Hardware Support for Out-of-Order Instruction Profiling on Alpha 21264a

Lance Berc & Mark Vandevoorde

Joint work with: Jennifer Anderson, Jeff Dean, Sanjay Ghemawat, Shun-Tak Leung, Mitch Litchenberg, Gerard Vernes, Carl Waldspurger, William E. Weihl, and Jonathan White

dcpi@pa.dec.com

http://www.research.digital.com/SRC/dcpi/

Compaq Systems Research Center

Palo Alto, CA 94301 USA

COMPAQ

Better answers

www.compaq.com

Related Trends

- More aggressive CPUs
  - More performance puzzles
- Widening gap in peak-vs-actual performance
- More sophisticated performance tools
  - Digital Continuous Profiling Infrastructure (DCPI)
    - Where CPU cycles went
    - Where peak performance was lost and why
  - Others: Morph, SGI Speedshop, VTune

Detailed Information Matters

DCPI experience on the Alpha

- TPC-D: 10% speedup
- Duplicate filtering for AltaVista: part of 19X
- Compress program: 22%
- Compiler improvements: 20% in several SPEC benchmarks

All required instruction-level information

COMPAQ
Better answers

Traditional Performance Counters

- Count events, interrupt when counter rolls over
  - cycles, issues, loads, L1 Dcache misses, branch mispredicts, uops retired, ...
    - Alpha 21064, 21164; Ppro, PII; R10k, …
    - Easy to measure total cycles, issues, CPI, etc.
- Basic information is restart PC

COMPAQ
Better answers

DCPI on In-Order Alpha 21164

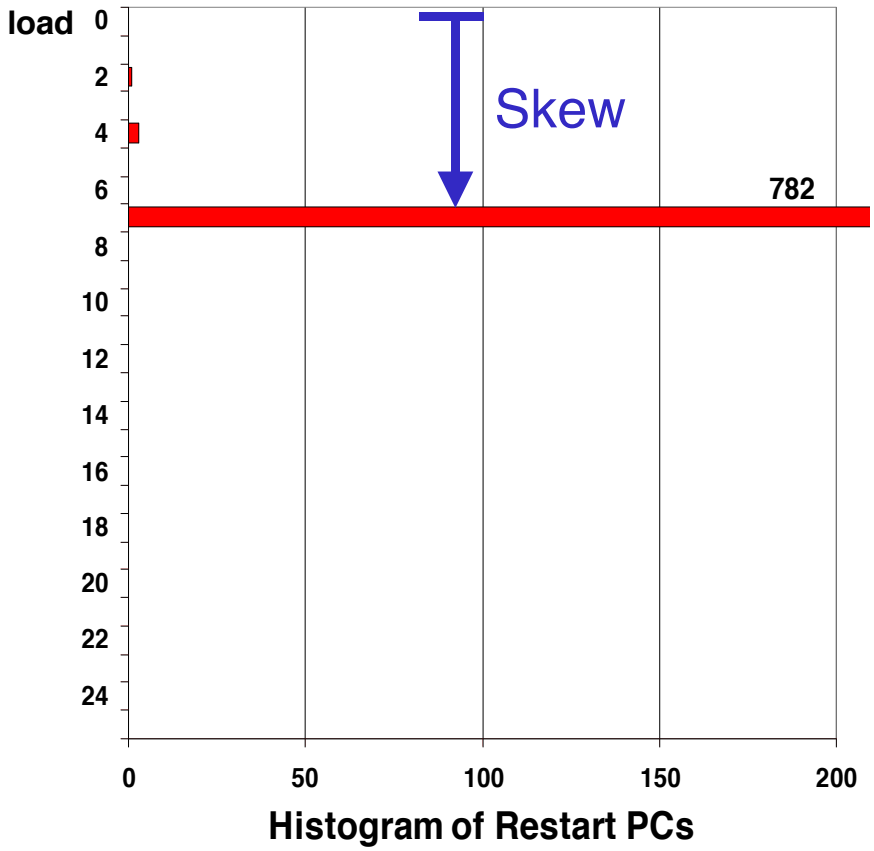
```
Address  Instruction          CPI
    9618  addq  s0,t6,t6      1.0 cycles
      b                            (b = data dep on t6)
      D                            (D = DTLB miss)
      :    3.5 cycles
      D
    961c  ldl   t4,0(t6)       3.5 cycles
      a
      a                            (a = data dep on t4)
      a     21.0 cycles
      di                           (d = d-cache miss)
      :                            (i = i-cache miss)
      di
    9620  xor   t4,t12,t5     21.0 cycles
```

Where peak performance is lost and why

COMPAQ
Better answers

Problem: Inaccurate Attribution

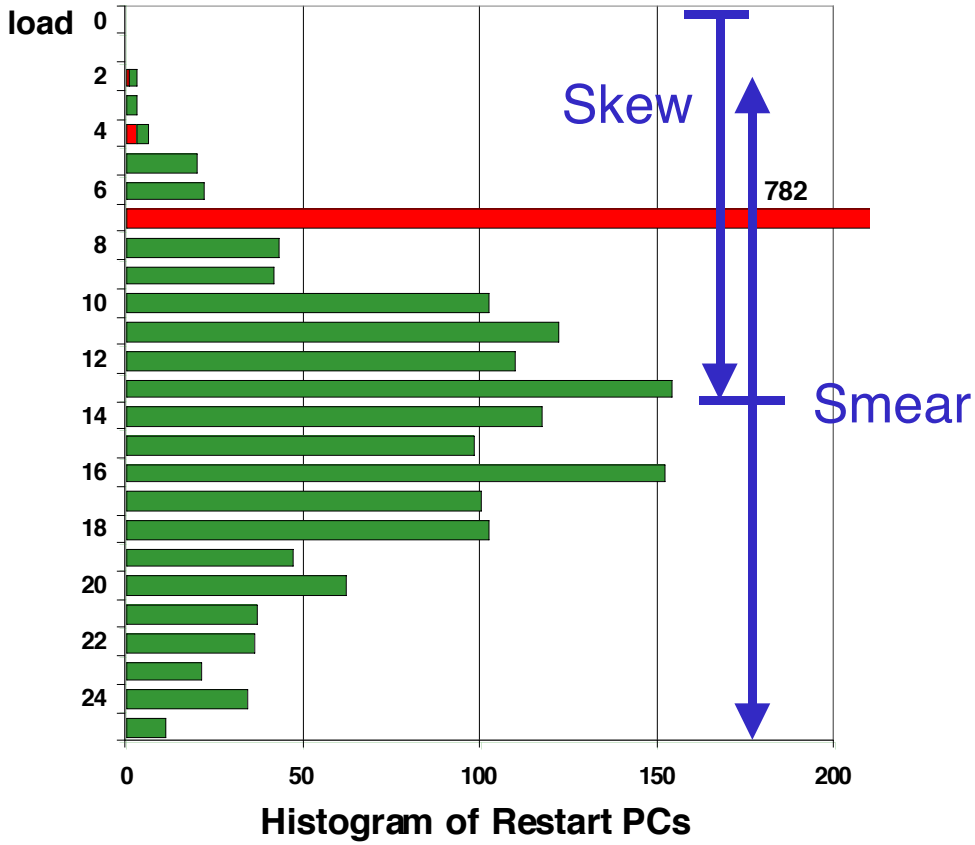
- Experiment
  - count data loads
  - loop: single load + hundreds of nops
- In-Order Processor
  - Alpha 21164
  - skew
  - one large peak



COMPAQ
Better answers

Problem: Inaccurate Attribution

- Experiment
  - count data loads
  - loop: single load + hundreds of nops
- In-Order Processor
  - Alpha 21164
  - skew
  - one large peak
- Out-of-Order Processor
  - Intel Pentium Pro
  - skew
  - smear



COMPAQ
Better answers

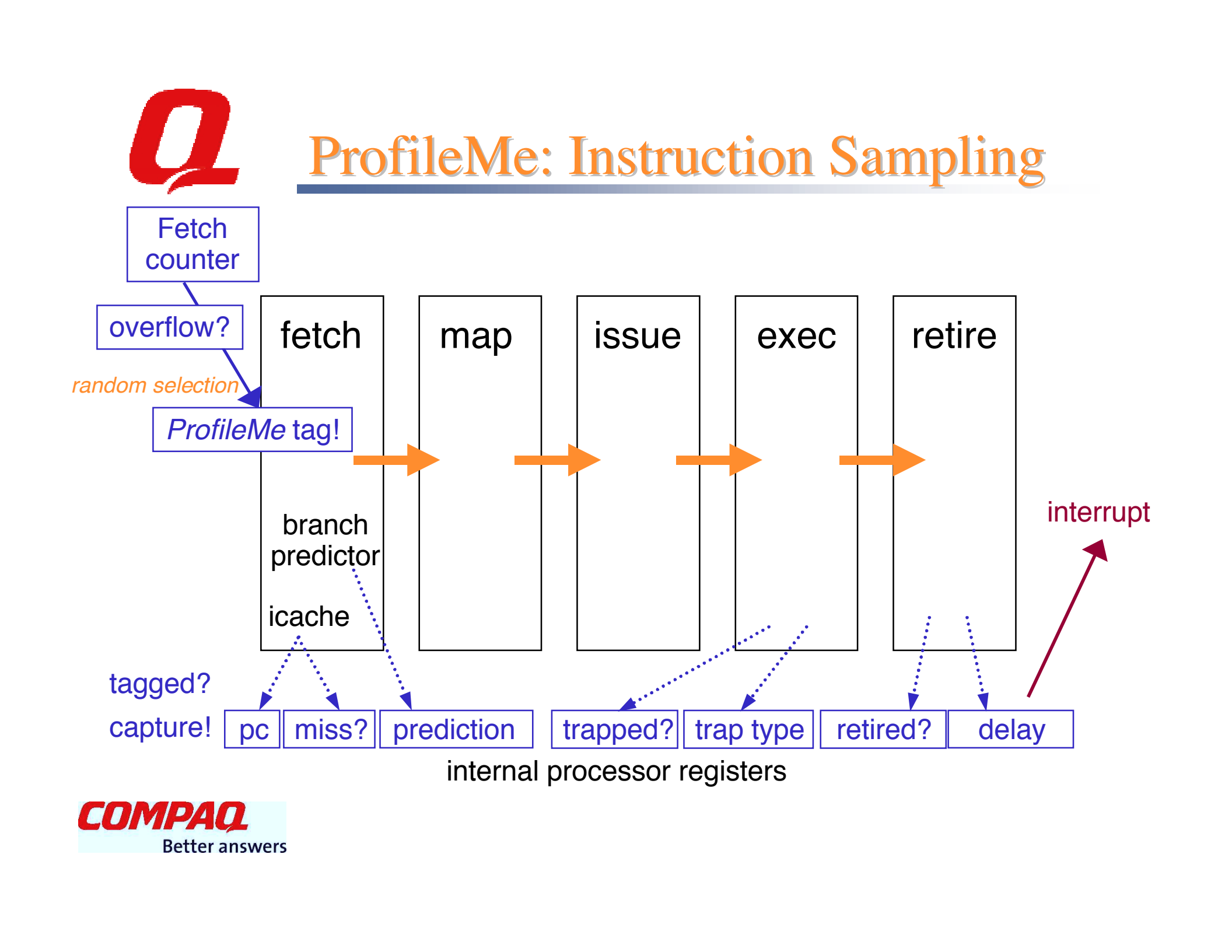
Impact of Misattribution

- No skew or smear
  - Instruction-level analysis is easy!
- If skew is a constant number of cycles
  - Instruction-level analysis may be possible: DCPI
  - Adjust sampling period by amount of skew
  - Infer execution counts, CPI, stalls, and stall explanations from cycles samples and program
- Smear
  - Instruction-level analysis seems hopeless
  - Examples: PII, StrongARM

ProfileMe on Alpha 21264a

- Count fetched instructions instead of events
- Save PC of sampled instruction
  - Interrupt handler reads Internal Processor Register
  - Makes skew and smear irrelevant
- Save execution information in IPRs

COMPAQ
Better answers


ProfileMe: Instruction Sampling
Fetch counter
overflow?
random selection
ProfileMe tag!
fetch
map
issue
exec
retire
branch predictor
icache
interrupt
tagged?
capture!
pc
miss?
prediction
trapped?
trap type
retired?
delay
internal processor registers
COMPAQ
Better answers

Instruction-Level Information

- PC + Retire Status ⇨ execution frequency
- PC + Cache Miss Flag ⇨ cache miss rates
- PC + Mispredict ⇨ mispredict rates
- PC + Event Flag ⇨ event rates
- PC + Retire Delay ⇨ ILP

COMPAQ
Better answers

Pointer-Chasing Loops

```
while (p) p = *p;
```

```
retires    delay   misp    PC
   8537     1.99           0x30   ldq   a0, 0(a0) # L1 hit
   8661     1.01   .006    0x34   bne   a0, 0x30

    610     2.00           0x30   ldq   a0, 0(a0) # L2 hit
    605    23.06   .007    0x34   bne   a0, 0x30

    241     1.99           0x30   ldq   a0, 0(a0) # Main Mem
    205   138.13   .005    0x34   bne   a0, 0x30
```

COMPAQ
Better answers

Good ILP in OpenGL

```
retires   delay      PC
   2563           0xed0   lds   $f14, 13052(a0)
   2515           0xed4   addq  t11, s4, t11
   2519           0xed8   adds  $f1,$f15,$f1
   2577     1.0   0xedc   muls  $f17,$f3,$f17
   2485           0xee0   ldq_u zero, 0(sp)
   2490     2.0   0xee4   subs  $f19,$f20,$f20
   2525           0xee8   muls  $f18,$f4,$f18
   2546           0xeec   muls  $f27,$f4,$f3
   2546           0xef0   adds  $f0,$f10,$f0
   2501           0xef4   lds   $f15, 13072(a0)
   2498           0xef8   lds   $f10, 13060(a0)
   2521           0xefc   muls  $f13,$f4,$f13
   2456           0xf00   adds  $f16,$f11,$f16
   2440           0xf04   adds  $f17,$f12,$f17
   2579           0xf08   ldq_u zero, 0(sp)
   2502     1.0   0xf0c   lds   $f12, 13068(a0)
```

COMPAQ Better answers

16 instructions in 4 cycles

Poor ILP in OpenGL

```
retires  delay      PC
   2262          0x210  addq    t5, 0x10, t5
*  2308          0x214  cmptlt  $f7,$f3,$f10
   2231          0x218  subq    t4, 0x1, t4
*  2285    1.0   0x21c  cmptlt  $f4,$f7,$f11
*  2224    0.9   0x220  cmptlt  $f8,$f5,$f12
*  2227    1.0   0x224  cmptlt  $f6,$f8,$f13
*  2257    1.0   0x228  cmptlt  $f9,$f1,$f14
*  2390    1.0   0x22c  cmptlt  $f2,$f9,$f15
   2265          0x230  lds     $f7, 0(t5)
*  2343    1.0   0x234  adds    $f10,$f16,$f16
   2357          0x238  lds     $f8, 4(t5)
*  2249    1.0   0x23c  adds    $f11,$f17,$f17
   2309    0.1   0x240  lds     $f9, 8(t5)
*  2214    1.0   0x244  adds    $f12,$f18,$f18
*  2292    1.0   0x248  adds    $f13,$f19,$f19
*  2234    1.0   0x24c  adds    $f14,$f20,$f20
*  2282    1.0   0x250  adds    $f15,$f21,$f21
   2278    1.0   0x254  bgt     t4, 0x210
```

COMPAQ Better answers

12 Floating point adds in 12 cycles

Eight Queens Code

```
while ((! *q) && (j != 8)) {
    j = j + 1; *q = false;
    if (b[j] && a[i+j] && c[i-j+7]) {…}
```

retires	delay	mispred	pc		
3807			20	cmpeq	s6, 0x8, v0
3858			24	lda	a1, 4(a1)
3922			28	lda	a0, 4(a0)
3909	0.28		2c	lda	a3, -4(a3)
3757			30	bis	a2, v0, v0
3919			34	addl	s6, 0x1, s6
3952	1.01	0.13	38	bne	v0, f0
3543	0.31		3c	stl	zero, 0(s0)
3457	0.42		40	ldl	v0, 0(a1)
3573	0.25		44	ldl	a2, 0(a0)
3547	0.39		48	ldl	t0, 0(a3)
3509	0.70		4c	cmoveq	a2, zero, v0
3573			50	bis	zero, zero, a2
3392	2.06		54	cmoveq	t0, zero, v0
3543	2.00	0.14	58	beq	v0, 20

	7.42 cycles				

COMPAQ
Better answers

Optimized Eight Queens Code

```
retires delay  pc
   3910        20 cmpeq   s6, 0x8, v0
   3999        24 lda     a1, 4(a1)
   3998        28 lda     a0, 4(a0)
   3883  0.26   2c lda     a3, -4(a3)
   3873        30 bis     a2, v0, v0
   3926        34 addl    s6, 0x1, s6
   3869  1.06   38 bne     v0, f0
   3476  0.52   3c stl     zero, 0(s0)
   3481  0.52   40 ldl     v0, 0(a1)
   3413  0.26   44 ldl     a2, 0(a0)
   3439  0.39   48 ldl     t0, 0(a3)
   3448        4c and     a2, v0, v0  # was cmov
   3415        50 bis     zero, zero, a2
   3561  0.45   54 and     t0, v0, v0  # was cmov
   3518  2.16   58 beq     v0, 20
         ----
         5.62 cycles
```

COMPAQ
Better answers

Profiling Aborted Instructions

retires	aborts	traps	ldstore	PC		
24	0	0	0	0xca8c	stt	$f16, 56(sp)
36	0	0	0	0xca90	addssu	$f25,$f28,$f16
27	0	0	0	0xca94	ldl	at, 8(a2)
26	0	0	0	0xca98	cmpule	at, 0xc, at
29	0	0	0	0xca9c	bne	at, 0xdcb0
21	0	0	0	0xcaa0	stt	$f20, 72(sp)
17	23	23	23	0xcaa4	ldt	$f20, 56(sp)
29	28	0	0	0xcaa8	sts	$f20, 60(a2)
39	20	0	0	0xcaac	ldl	at, 8(a2)
21	21	0	0	0xcab0	cmpule	at, 0x4, at
21	26	0	0	0xcab4	bne	at, 0xdcb4
20	29	8	7	0xcab8	ldt	$f20, 72(sp)
31	37	0	0	0xcabc	sts	$f20, 28(a2)
28	33	0	0	0xcac0	ldl	at, 8(a2)

COMPAQ
Better answers

Trap shadow is 70 instructions long!
Fixed with better register allocation

Avoiding Traps

- Traps (pipeline aborts) are expensive
  - Mispredicts, DTB misses, replays, etc.
- Profiles identify trapping PCs and trap type
  - Aborted instructions are profiled, too
  - But how many cycles were lost?
  - Can analysis deduce missing information?

Status

- ProfileMe works on Alpha 21264a prototypes
- Initial experience
  - 17% speedup for a Java Virtual Machine
- Still working on enhancements
  - Analysis software for 21264a
  - Counters on future Alphas

COMPAQ
Better answers

Summary

- Instruction-level information improves program optimizations
- ProfileMe: Sample instructions rather than events
  - Event sampling inaccurate on O-O-O machines
  - Direct observation eliminates misattribution
- ProfileMe first implemented in Alpha 21264a
  - Has led to significant insight and improvements

COMPAQ
Better answers

www.compaq.com