Linux Kernel Hacking Free Course, 3rd edition

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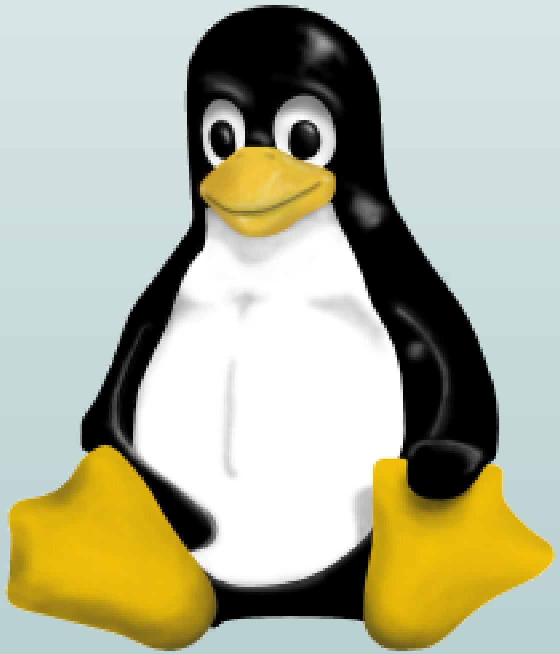
Linux, the caches, and you



March 8, 2006

About this lecture

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About this lecture

While preparing this lecture, I asked myself:

> "*What have you learned from Linux that might be of interest for any programmer?*"

I was quickly forced to focus on some specific topic, otherwise this lecture would become way too long

And the winner is: **Linux and the caches (and you, of course!)**

Roadmap (sort of)

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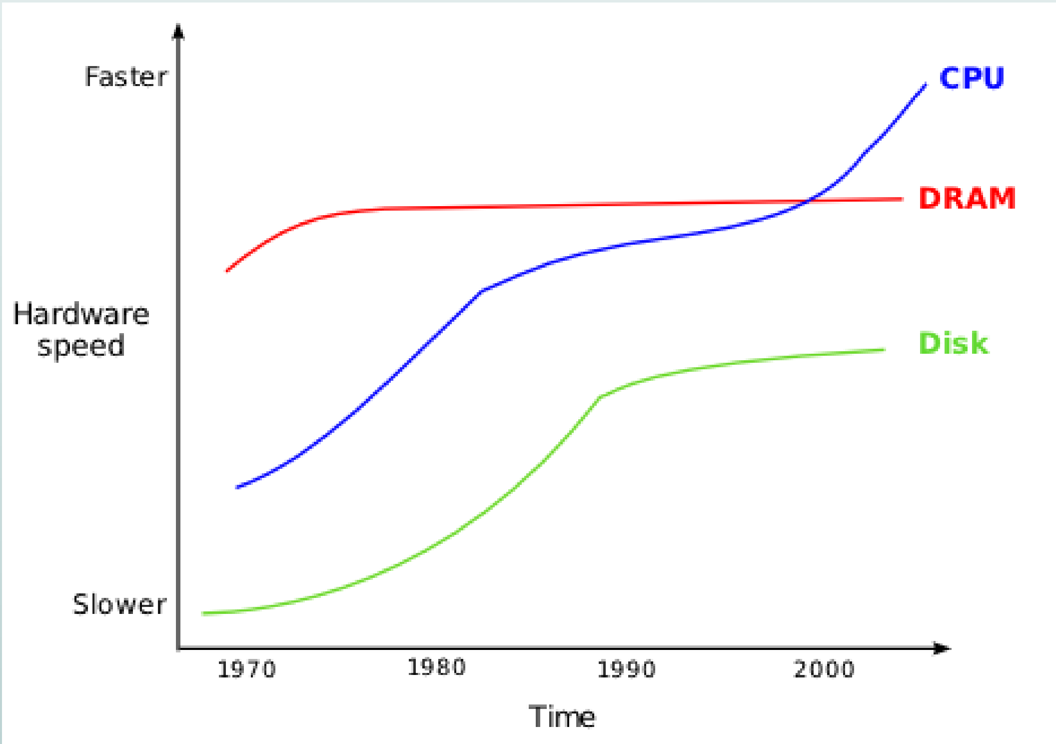
So, now I'll try my best to:

- explain the "cache problem"
- present some scenarios in which caches make really a difference
- introduce some techniques (learned from the Linux source code) to fully exploit the caches
- keep you awake!

Memory can't keep up

CPU speed grows much faster than hard disk and DRAM speed:



What's the matter, then?

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and also a matter of costs:

- DRAM cells are relatively cheap: $\approx$ 0.075 €/ MB
- SRAM cells (registers) are costly (they require six transistors per bit instead of just one, more wiring, more space): $\approx$ 0.75 €/ MB

The solution: caching, caching and more caching

Modern computer architectures use a large amount of slow and cheap DRAM cells, as well as a small amount of fast and costly SRAM cells:

- L3 (unified) cache
- L2 (unified) cache
- L1 unified cache / L1 data cache
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- Write combining registers
- CPU general-purpose registers

A new idea?! (A digression)

> "Ideally one would desire an indefinitely large memory capacity such that any particular [word] would be immediately available. . . It does not seem possible to achieve such a capacity. We are therefore forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less quickly accessible."

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Preliminary discussion of the logical design of an electronic computing instrument, Burks, Goldstine, von Neumann, 1946

Locality principles

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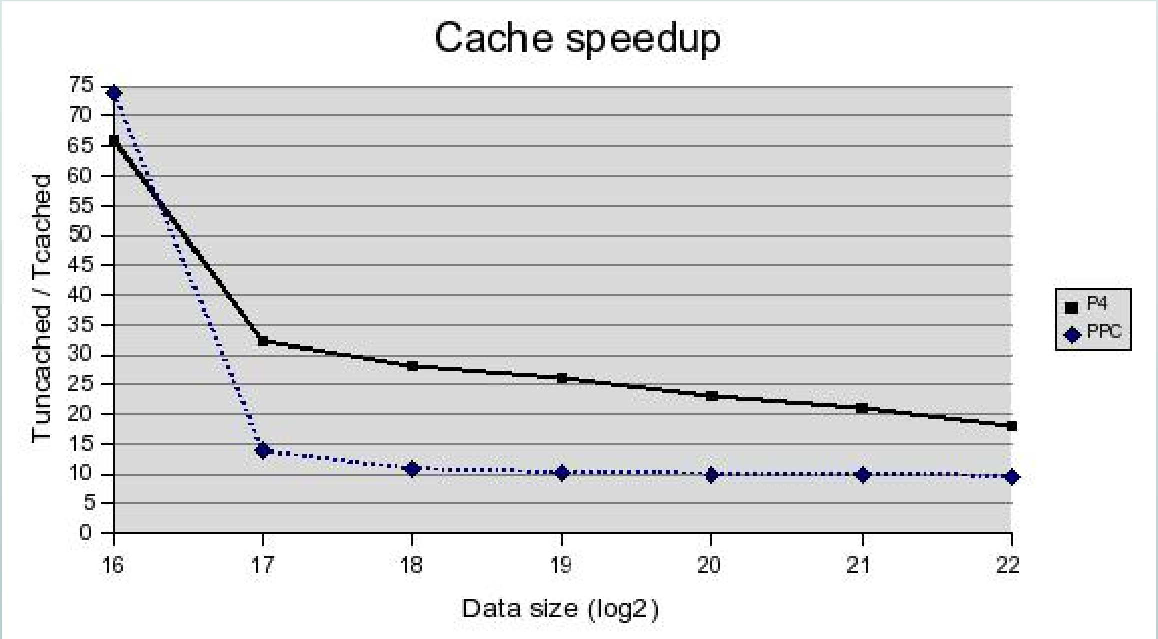
Temporal locality: In a short time frame, the executed instructions

- are likely to be executed again
- access memory cells that will likely be accessed again

Performance gain of caches

We measured execution times of a discrete FFT on increasingly larger data sets with and without L1/L2 caches, both on an Intel Pentium 4 and on a Freescale MPC7447A PowerPC



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In many cases, *cache-conscious* algorithms achieve significant performance gains

A “real-world” code fragment as a cache benchmark

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for (i=0; i<reps; ++i) {
    t += x[j];
    j += d;
    if (j >= n)
        j -= n;
}
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The number of iterations `reps` is large (e.g., 10000000), so each benchmark value is roughly the average execution time of one access to the array `x`

Measuring the execution time

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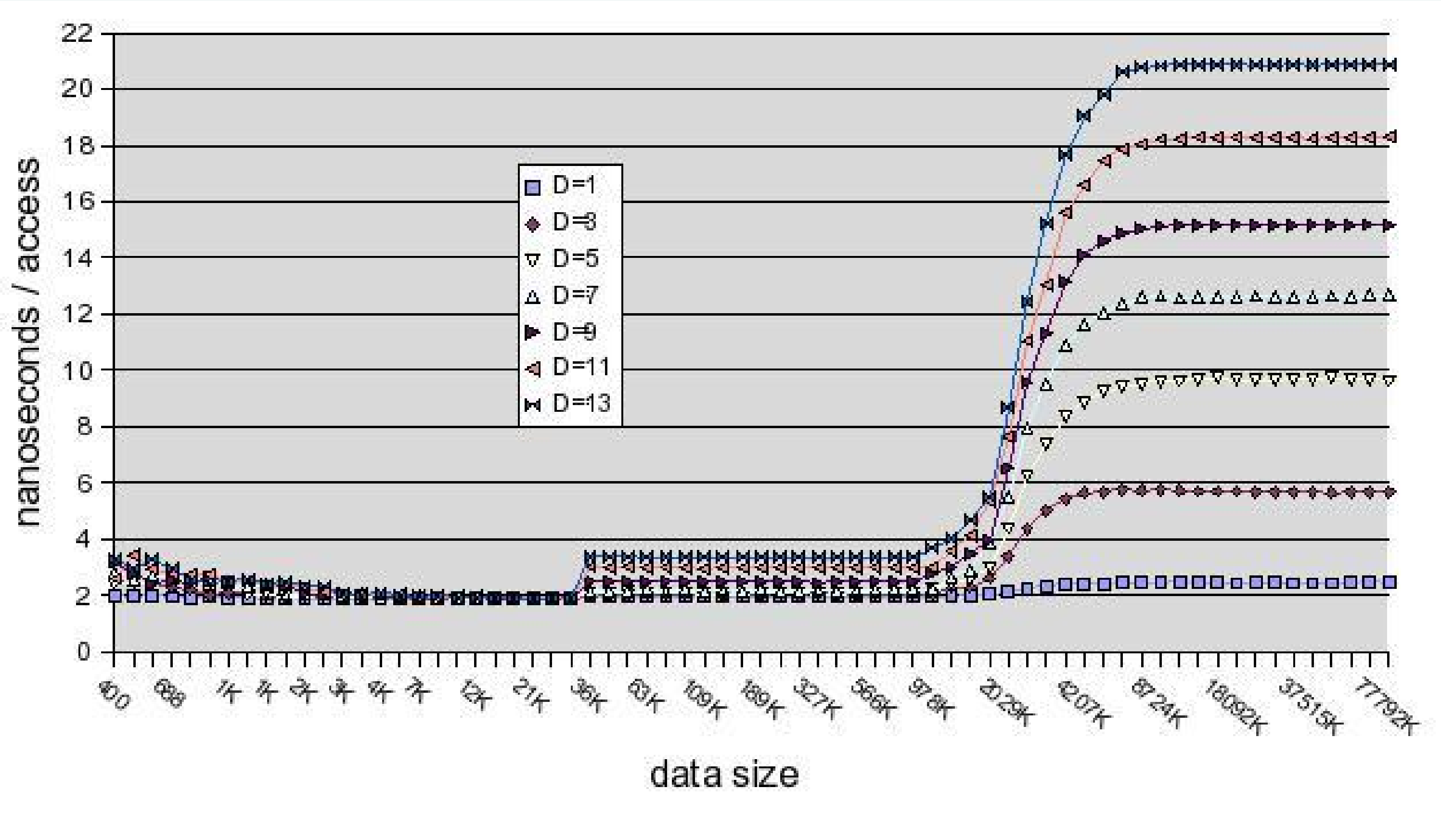
The `rdtsc` Assembly language instruction reads the value in this register and stores it into the `eax` and `edx` general-purpose registers

Thus, all we need is a bit of *gcc*'s extended inline Assembly magic:

```
#define __rdtscll(val) asm volatile("rdtsc" :  "=A" (val))
```

Making sense out of benchmark values



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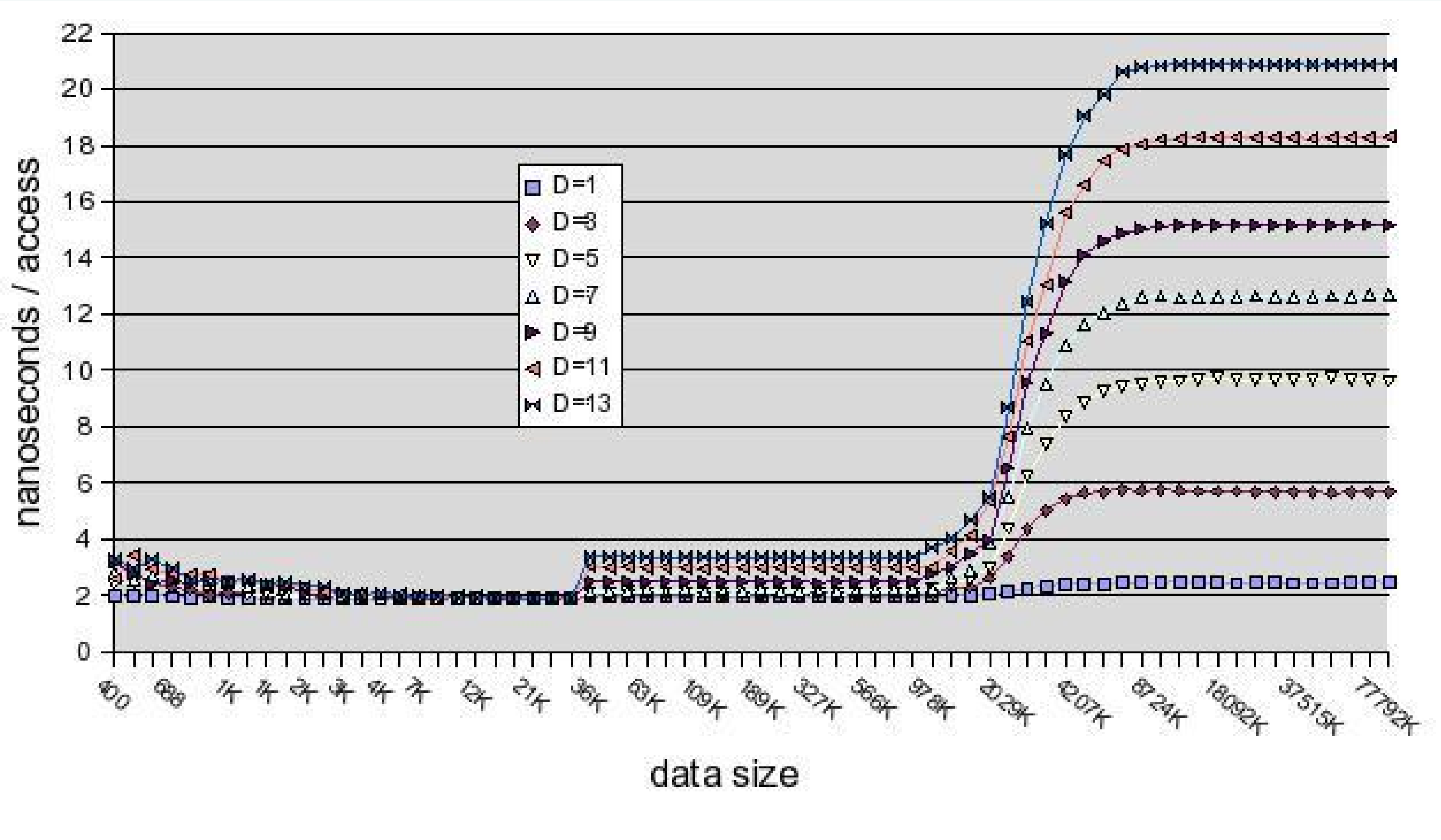

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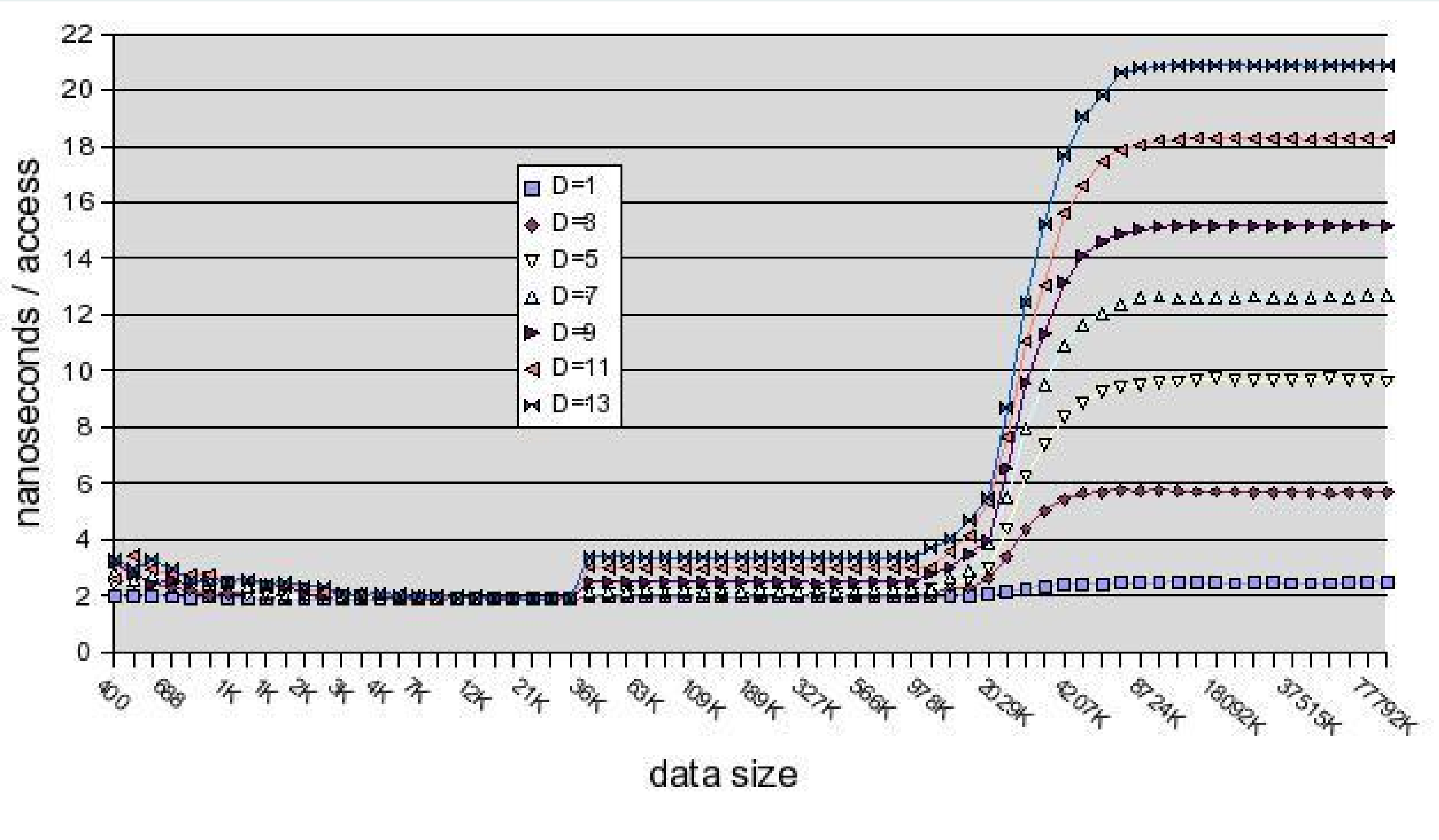

- Each curve is a different delta `d` (cache line=32 byte)
- At smallest data sizes, caches are not fully exploited
- “Knees” at cache size boundaries (L1=32 KB, L2=2 MB)

Cache-friendly access to data

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We can sequentially scan the elements of a matrix in two ways:

Row by row:

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for (row=0; row<n; ++row)
    for (col=0; col<n; ++col)
        x[row][col] *= c;
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Column by column:

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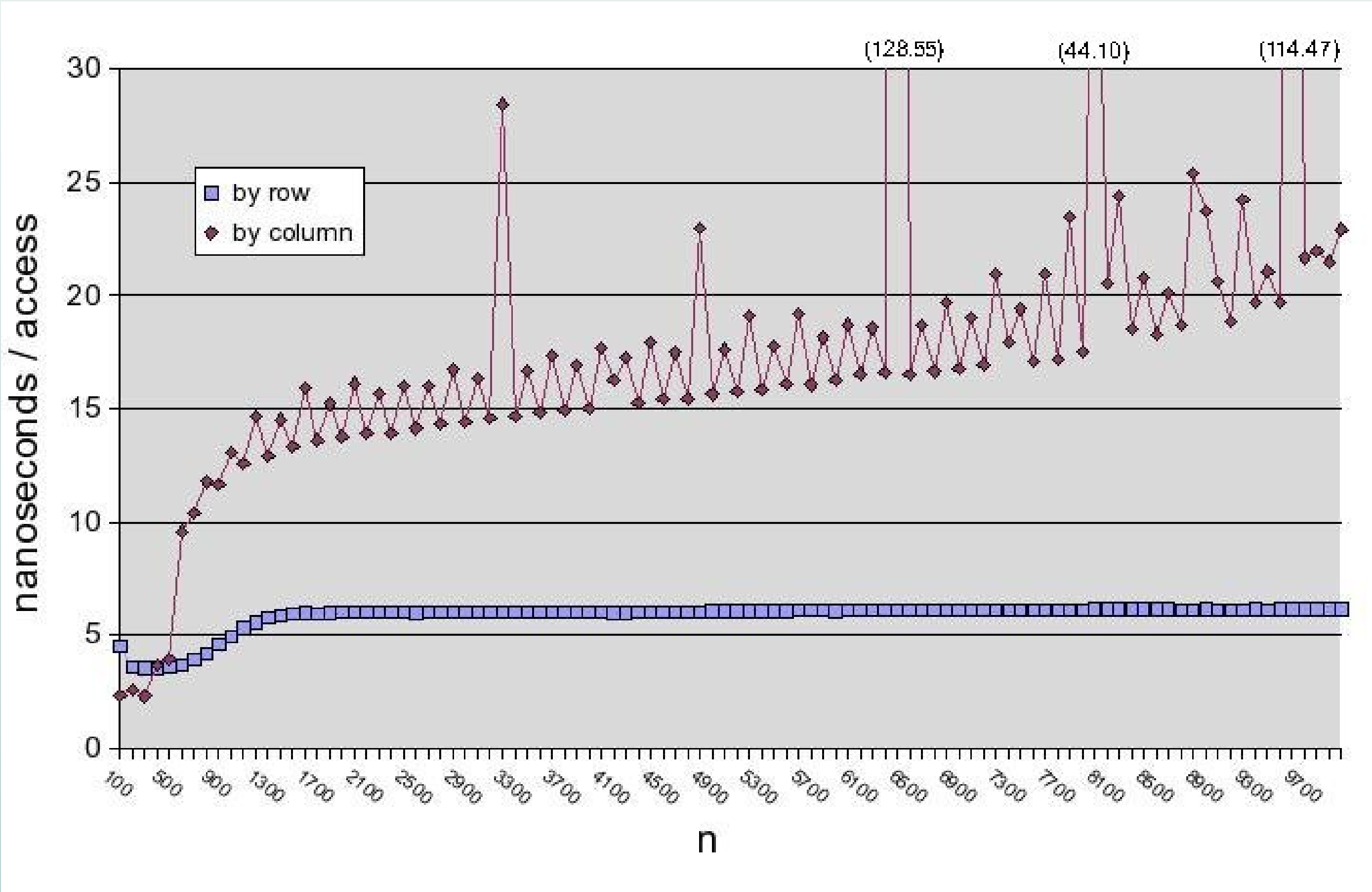
Although these code fragments are functionally equivalent, their execution times differ significantly

Execution times of “row by row” and “column by column” scannings



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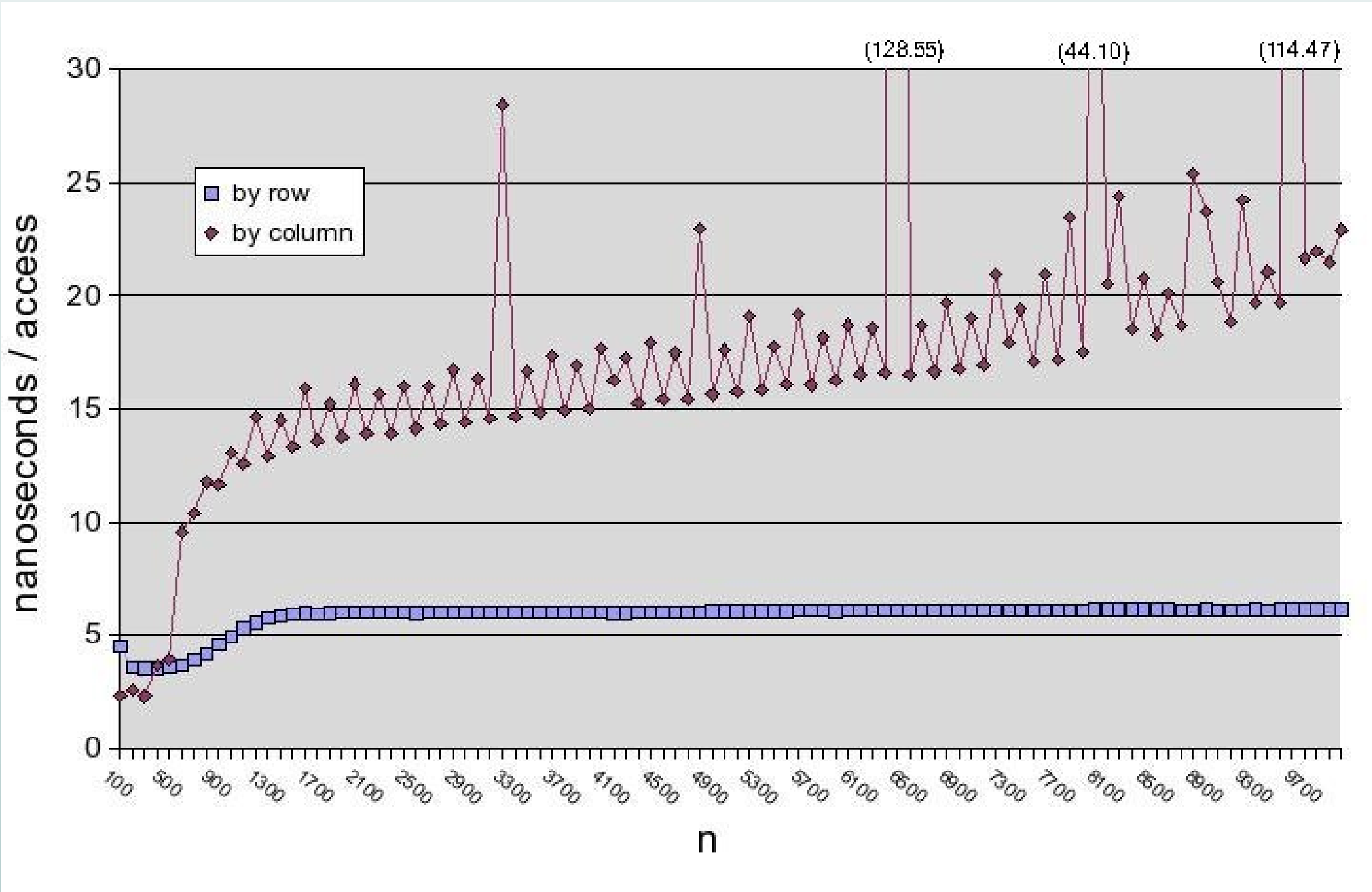

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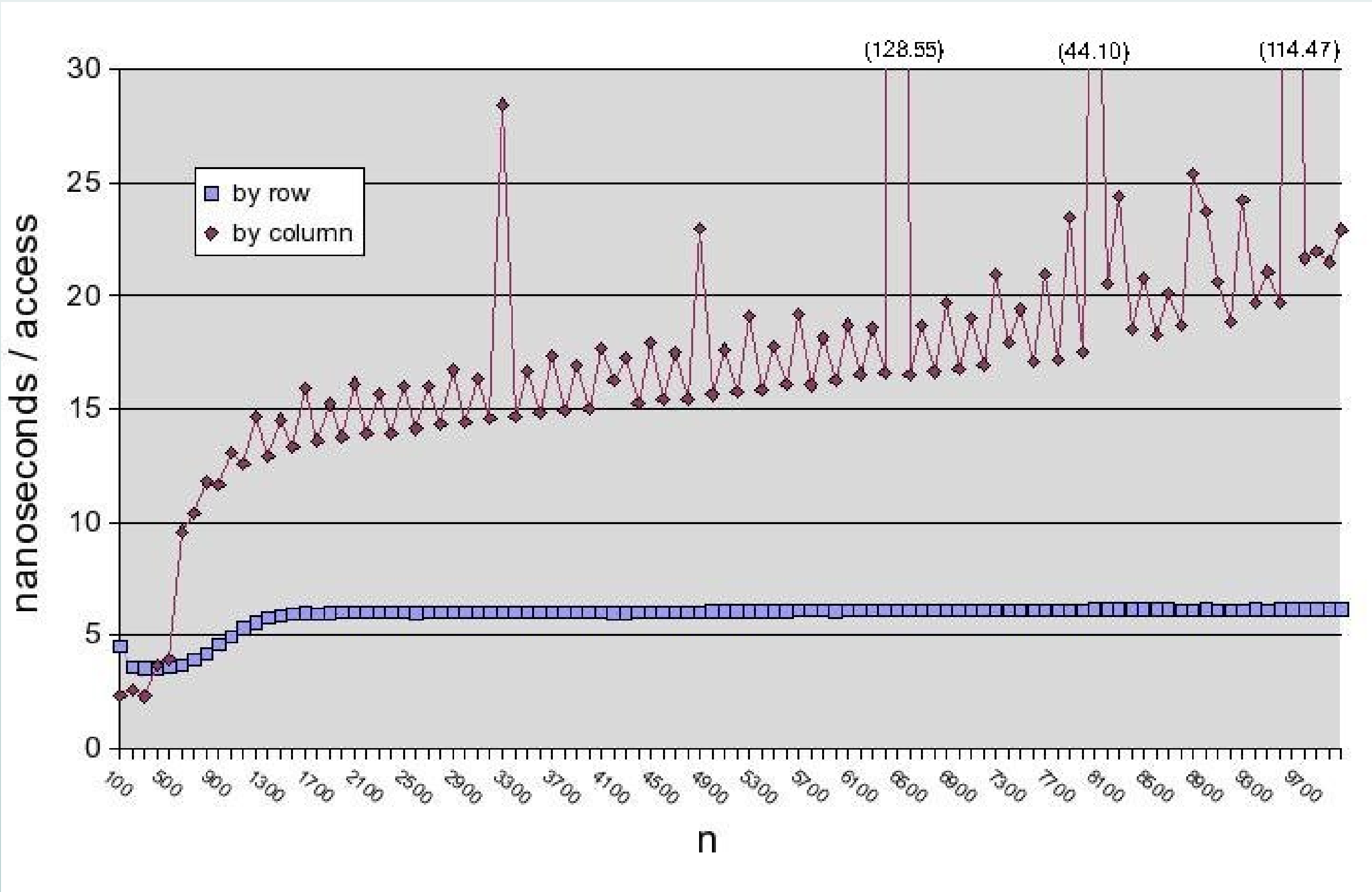

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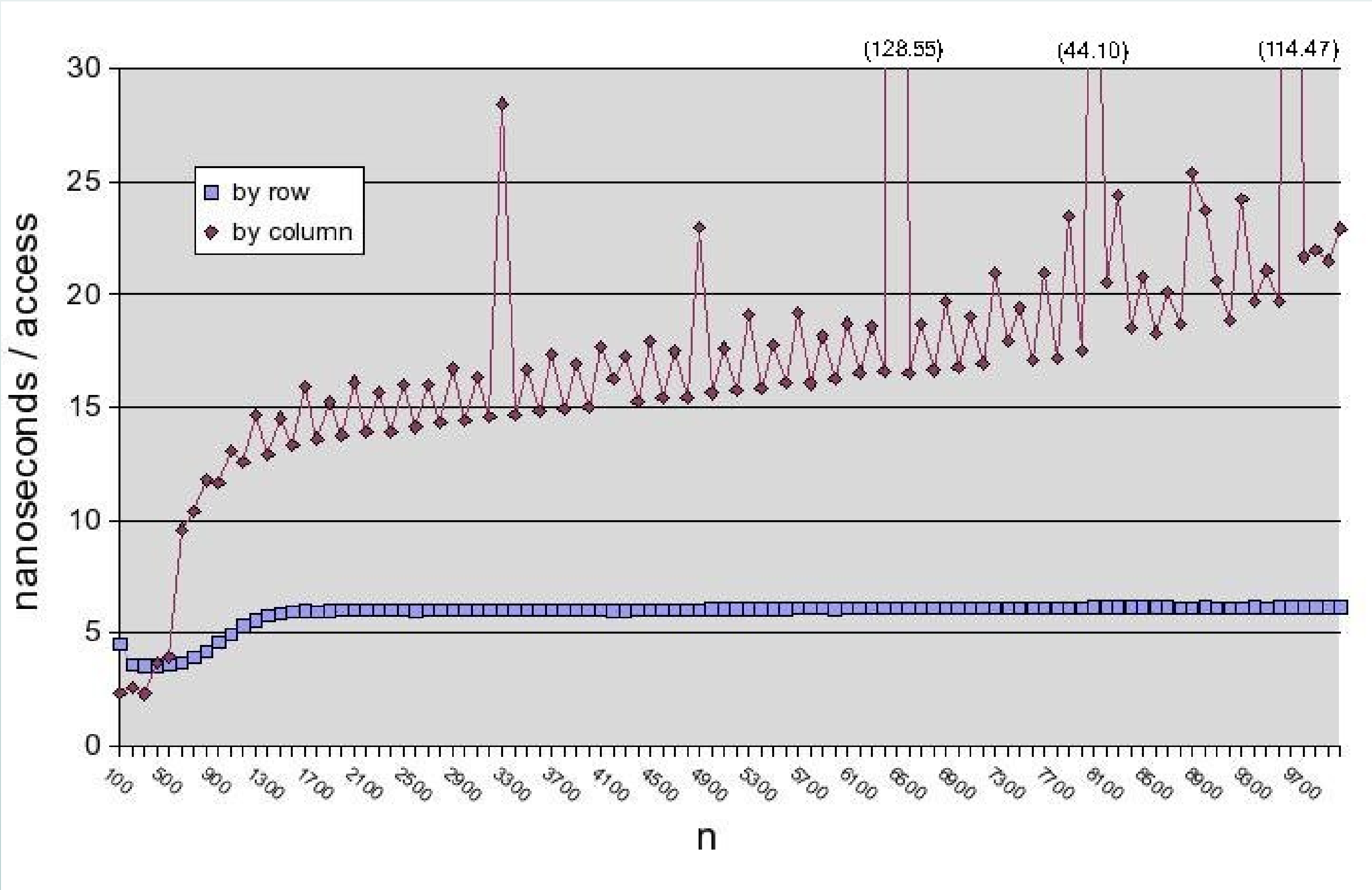

- In the row by row scanning, access time to each element is constant
- In the column by column scanning, access time grows with matrix size
- In the column by column scanning there are high peaks when matrix size `n` is a multiple of some cache size parameter (`n` equal to 3200, 4800, 6400, 8000, 9600. . .)

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However, sticking to it should never make any harm

Field reordering in Linux

For example, the first fields of the process descriptor in Linux 2.6.15 are:

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struct task_struct {
    volatile long state;
    struct thread_info *thread_info;
    atomic_t usage;
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First cache line (32 bytes)

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The `prefetch` macro is a hint for the CPU to read in advance the memory location at `pos->next`; the list element referenced by `pos->next` will be accessed in the next iteration of the loop

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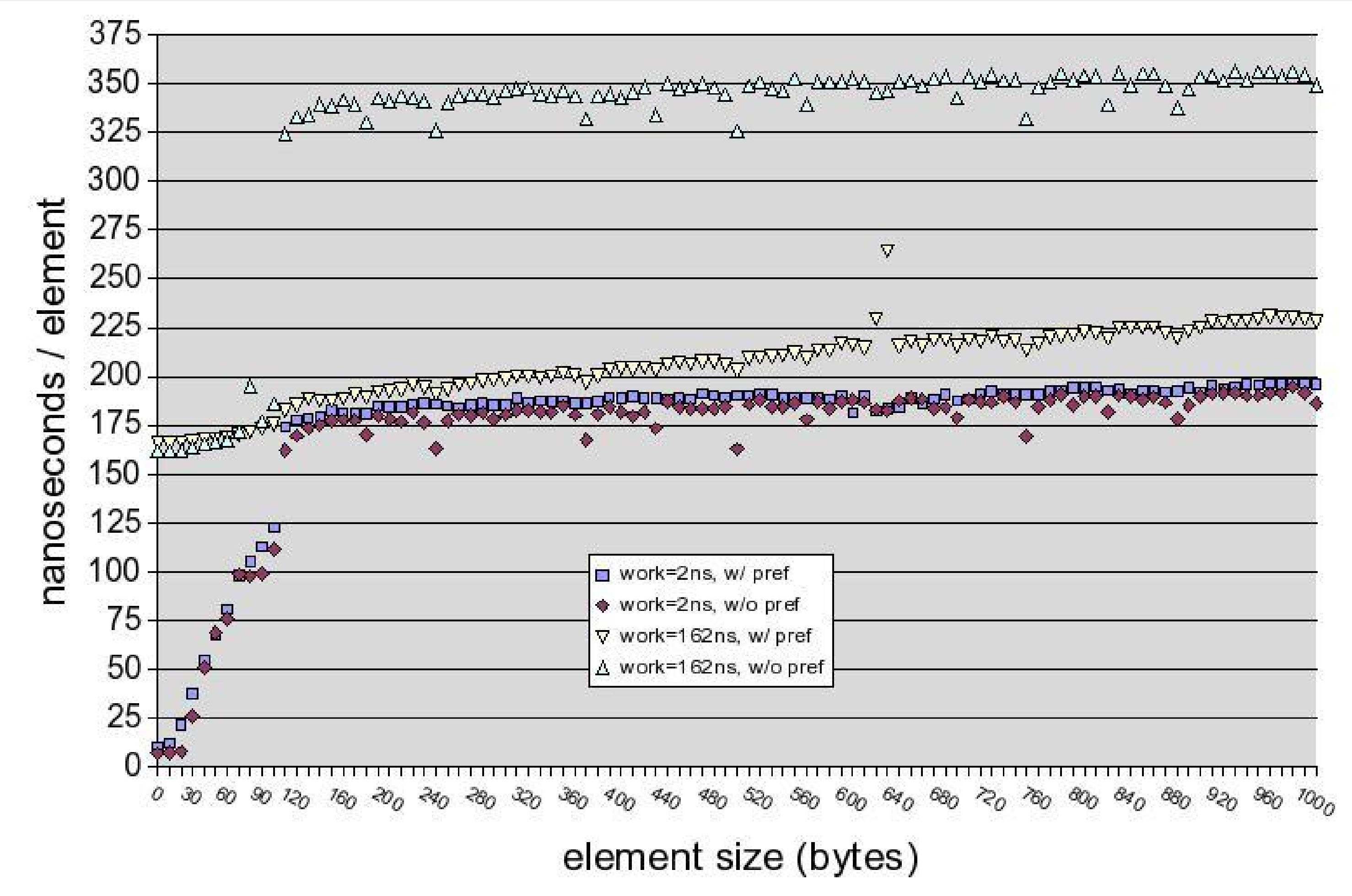
Thus, by using explicit prefetching you might actually impair your code!

Prefetching on list scanning



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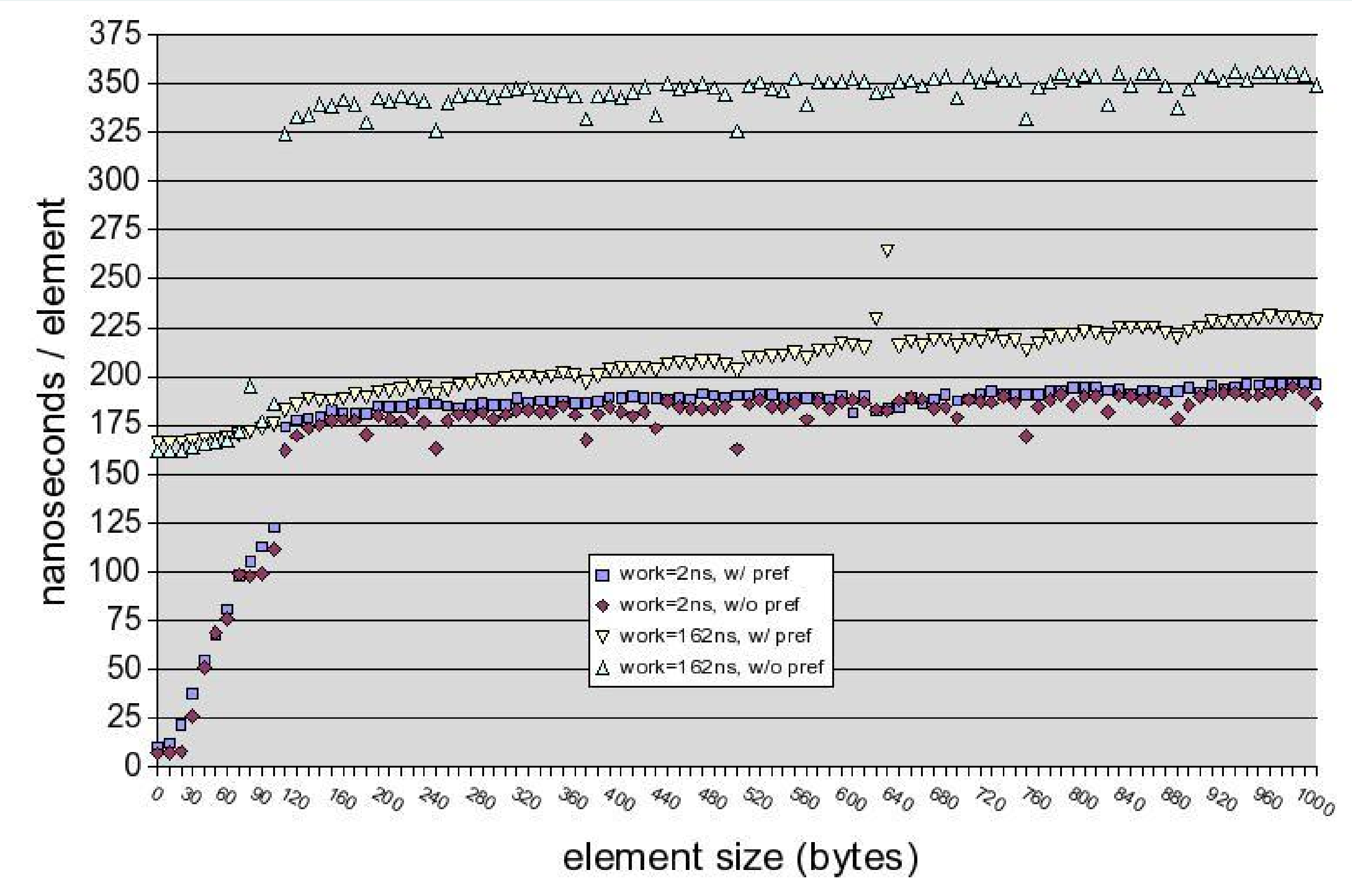

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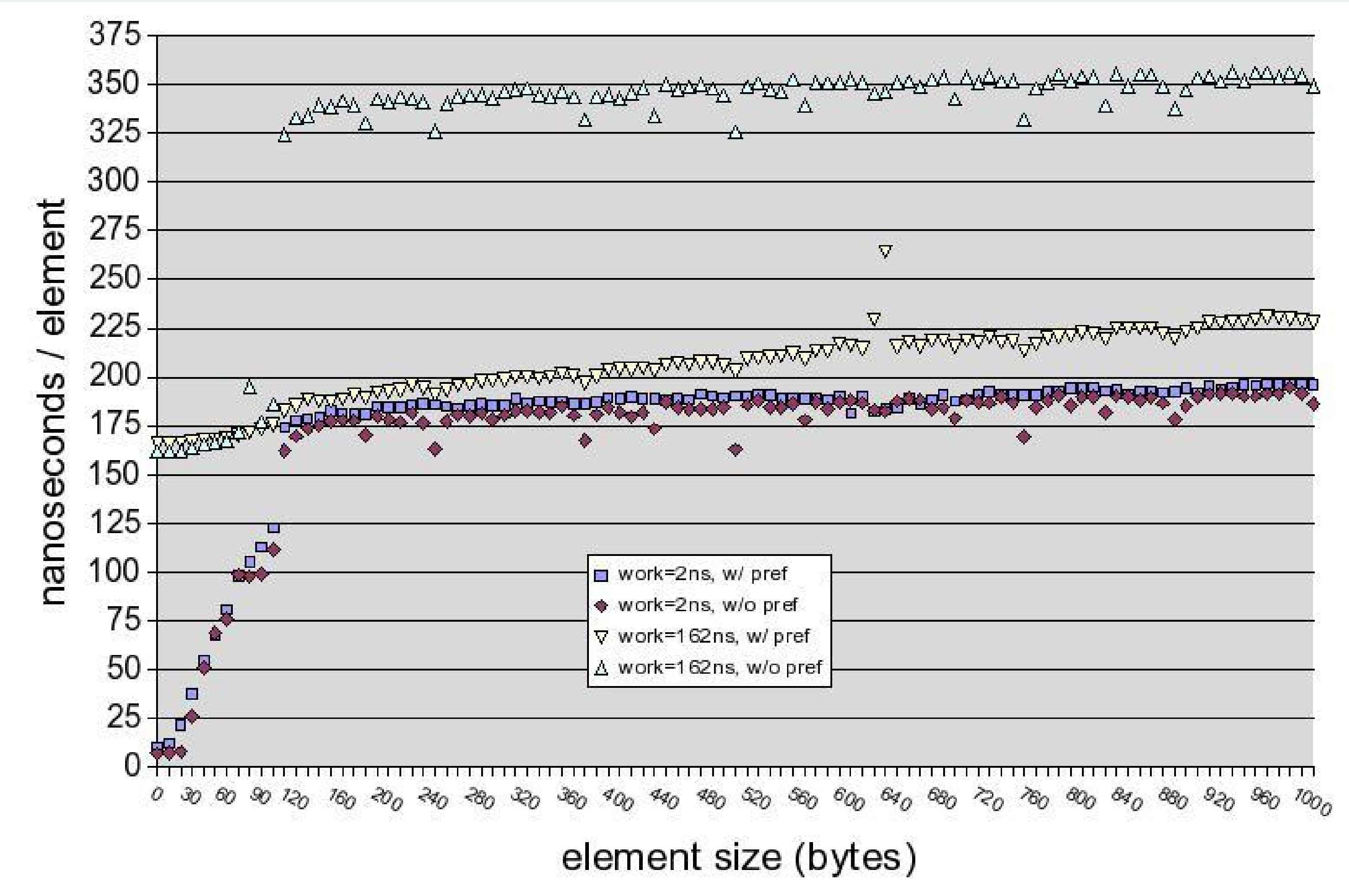

- If the time spent in processing each list element is small (2 nsec), scanning without prefetching is faster; time difference is roughly the execution time of the `prefetch` instruction
- If the time spent in processing each list element is comparable to the DRAM access time, scanning with prefetching is much faster

Branch prediction

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A well-predicted jump is very cheap (typically, zero or one CPU cycles), while a mispredicted jump is very costly, because the instructions of the path not taken must be removed from the pipeline

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    (likely branch)
l0:
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Static branch prediction

The rule for *static branch prediction* in IA-32 CPUs is simple:

- Any forward jump (positive offset) is predicted not to be taken
- Any backward jump (negative offset) is predicted to be taken

Forward jump:

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    jxx l0
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l0:
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Backward jump:

```
l1:
    (likely branch)
    jxx l1
    (unlikely branch)
```

Exploiting the static branch prediction

In order to generate code that is aware of the static branch prediction rule, Linux defines the following macros:

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On IA-32, "`if (unlikely(current->state == TASK_STOPPED))`" generates either a branch-if-true forward jump or a branch-if-false backward jump

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3. Compile again your program by using the same optimization flags as in step 1 (`-O2`) and by using the `-fbranch-probabilities` option to *gcc*

Static branch prediction with *gcc* 4.1

The *gcc* 4.1 compiler allows you to tag the branches in your code without “wild guesses”:

1. Compile your program by enabling code optimization (for instance, `-O2`) and by using the `-fprofile-arcs` option to *gcc*

2. Run your program in a typical scenario

3. Compile again your program by using the same optimization flags as in step 1 (`-O2`) and by using the `-fbranch-probabilities` option to *gcc*

All done! The compiler will generate code optimized for the branches effectively taken in the run at step 2

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```
        jxx oops
        (normal, likely branch)
        .section .fixup
oops:
        (exceptional, unlikely branch)
        .previous
```

Out-of-section branching in C

A sort of out-of-section branching can be implemented directly in C by means of a *gcc*'s extension:

```
void oops_handler(void)
        __attribute__((section(".exceptions")));
```

[. . .]

```
if (unlikely(oops_condition))
    oops_handler();
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in *ld*: `ld --section-start .exceptions=0x08049000 prog.o`
in *gcc*: `gcc -O2 -Wl,--section-start,.exceptions=0x08049000 prog.c`

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This can be done automatically by the *gcc* 4.1 compiler! You must enable optimization, use the `-fprofile-arcs` option, and compile twice, as described earlier

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In some *lmbench* benchmarks, Arjan claims a 10% gain in performances!!

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- Reading Linux source code may expose a programmer to new, risky, and amazing ideas
- Finally, Linux might help you in many ways. . . even if you don't run it!