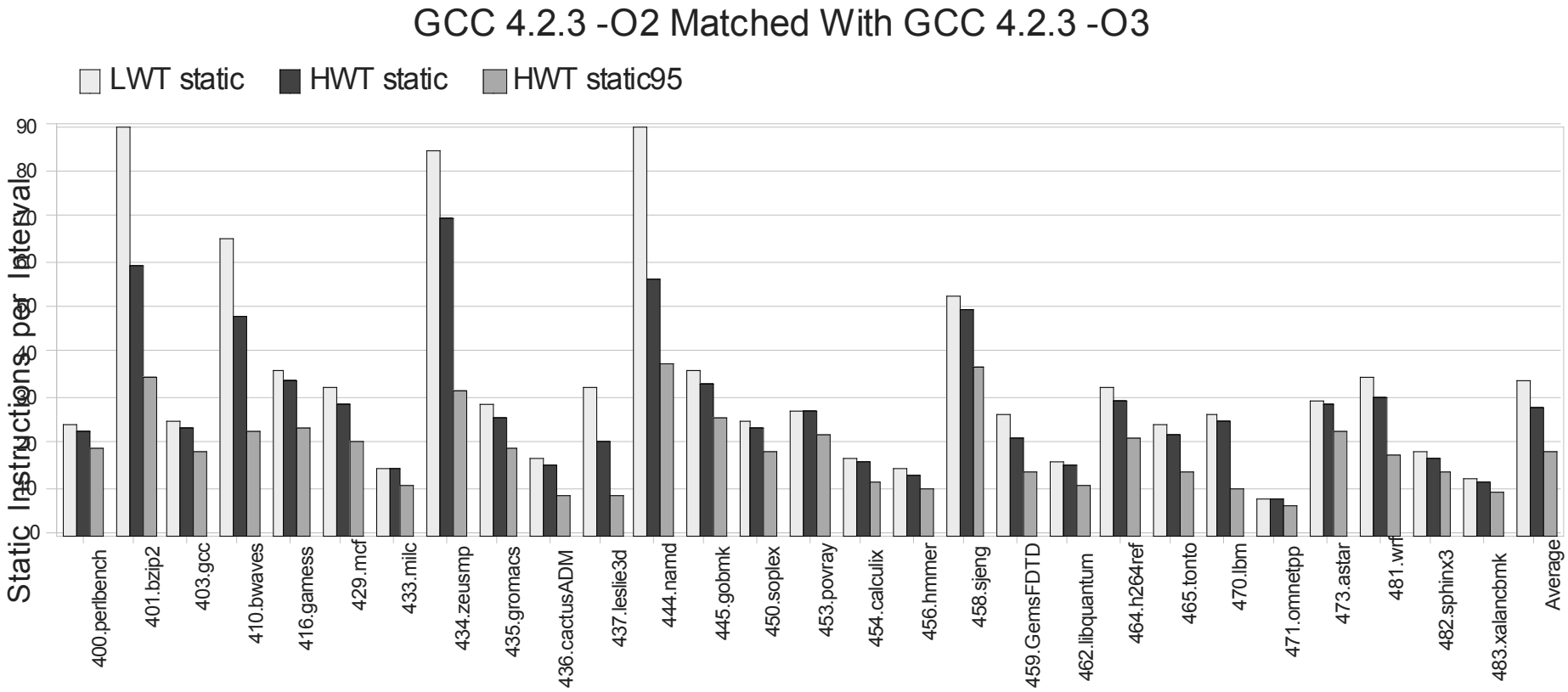
Chainsaw Overview



LWT Matching Rate

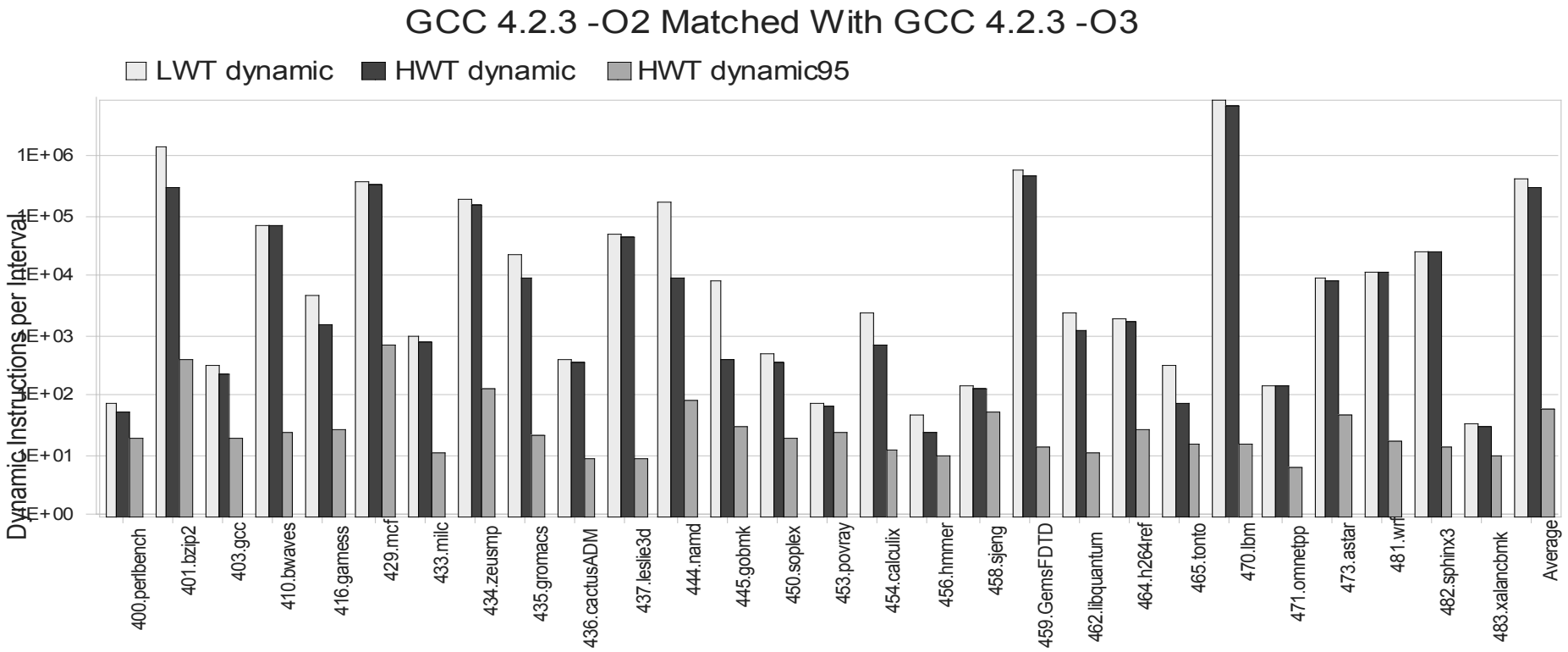


Static Instructions per Interval



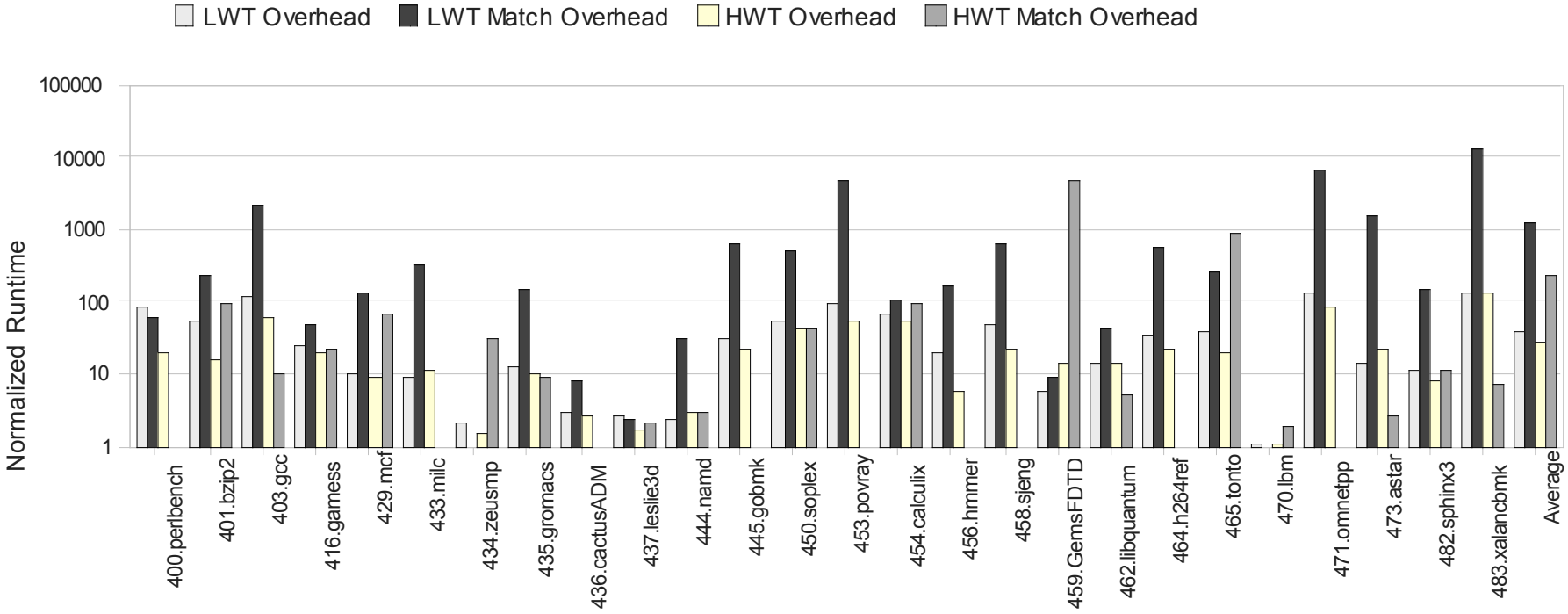
- 95% of intervals have less than 19 static instructions

Dynamic Instructions per Interval



- 95% of intervals have less than 64 dynamic instructions

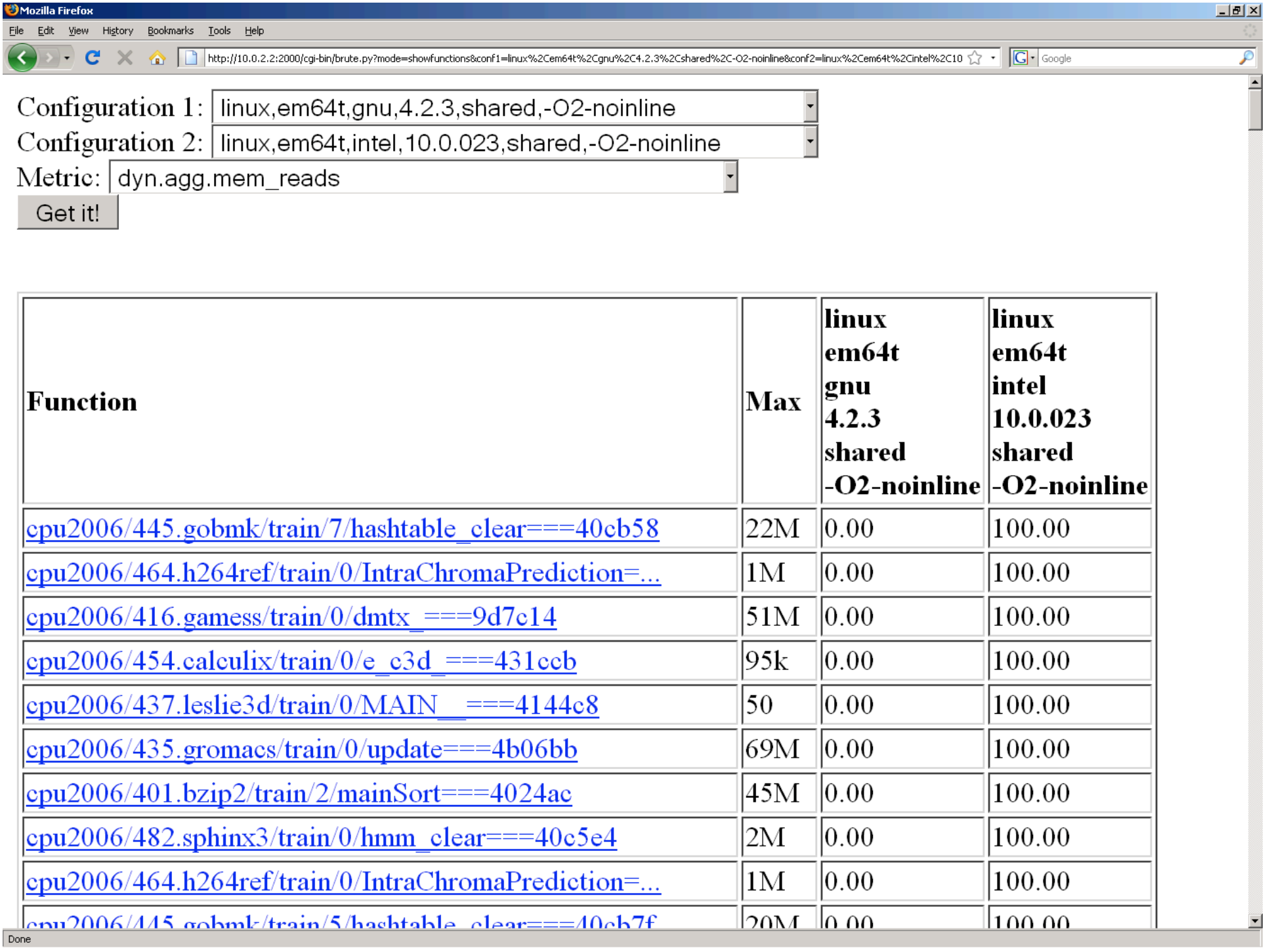
Analysis Overhead



- Total overhead around 1600X

Storage Overhead

- SPEC2006 test suite takes about 1.2GB



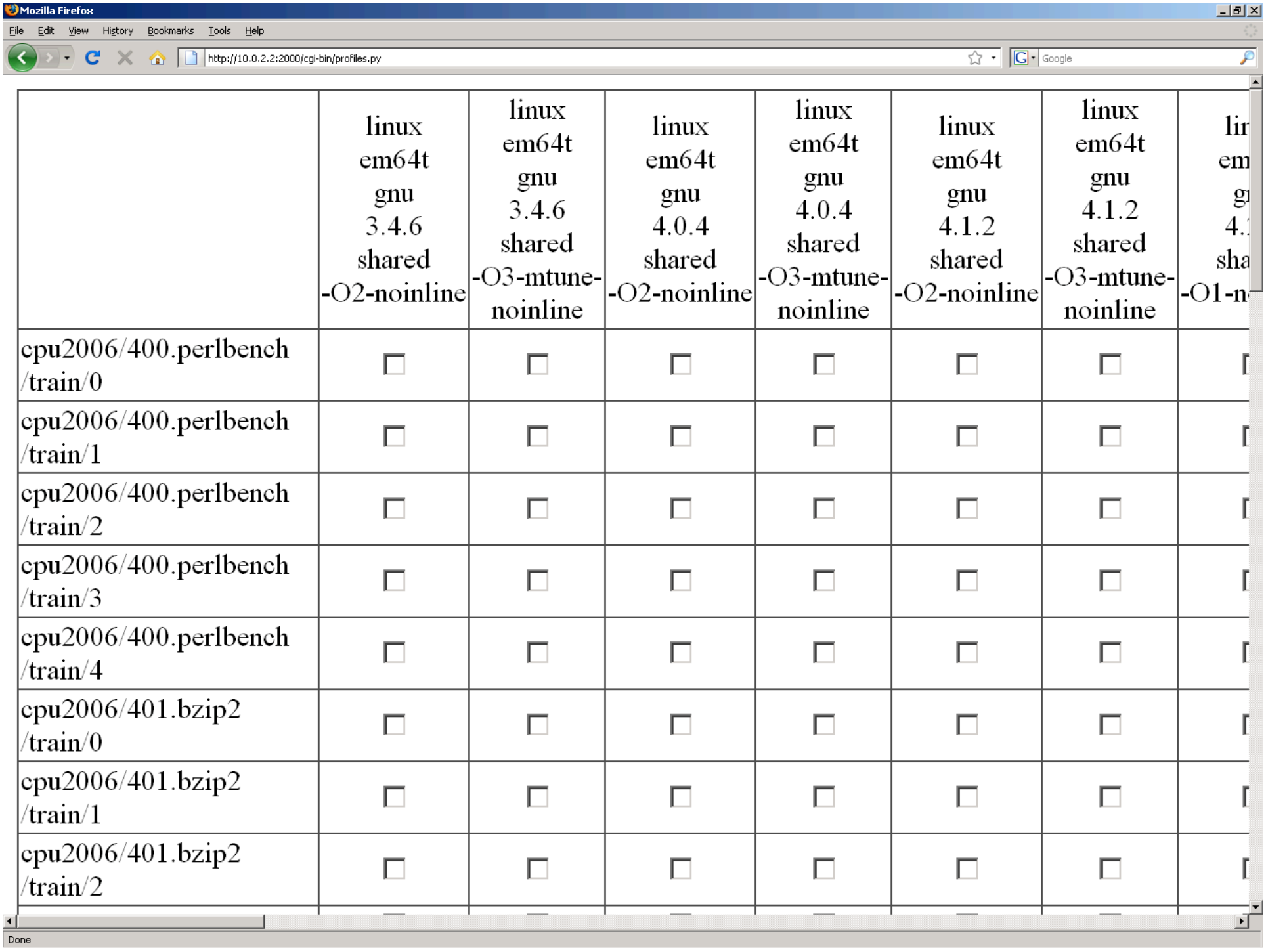
Configuration 1: linux,em64t,gnu,4.2.3,shared,-O2-noinline

Configuration 2: linux,em64t,intel,10.0.023,shared,-O2-noinline

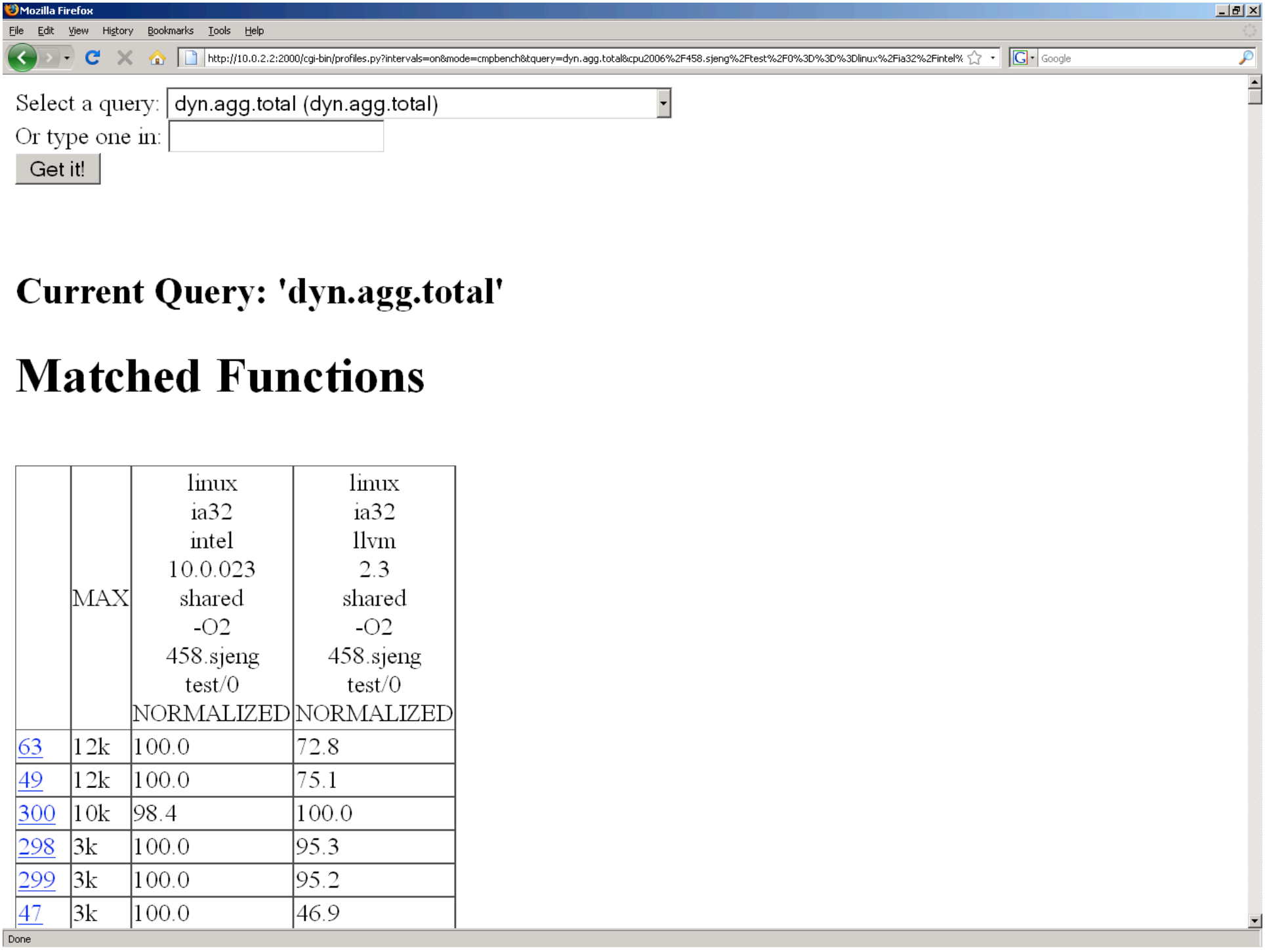
Metric: dyn.agg.mem_reads

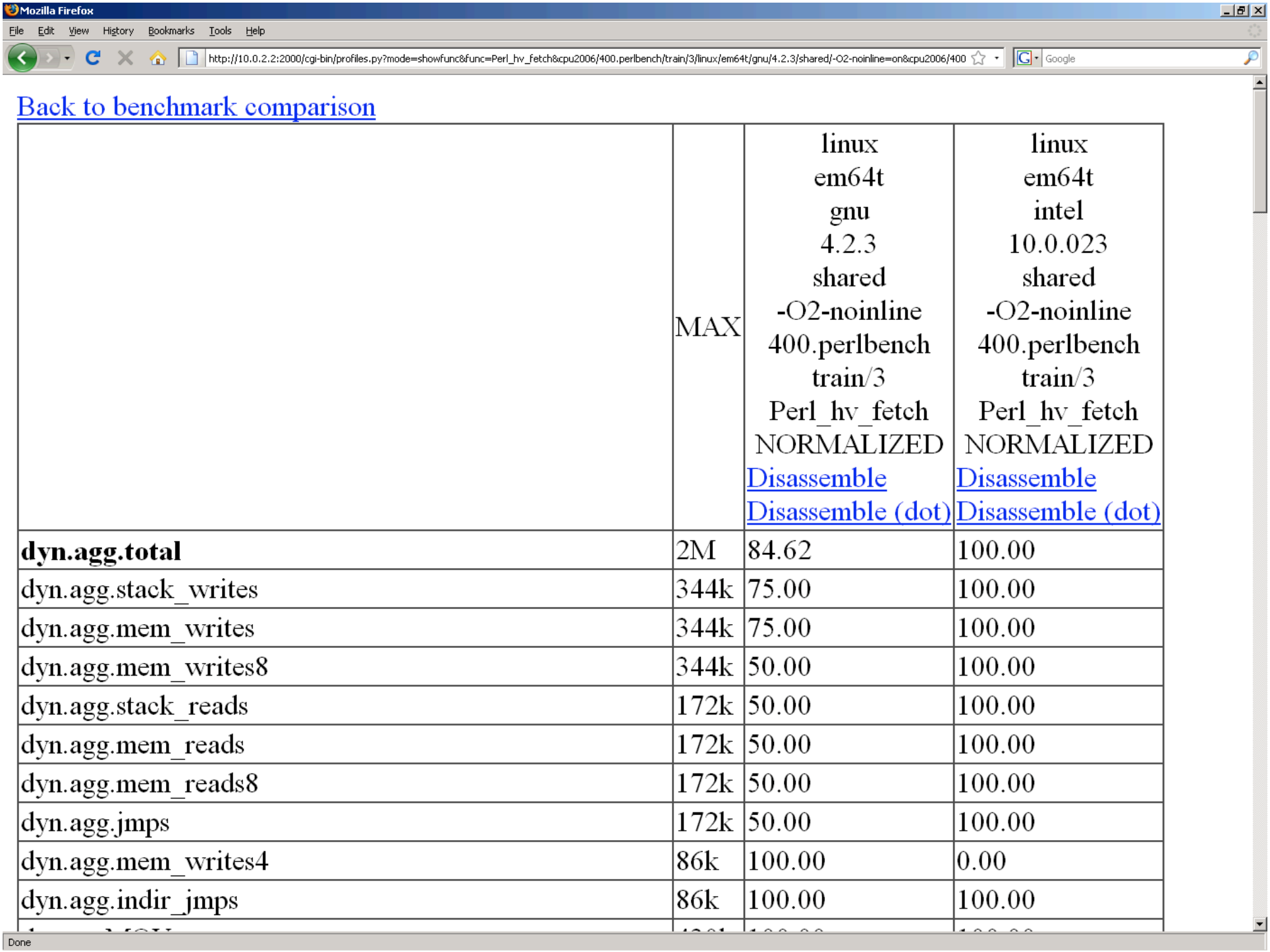
Get it!

Function	Max	linux em64t gnu 4.2.3 shared -O2-noinline	linux em64t intel 10.0.023 shared -O2-noinline
cpu2006/445.gobmk/train/7/hashtable_clear===40cb58	22M	0.00	100.00
cpu2006/464.h264ref/train/0/IntraChromaPrediction=...	1M	0.00	100.00
cpu2006/416.gamess/train/0/dmtx_===9d7c14	51M	0.00	100.00
cpu2006/454.calculix/train/0/e_c3d_===431ccb	95k	0.00	100.00
cpu2006/437.leslie3d/train/0/MAIN__===4144c8	50	0.00	100.00
cpu2006/435.gromacs/train/0/update===4b06bb	69M	0.00	100.00
cpu2006/401.bzip2/train/2/mainSort===4024ac	45M	0.00	100.00
cpu2006/482.sphinx3/train/0/hmm_clear===40c5e4	2M	0.00	100.00
cpu2006/464.h264ref/train/0/IntraChromaPrediction=...	1M	0.00	100.00
cpu2006/445.gobmk/train/5/hashtable_clear===40cb7f	20M	0.00	100.00



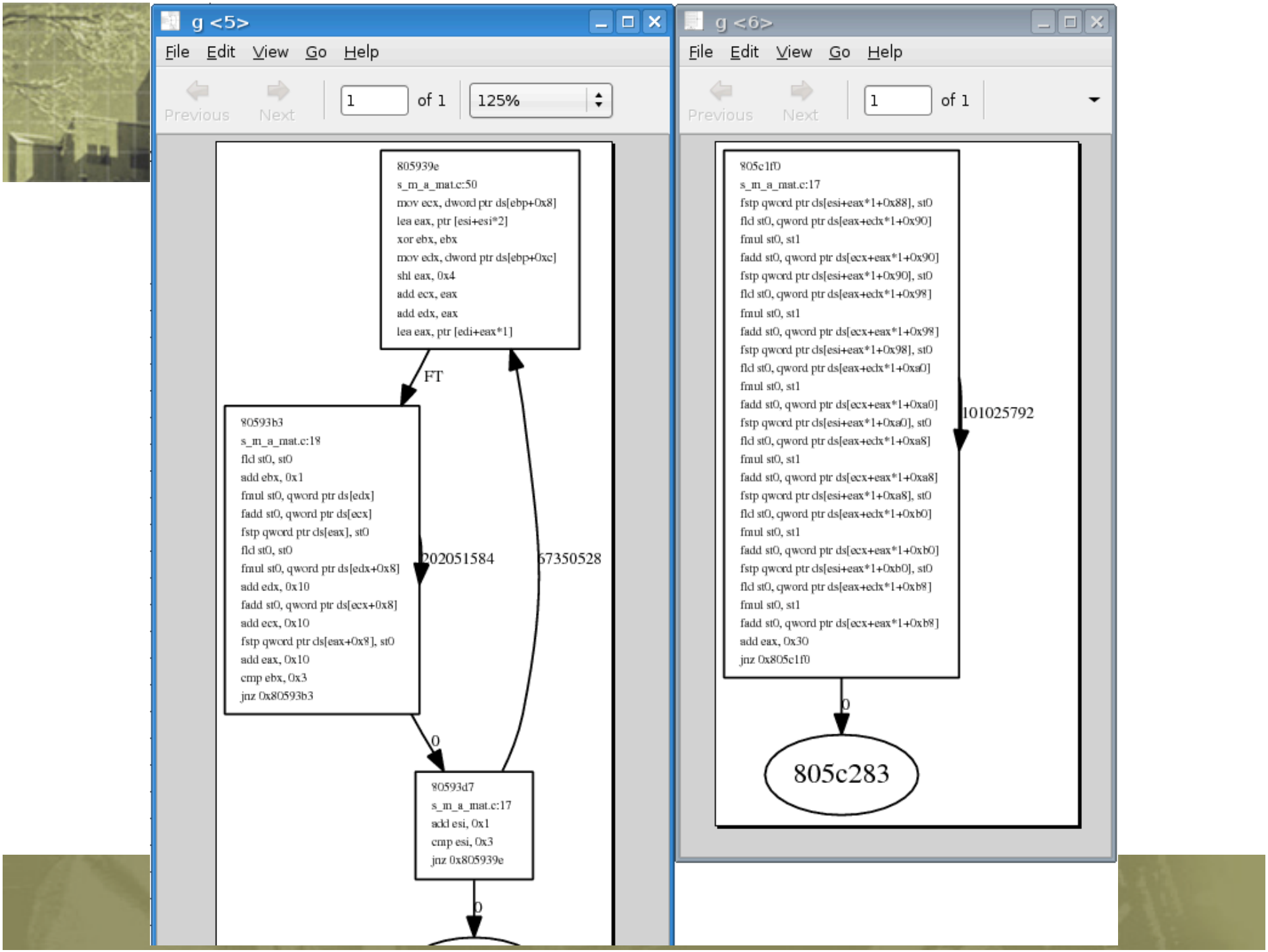
	linux em64t gnu 3.4.6 shared -O2-noinline	linux em64t gnu 3.4.6 shared -O3-mtune-noinline	linux em64t gnu 4.0.4 shared -O2-noinline	linux em64t gnu 4.0.4 shared -O3-mtune-noinline	linux em64t gnu 4.1.2 shared -O2-noinline	linux em64t gnu 4.1.2 shared -O3-mtune-noinline	lir em g 4. sha -O1-n
cpu2006/400.perlbench /train/0	☐	☐	☐	☐	☐	☐	☐
cpu2006/400.perlbench /train/1	☐	☐	☐	☐	☐	☐	☐
cpu2006/400.perlbench /train/2	☐	☐	☐	☐	☐	☐	☐
cpu2006/400.perlbench /train/3	☐	☐	☐	☐	☐	☐	☐
cpu2006/400.perlbench /train/4	☐	☐	☐	☐	☐	☐	☐
cpu2006/401.bzip2 /train/0	☐	☐	☐	☐	☐	☐	☐
cpu2006/401.bzip2 /train/1	☐	☐	☐	☐	☐	☐	☐
cpu2006/401.bzip2 /train/2	☐	☐	☐	☐	☐	☐	☐


Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://10.0.2.2:2000/cgi-bin/profiles.py?intervals=on&mode=cmpbench&query=dyn.agg.total&cpu2006%2F458.sjeng%2Ftest%2F0%3D%3D%3Dlinux%2Fia32%2Fintel%
Google
Select a query: dyn.agg.total (dyn.agg.total)
Or type one in:
Get it!
Current Query: 'dyn.agg.total'
Matched Functions
MAX
linux ia32 intel 10.0.023 shared -O2 458.sjeng test/0 NORMALIZED
linux ia32 llvm 2.3 shared -O2 458.sjeng test/0 NORMALIZED
63 12k 100.0 72.8
49 12k 100.0 75.1
300 10k 98.4 100.0
298 3k 100.0 95.3
299 3k 100.0 95.2
47 3k 100.0 46.9
Done



[Back to benchmark comparison]

	MAX	linux em64t gnu 4.2.3 shared -O2-noinline 400.perlbench train/3 Perl_hv_fetch NORMALIZED Disassemble Disassemble (dot)	linux em64t intel 10.0.023 shared -O2-noinline 400.perlbench train/3 Perl_hv_fetch NORMALIZED Disassemble Disassemble (dot)
dyn.agg.total	2M	84.62	100.00
dyn.agg.stack_writes	344k	75.00	100.00
dyn.agg.mem_writes	344k	75.00	100.00
dyn.agg.mem_writes8	344k	50.00	100.00
dyn.agg.stack_reads	172k	50.00	100.00
dyn.agg.mem_reads	172k	50.00	100.00
dyn.agg.mem_reads8	172k	50.00	100.00
dyn.agg.jmps	172k	50.00	100.00
dyn.agg.mem_writes4	86k	100.00	0.00
dyn.agg.indir_jmps	86k	100.00	100.00


g <5>
File Edit View Go Help
Previous Next
1 of 1
125%
805939e
s_m_a_mat.c:50
mov ecx, dword ptr ds[ebp+0x8]
lea eax, ptr [esi+esi*2]
xor ebx, ebx
mov edx, dword ptr ds[ebp+0xc]
shl eax, 0x4
add ecx, eax
add edx, eax
lea eax, ptr [edi+eax*1]
FT
80593b3
s_m_a_mat.c:18
fld st0, st0
add ebx, 0x1
fmul st0, qword ptr ds[edx]
fadd st0, qword ptr ds[ecx]
fstp qword ptr ds[eax], st0
fld st0, st0
fmul st0, qword ptr ds[edx+0x8]
add edx, 0x10
fadd st0, qword ptr ds[ecx+0x8]
add ecx, 0x10
fstp qword ptr ds[eax+0x8], st0
add eax, 0x10
cmp ebx, 0x3
jnz 0x80593b3
202051584
67350528
0
80593d7
s_m_a_mat.c:17
add esi, 0x1
cmp esi, 0x3
jnz 0x805939e
0
g <6>
File Edit View Go Help
Previous Next
1 of 1
805c1f0
s_m_a_mat.c:17
fstp qword ptr ds[esi+eax*1+0x88], st0
fld st0, qword ptr ds[eax+ecx*1+0x90]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0x90]
fstp qword ptr ds[esi+eax*1+0x90], st0
fld st0, qword ptr ds[eax+ecx*1+0x98]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0x98]
fstp qword ptr ds[esi+eax*1+0x98], st0
fld st0, qword ptr ds[eax+ecx*1+0xa0]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0xa0]
fstp qword ptr ds[esi+eax*1+0xa0], st0
fld st0, qword ptr ds[eax+ecx*1+0xa8]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0xa8]
fstp qword ptr ds[esi+eax*1+0xa8], st0
fld st0, qword ptr ds[eax+ecx*1+0xb0]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0xb0]
fstp qword ptr ds[esi+eax*1+0xb0], st0
fld st0, qword ptr ds[eax+ecx*1+0xb8]
fmul st0, st1
fadd st0, qword ptr ds[ecx+eax*1+0xb8]
add eax, 0x30
jnz 0x805c1f0
101025792
0
805c283

Case Studies

- ISAs
  - IA-32, EM64T, IA-64
- Compilers
  - GCC 3.2.3, 3.4.6, 4.0.4, 4.1.2, 4.2.4, 4.3.0
  - ICC 9.1, 10.0, 11.0
  - LLVM 2.3 (IA-32 only)
- Machines
  - 3.0 GHz Core 2 Xeon
  - 900 MHz Itanium 2 McKinley

Algorithmic Impact

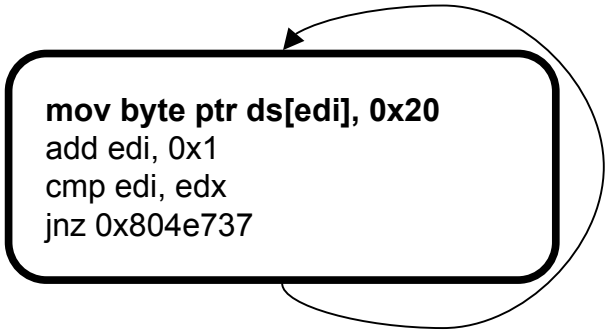
```
// Source: O(N)
int gx;
void Tailcall(int c) {
  if (c > 0) {
    gx += 100;
    Tailcall(c - 1);
  }
}
```

```
// ICC: O(N)
while (c > 0) {
  gx += 100;
   c--;
}
```

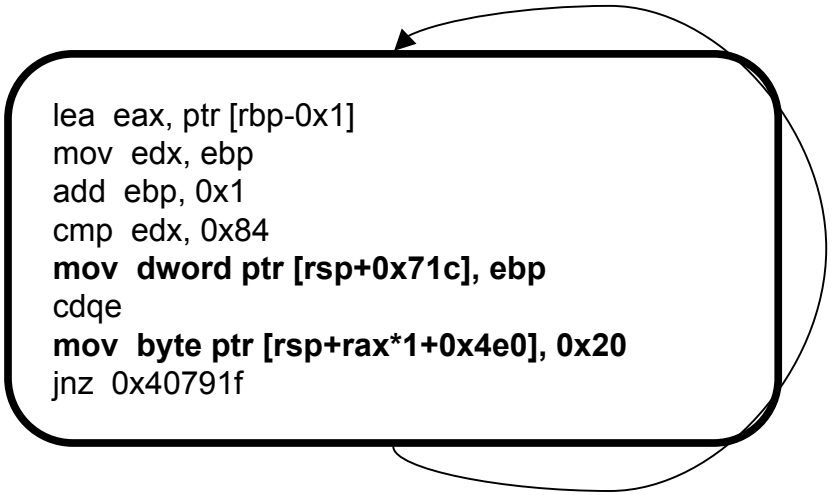
```
// GCC: O(1)
if (c > 0) {
  gx += c * 100;
}
```

Cross-ISA Comparison

```
do i=1,132
  text(i:i)=' '
```



(a) IA-32 GCC 4.2.3 -O2



(b) EM64T GCC 4.3.0 -O2

Data Alignment

Metric	Max Count	ICS 10.0 –O2	ICS 10.0 –O3 –mtune
dyn.agg.total	5B	100%	81.75%
dyn.agg.mem_reads	1B	100	84.09
dyn.agg.mem_writes	738M	100	94.74
dyn.cat.X87_ALU	4B	100	0
dyn.cat.DATAXFER	2B	20.54	100
dyn.cat.SSE	1B	0	100
dyn.cat.COND_BR	19M	100	100
dyn.pmu.MISALIGN_MEM_REF	**347k**	**0**	**100**

- With –O3 enabled, ICS doesn't align array variable on the stack for loop from 444.namd
  - 87% slower

Performance Regression

```
// 464.h264ref loop in image.c:1441
jj = max(0, min(s->size_y - 1, j)
```

- GCC 4.2.3 uses CMOV instruction
- GCC 4.3.0 uses branches
  - 90% slower,
    25X more cond. branches

Inlining

```
for(XalanDOMString::size_type i = start; i < n; ++i) {
     accumCharUTF(chars[i]);
   }
}
```

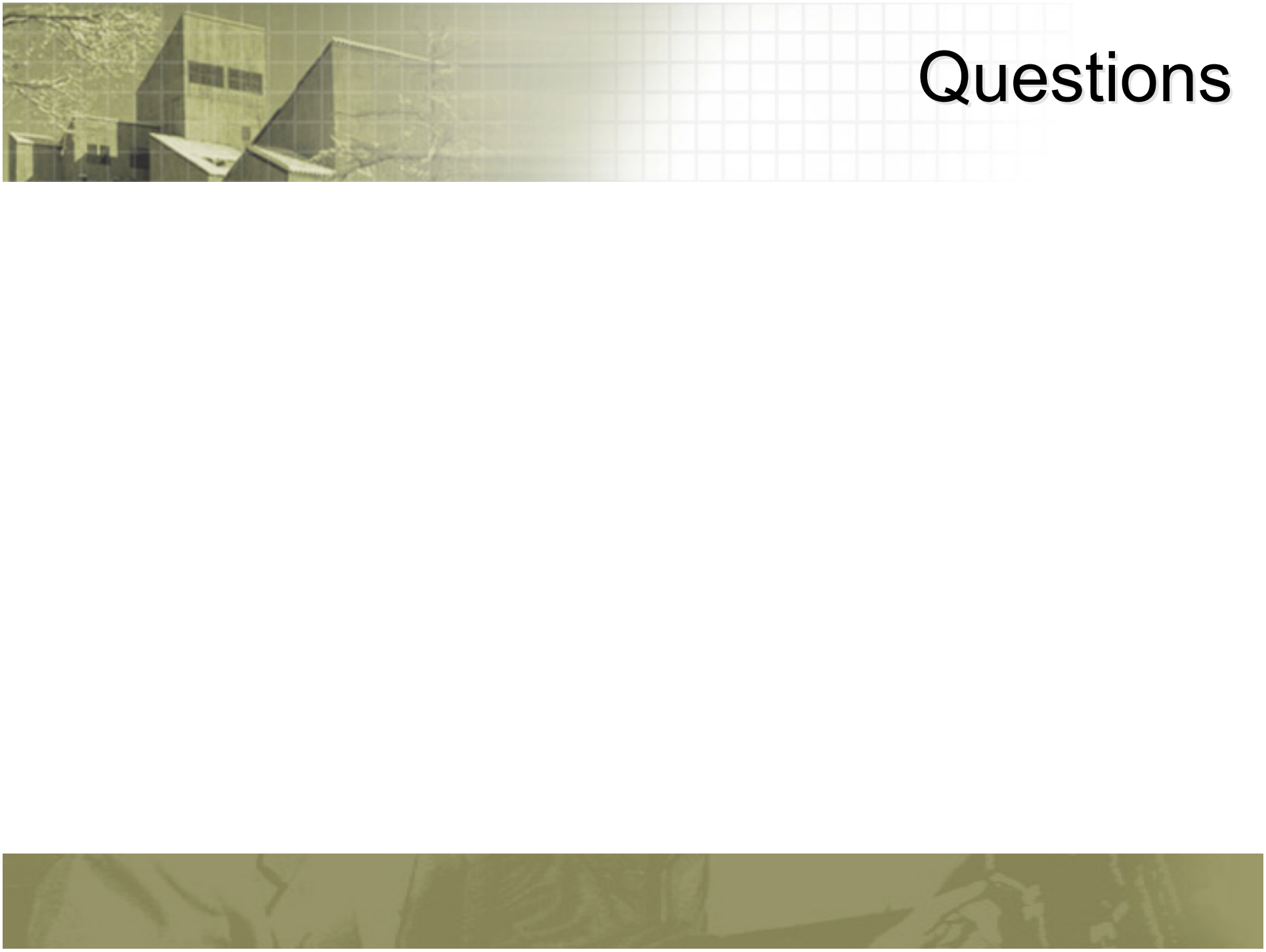
- ICPC inlines accumCharUTF, does not unroll
- LLVM unrolls loop 8 times
  - 8 calls to `accumCharUTF`
  - 5X more space, 2X more dyn. insts.,
    3X more mem reads, 7X more mem writes

Observations

- Finding performance bugs is easy!
  - "Big" anomalies take 1-2 hours of analysis
  - Smaller differences more abundant
- Compilers *still* do silly things
  - Direct jump to next instruction
  - Jump to return instruction
  - Spill all registers, then immediately refill

Summary

- Chainsaw: Infrastructure for relative profile comparison tools
  - Binary matching
  - Web-based profile viewer


Questions