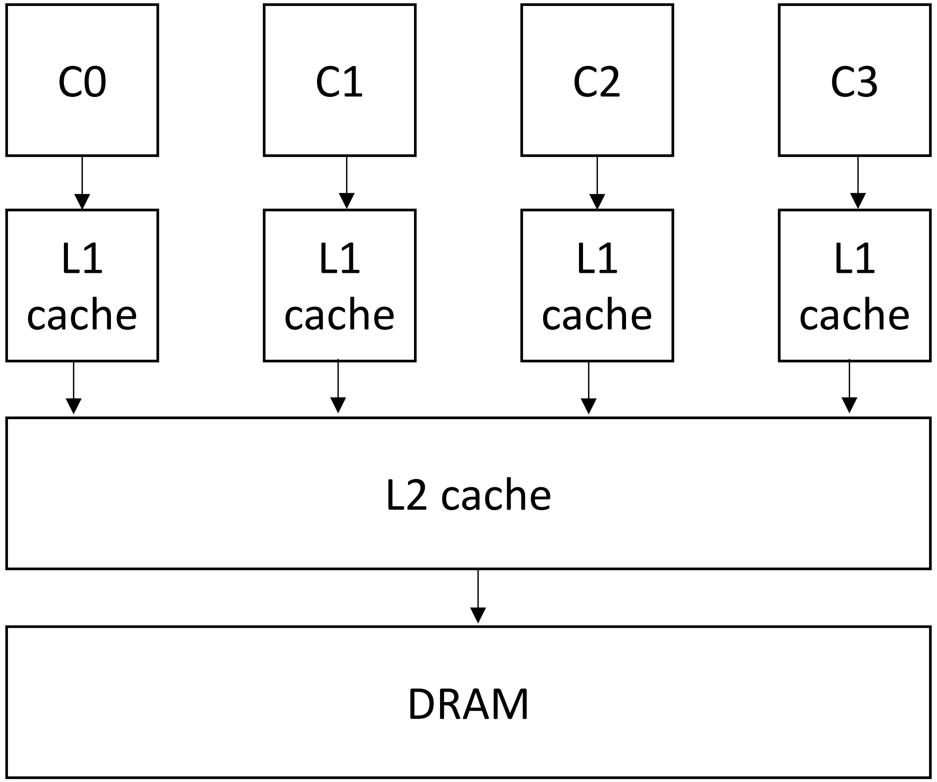
CSE211: Compiler Design

Nov. 15, 2023

- **Topic**: SMP parallelism
  - Candidate DOALL loops
  - Safety checking

- **Discussion questions**:
  - What parallel frameworks have you used?
  - Do you achieve linear speedup?
  - When is it safe to parallelize for loops?



Announcements

- Homework 2 is out
  - Due on *Wednesday*
  - I have office hours today
  - Rithik has office hours tomorrow

- Start thinking about 2nd paper
- Start thinking about final project
  - Deadline is to get final project APPROVED, not start brainstorming

- Homework 3 is assigned on Wednesday

Announcements

- Grading:
  - HW 1 grades and midterm are completely finished
    - Come see us during office hours if you have questions
  - Please make some time to see Rithik (for HW 1 or midterm) or me (midterm) if you lost any points that you don’t think you should have.
  - We released the tests so you can see what you passed/failed

  - Paper report *nearly* finished
  - 2 week deadline to discuss grades

Review ILP

Finding dependencies in the compiler

- What type of instructions can be done in parallel?

two instructions can be executed in parallel if they are independent

```
x = z + w;
a = b + c;
```

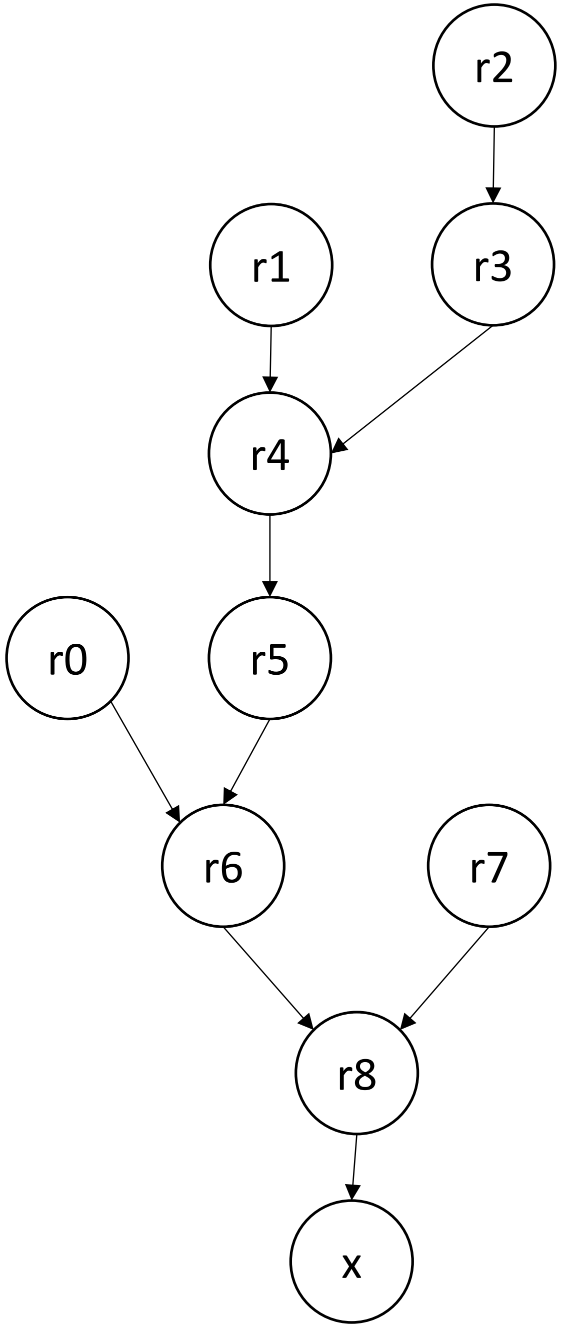
Two instructions are independent if the operand registers are disjoint from the result registers

instructions that are not independent cannot be executed in parallel

```
x = z + w;
a = b + x;
```

Data Dependencies

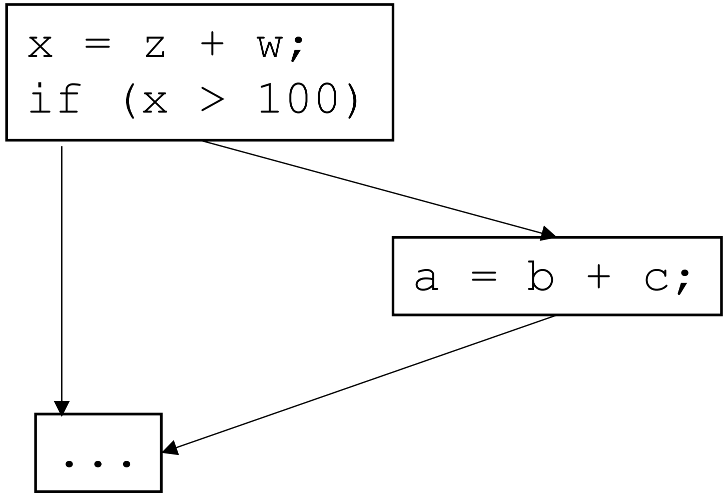
```
r0 = neg(b);
r1 = b * b;
r2 = 4 * a;
r3 = r2 * c;
r4 = r1 - r3;
r5 = sqrt(r4);
r6 = r0 - r5;
r7 = 2 * a;
r8 = r6 / r7;
x  = r8;
```



Control dependencies

```
x = z + w;
if (x > 100)
    a = b + c;
```

Instructions in different CFG nodes have control-dependencies



Memory dependencies

True dependence:
Read-after-write

```
a[i] = z + w;
x = a[i]
```

Output dependence:
Write-after-write

```
a[i] = z + w;
a[i] = a + b;
```

Dependencies can be removed

```
reg_a_i = z + w;
a[i] = a + b;
```

anti-dependence:
Write-after-read

```
x = a[i]
a[i] = z + w;
```

Dependencies can be delayed

```
x = a[i]
reg_a_i = z + w;
...
a[i] = reg_a_i;
```

How can hardware execute ILP?

- Pipeline parallelism

stage 1

stage 2

stage 3

- Abstract mental model for compiler:
  - N-stage pipeline
  - N instructions can be in-flight
  - Dependencies stall pipeline

```
instr1;
instrX0;
instrX1;
instr2;
instrX2;
instrX3;
instr3;
```

If there are non-dependent instructions from other places in the program that we can interleave then we can get back performance!

How can hardware execute ILP?

- Executing multiple instructions at once:
- Superscalar architecture:
  - Several sequential operations are issued in parallel
  - hardware detects dependencies

issue-width is maximum number of instructions that can be issued in parallel

```
instr0;
instr1;
instr2;
```

if instr0 and instr1 are independent, they will be issued in parallel

What does this look like in the real world?

- Intel Haswell (2013):
  - Issue width of 4
  - 14-19 stage pipeline
  - OoO execution
- Intel Nehalem (2008)
  - 20-24 stage pipeline
  - Issue width of 2-4
  - OoO execution
- ARM
  - V7 has 3 stage pipeline; Cortex V8 has 13
  - Cortex V8 has issue width of 2
  - OoO execution
- RISC-V
  - Ariane and Rocket are In-Order
  - 3-6 stage pipelines
  - some super scaler implementations (BOOM)

Other examples?

Using Loop Unrolling to Exploit ILP

- Simple loop unrolling:

```
for (int i = 0; i < SIZE; i+=2) {
    SEQ(i,1);
    SEQ(i,2);
    ...
    SEQ(i,N); // end iteration for i
    SEQ(i+1,1);
    SEQ(i+1,2);
    ...
    SEQ(i+1, N); // end iteration for i + 1
}
```

Let `SEQ(i,j)` be the jth instruction of `SEQ(i)`.

Let each instruction chain have N instructions

Using Loop Unrolling to Exploit ILP

- Simple loop unrolling:

```
for (int i = 0; i < SIZE; i+=2) {
      SEQ(i,1);
      SEQ(i+1,1);
      SEQ(i,2);
      SEQ(i+1,2);
      ...
      SEQ(i,N);
      SEQ(i+1, N);
}
```

They can be interleaved

Loop Unrolling for Reduction Loops

- Simple implementation:

```
for (int i = 1; i < SIZE; i++) {
    a[0] = REDUCE(a[0], a[i]);
}
```

If the reduction operator is associative, we can do better!

Loop Unrolling for Reduction Loops

- chunk array in equal sized partitions and do local reductions
- Consider size 2:

1	2	3	4	5	6	7	8

Loop Unrolling for Reduction Loops

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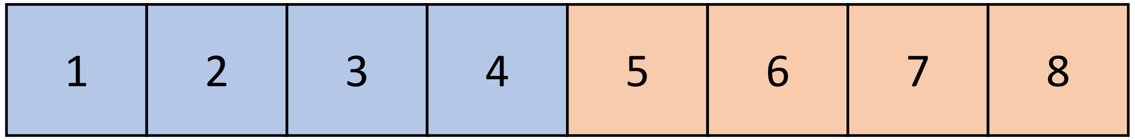

1	2	3	4	5	6	7	8

Loop Unrolling for Reduction Loops

- Simple implementation:

```
for (int i = 1; i < SIZE/2; i++) {
    a[0] = REDUCE(a[0], a[i]);
    a[SIZE/2] = REDUCE(a[SIZE/2], a[(SIZE/2)+i]);
}

a[0] = REDUCE(a[0], a[SIZE/2])
```

independent instructions can be done in parallel!

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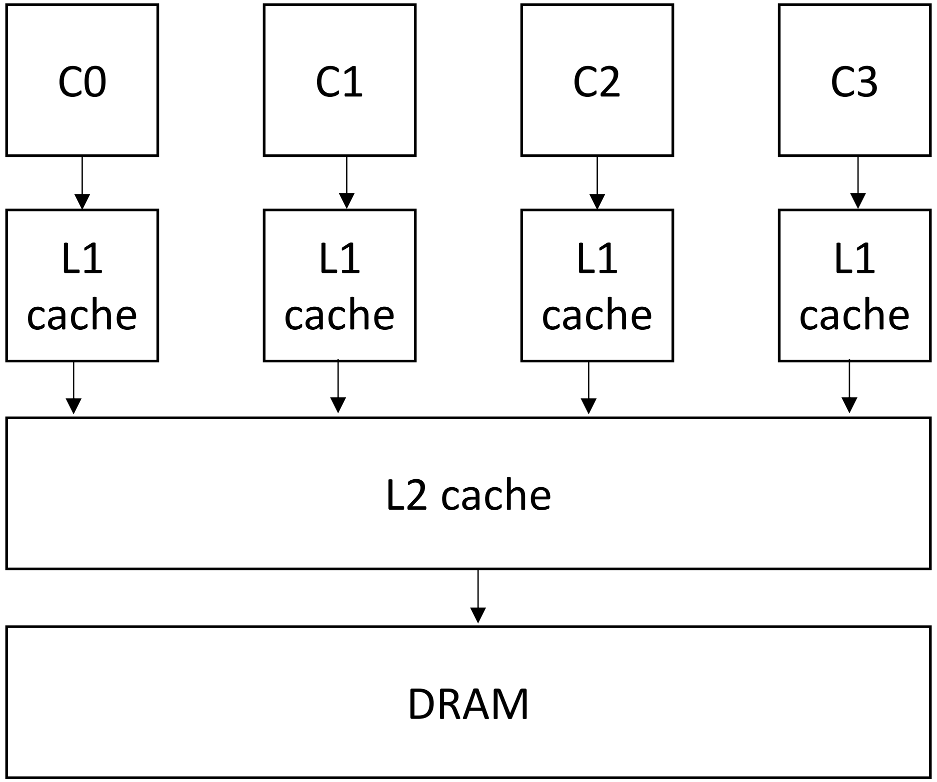
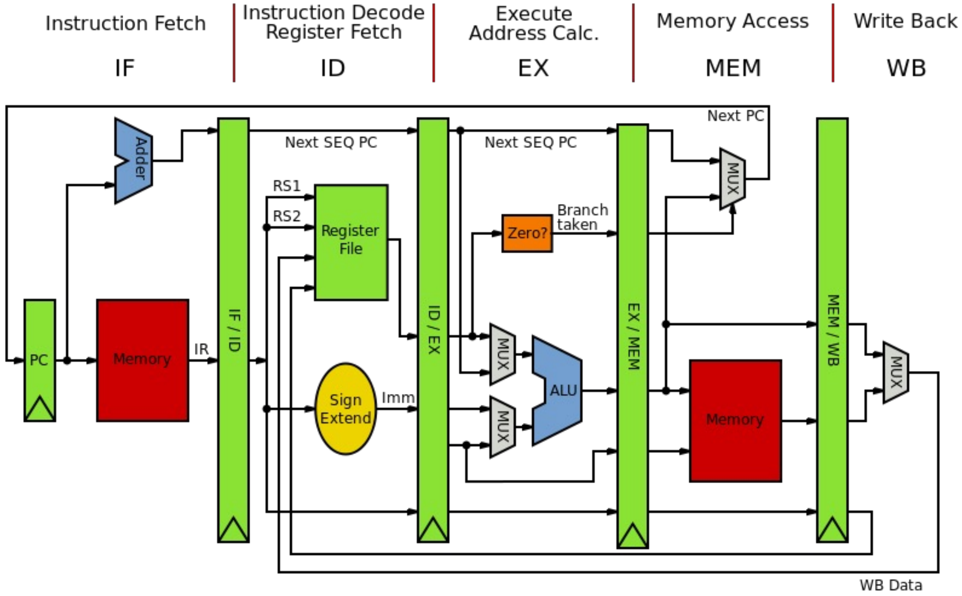


Limits of ILP?

- Pipelines?
  - Only so much meaningful work to do per-stage.
  - Stage timing imbalance
  - Staging overhead



- Superscalar width?
  - Hardware checking becomes prohibitive:

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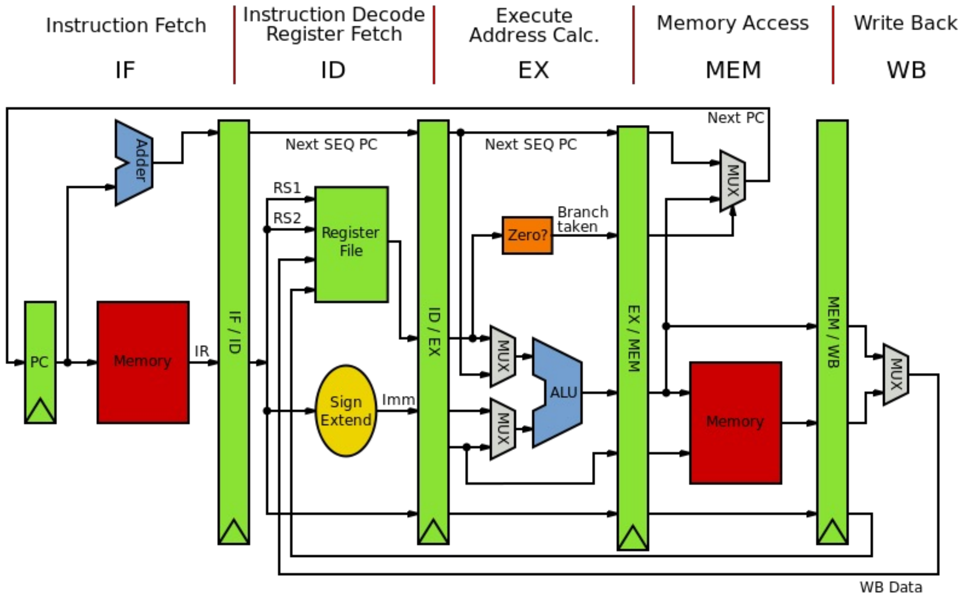
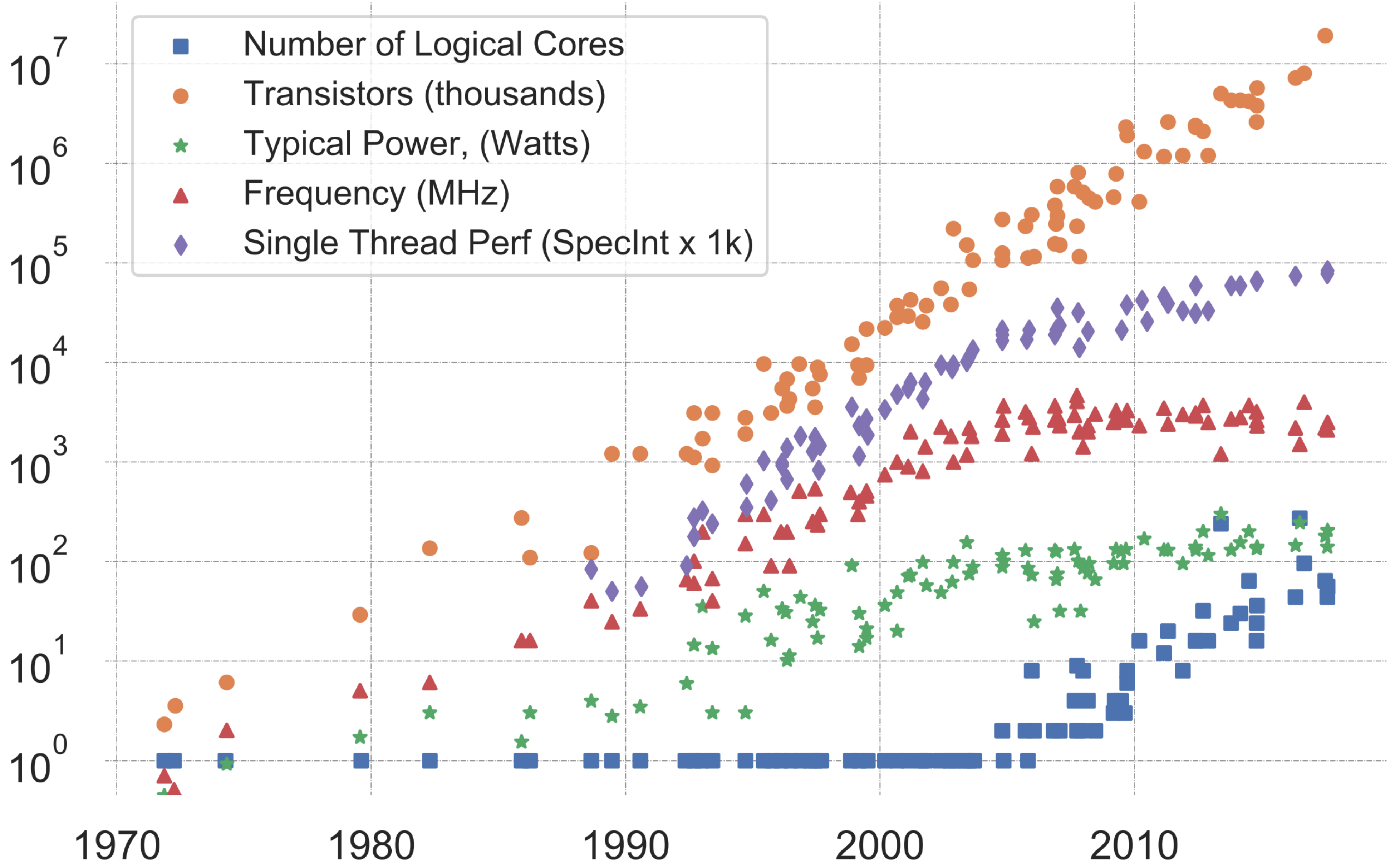


- Superscalar width?
  - Hardware checking becomes prohibitive:

Collectively the power consumption, complexity and gate delay costs limit the achievable superscalar speedup to roughly eight simultaneously dispatched instructions.

https://en.wikipedia.org/wiki/Superscalar_processor#Limitations



K. Rupp, “40 Years of Mircroprocessor Trend Data,” https://www. karlrupp.net/2015/06/40-years-of-microprocessor-trend-data, 2015.

Trends

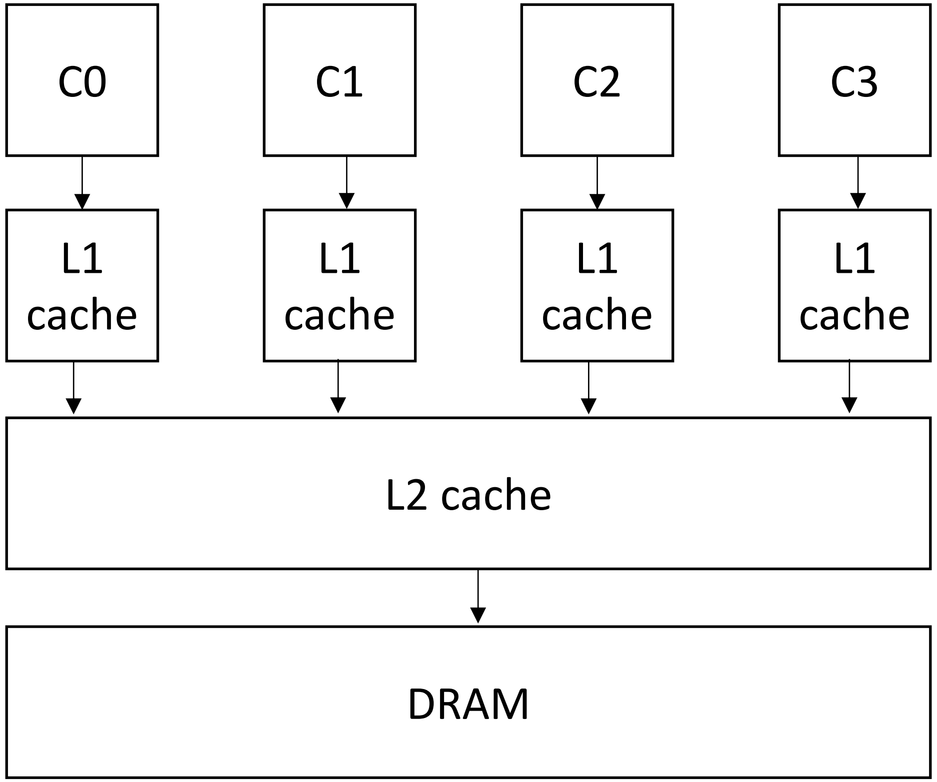
- Frequency scaling: **Dennard’s scaling**
  - Mostly agreed that this is over

- Number of transistors: **Moore’s law**
  - On its last legs?
  - Intel delayed 7nm chips (out now?). Apple has a 5nm. Roadmaps go to 3nm, or 1.8nm

- *Chips are not increasing in raw frequency, and space is becoming more valuable*

Symmetric Multiprocessing (SMP)

- Collection of “identical” cores
  - Shared memory (access to all system resources)
  - Managed by a single OS
- Pros:
  - Simple(r) HW design
  - Great for multitasking machines



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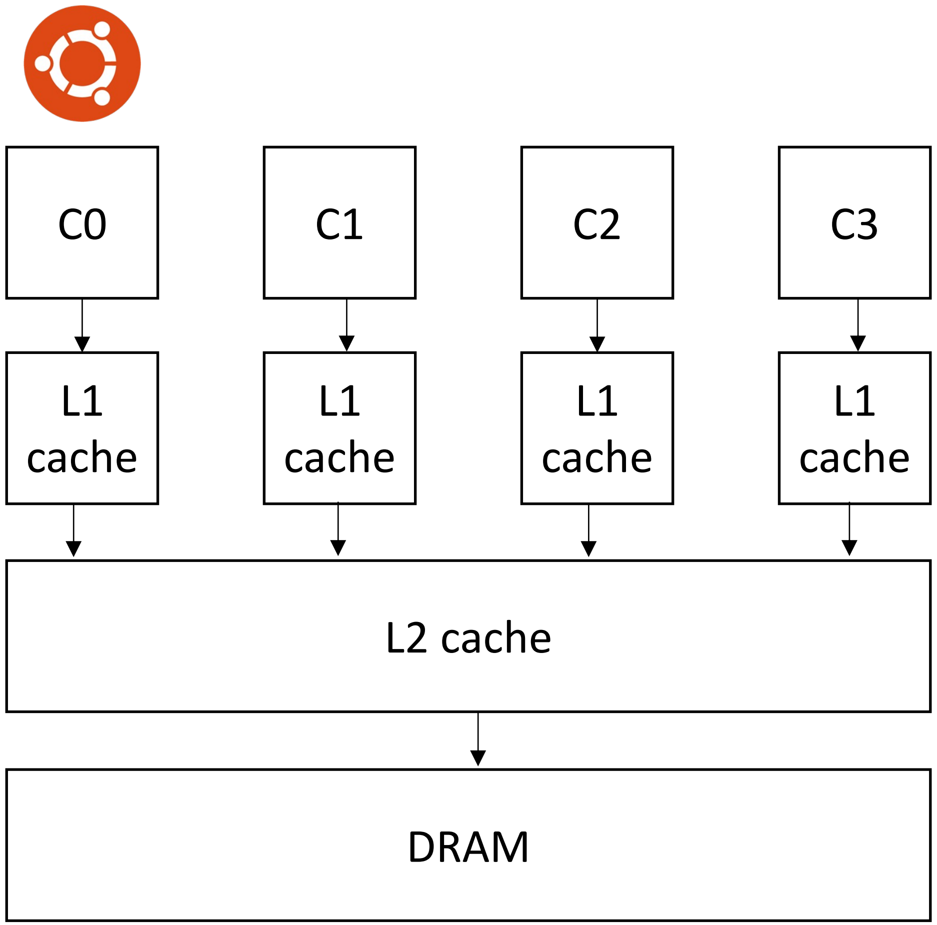

C0
C1
C2
C3

L1 cache
L1 cache
L1 cache
L1 cache

L2 cache

DRAM

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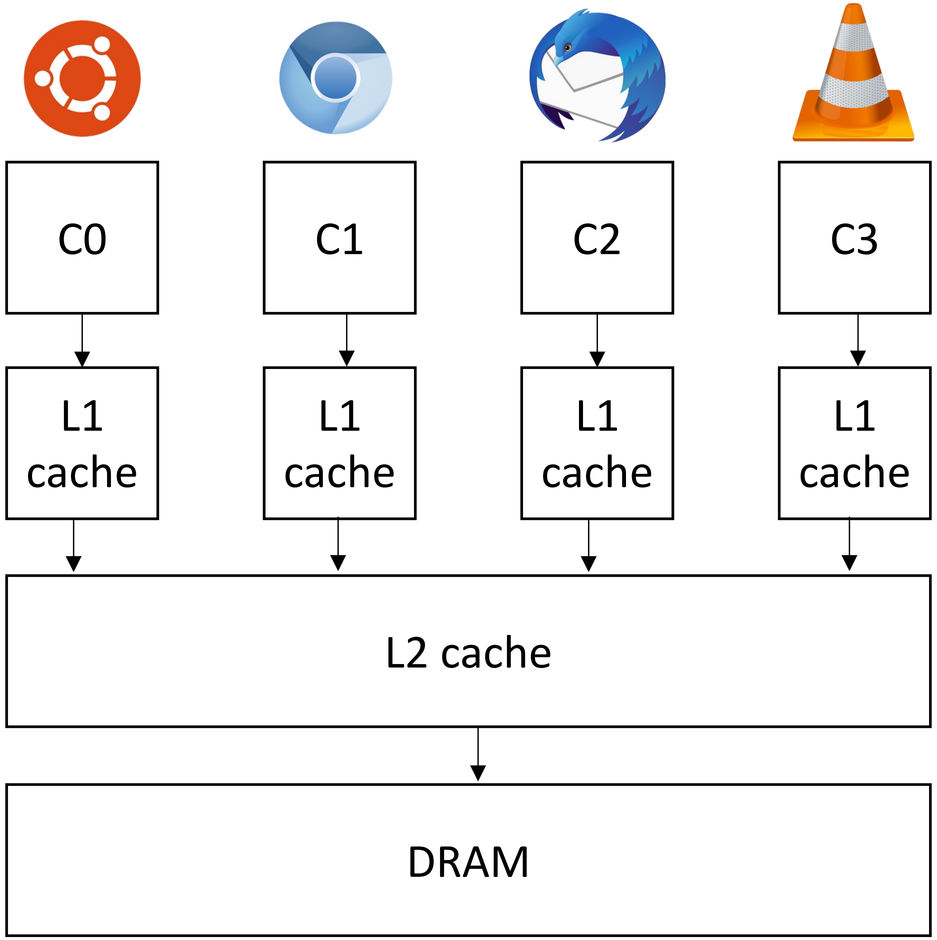

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Symmetric Multiprocessing (SMP)

PyTorch

- Collection of “identical” cores
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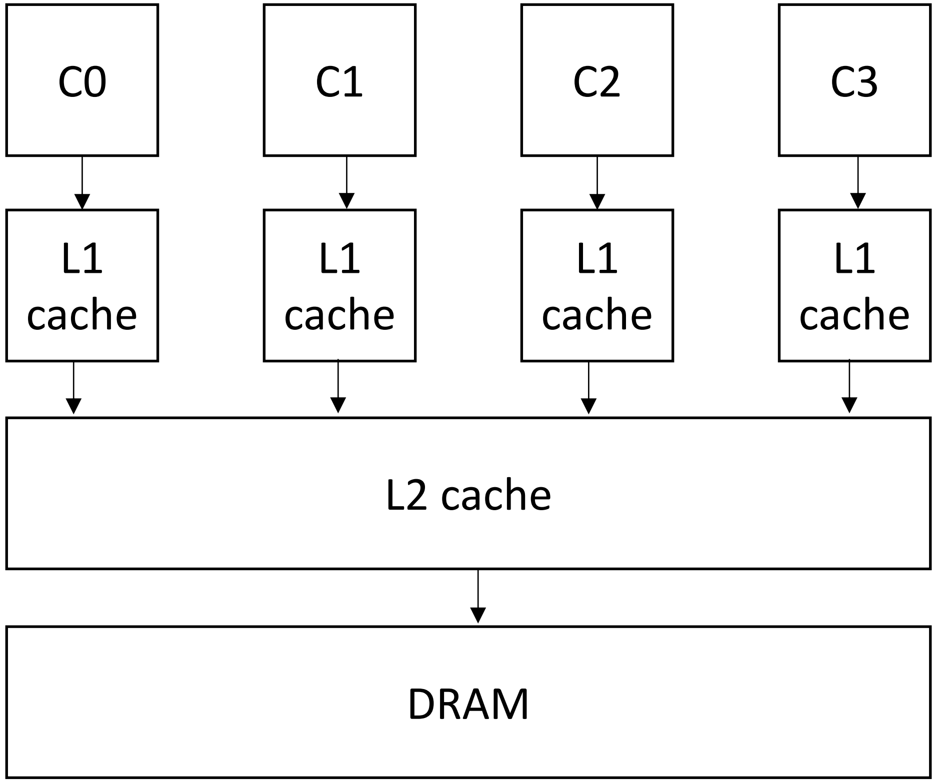

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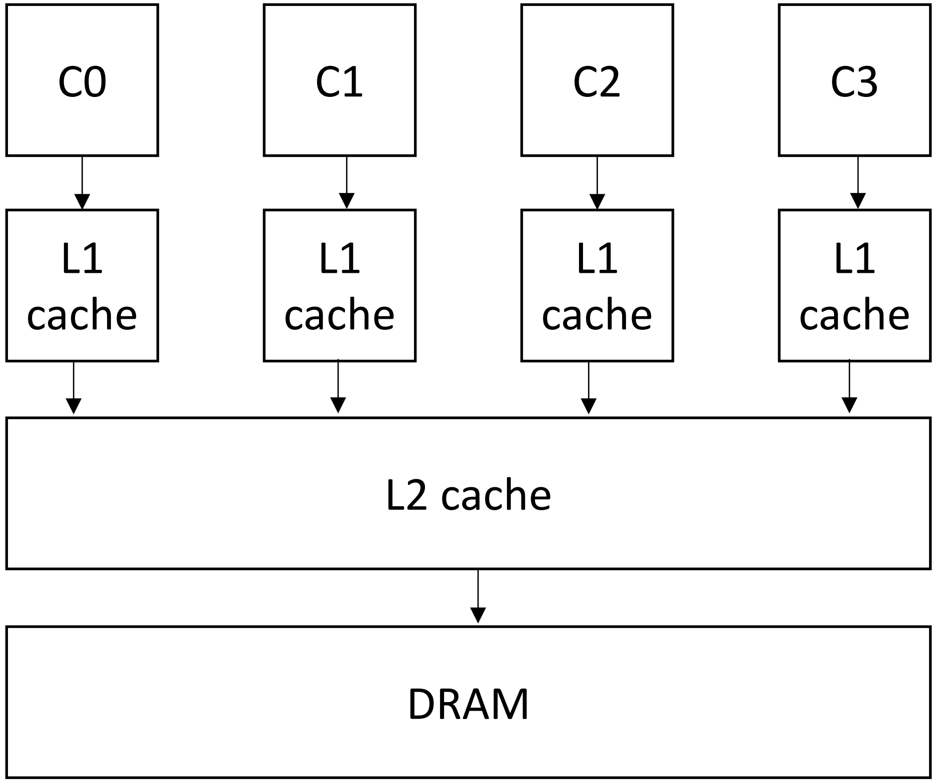
Symmetric Multiprocessing (SMP)

- Collection of “identical” cores
  - Shared memory (access to all system resources)
  - Managed by a single OS

- Pros:
  - Simple(r) HW design
  - Great for multitasking machines
  - Can provide (close to) linear speedups for parallel applications

- Cons: difficult to program!



SMP systems are widespread

- Laptops
  - My laptop has 8 cores
  - Most have at least 2
  - New Macbook: 16 core
- Workstations:
  - 2 - 64 cores
  - ARM racks: 128
- Phones:
  - iPhone: 2 big cores, 4 small cores
  - Samsung: 1 + 3 + 4

*https://www.crn.com/news/components-peripherals/ampere-s-new-128-core-altra-cpu-targets-intel-amd-in-the-cloud

SMP systems are widespread

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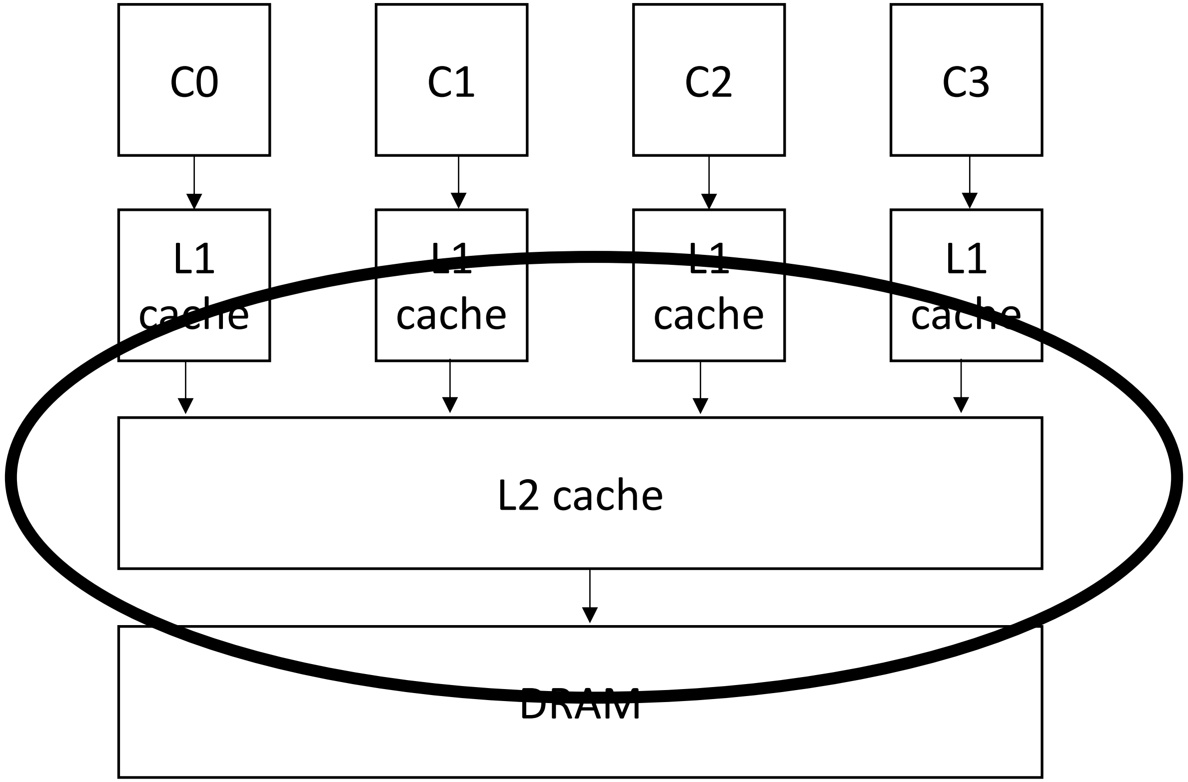


*https://www.crn.com/news/components-peripherals/ampere-s-new-128-core-altra-cpu-targets-intel-amd-in-the-cloud

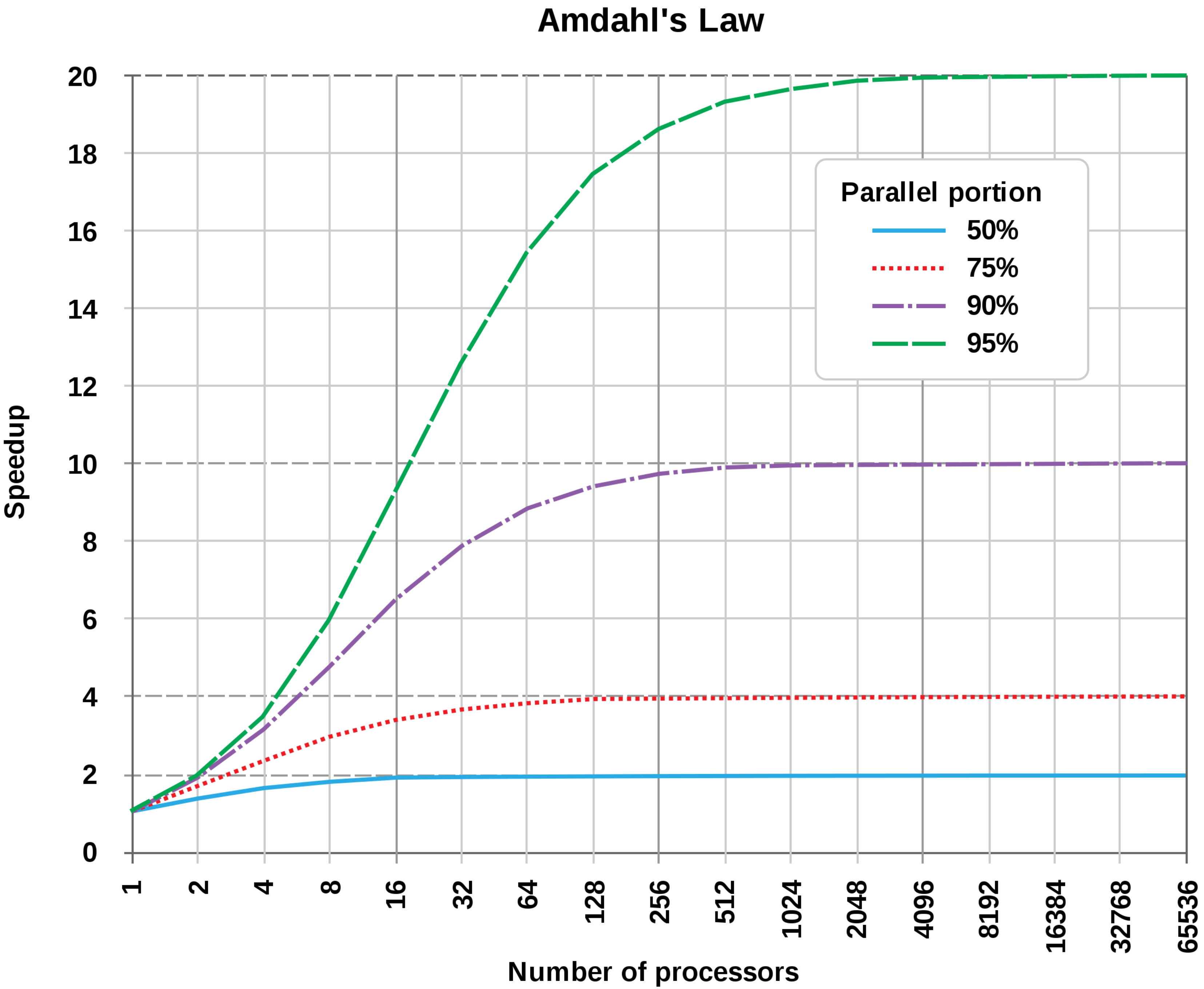
Potential for Parallel Speedup

- Amdahl's law

- *Speedup*(c) = $\frac{1}{(1-p)+\frac{p}{c}}$

- Where c is the number of cores and p is the percentage of the program execution time that would be improved by parallelism

- Assumes linear speedups



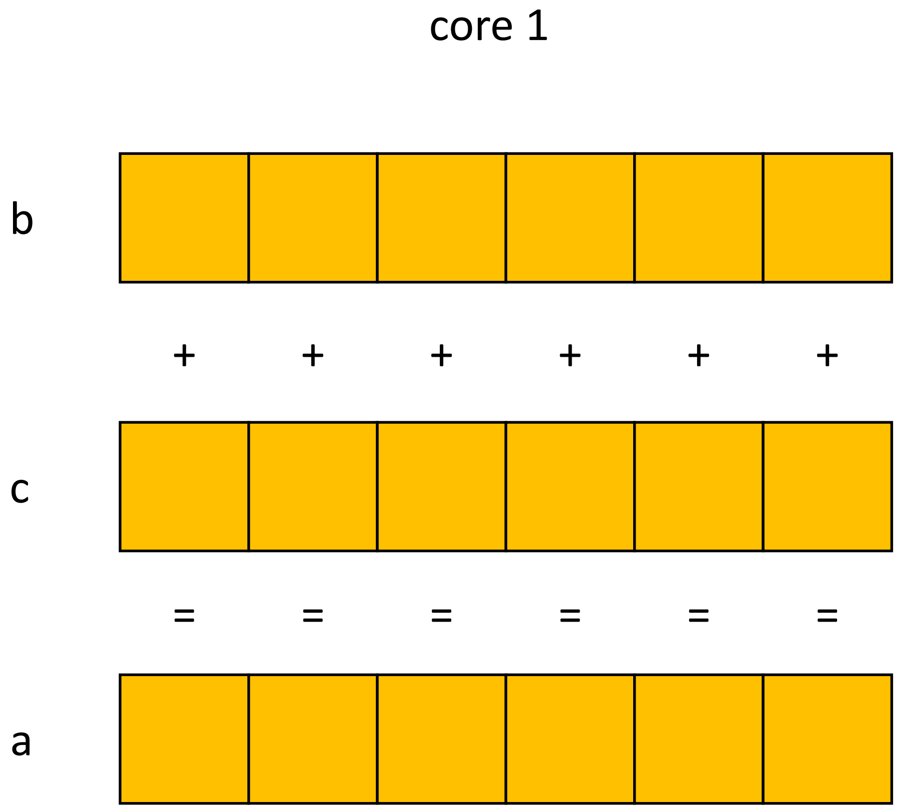
from wikipedia

Can compilers help?

- Much like ILP: convert sequential streams of computation in to SMP parallel code.
- Much harder constraints
  - Correctness
  - Performance
- For loops are a good target for compiler analysis

For loops are great candidates for SMP parallelism

```
for (int i = 0; i < 6; i++) {
   a[i] = b[i] + c[i]
}
```



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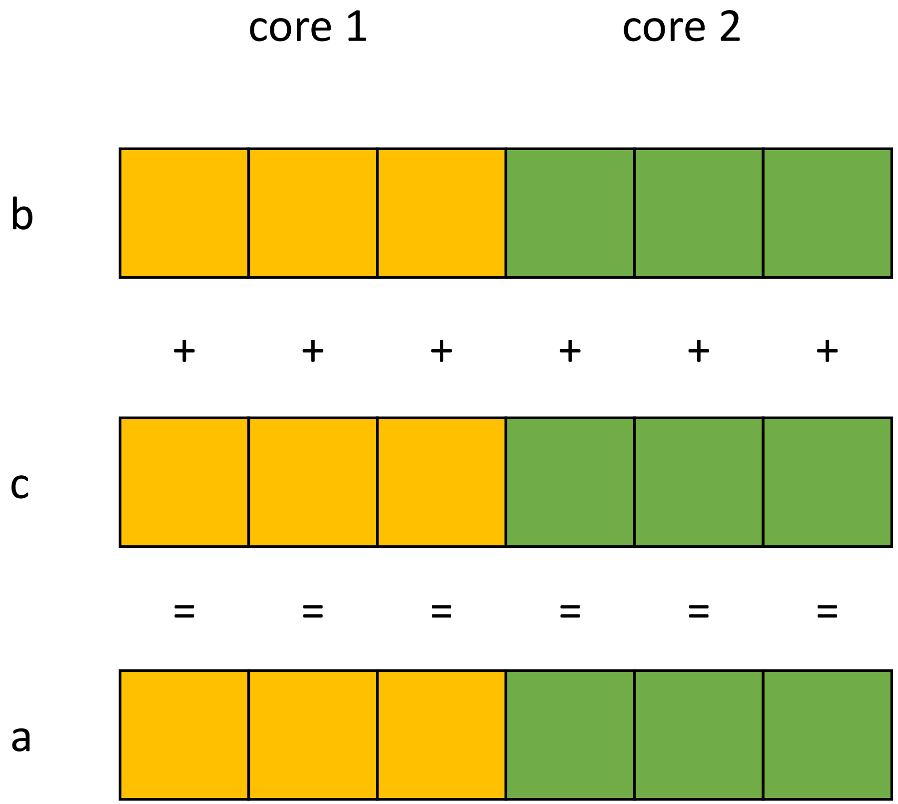

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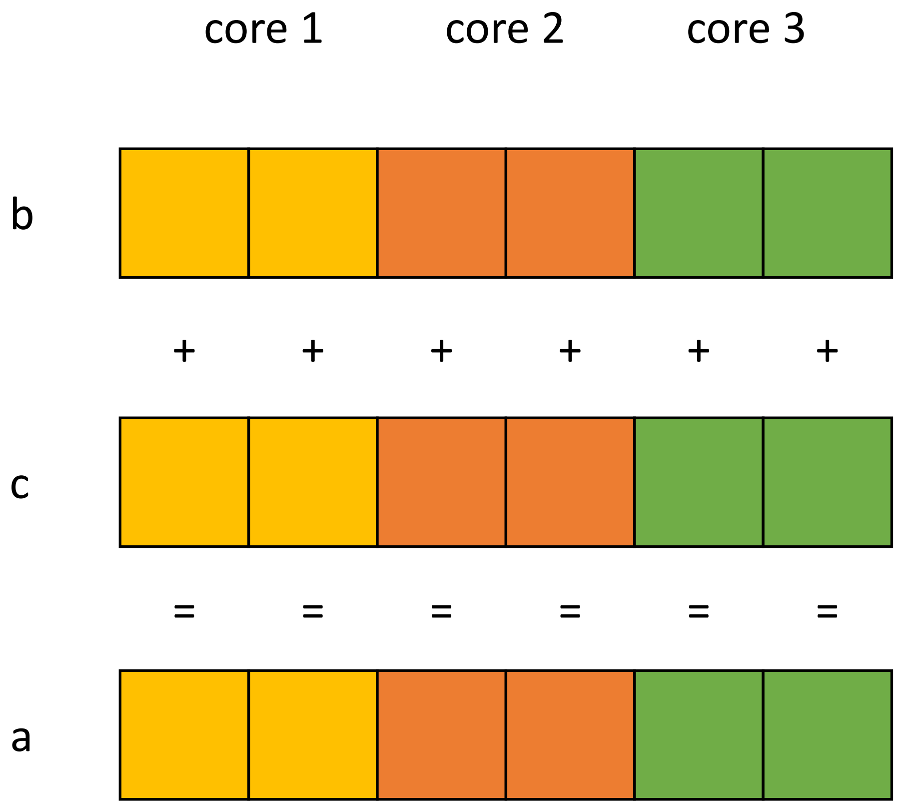

SMP Parallelism in For Loops

- Given a nest of For loops, can we make the outer-most loop parallel?
    - Safely
    - Efficiently

- We will consider a special type of for loop, common in scientific applications:
    - Operates on N dimensional arrays
    - Only side-effects are array writes
    - Array bases are disjoint and constant
    - Bounds and array indexes are a function of loop variables, input variables and constants*
    - Loops increment by 1 and start at 0

If the bounds and indexes are affine functions, then more analysis is possible, see dragon book

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```
for (int i = 0; i < dim1; i++) {
  for (int j = 0; j < dim3; j++) {
    for (int k = 0; k < dim2; k++) {
      a[i][j] += b[i][k] * c[k][j];
    }
  }
}
```

SMP Parallelism in For Loops

- We will consider a special type of for loop, common in scientific applications:
  - Operates on N dimensional arrays (only side-effects are array writes)
  - Array bases are disjoint and constant
  - Bounds, indexes are a function of loop variables, input variables and constants
  - Loops Increment by 1 and start at 0

```
for (int i = 2; i < 100; i+=3) {
  a[i] = c[i + 128];
}
```

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Make new loop bounds:
i = j

```
for (int i = 2; i < 100; i+=3) {
  a[i] = c[i + 128];
}
```

SMP Parallelism in For Loops

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    - Operates on N dimensional arrays (only side-effects are array writes)
    - Array bases are disjoint and constant
    - Bounds, indexes are a function of loop variables, input variables and constants
    - Loops Increment by 1 and start at 0

Make new loop bounds:
i = j*3 + 2

```
for (int j = 0; j < 32; j+=1) {
  a[j*3+2] = c[j*3+2 + 128];
}
```

subtract by constant to start at 0

SMP Parallelism in For Loops

- We will consider a special type of for loop, common in scientific applications:
  - Operates on N dimensional arrays (only side-effects are array writes)
  - Array bases are disjoint and constant
  - Bounds, indexes are a function of loop variables, input variables and constants
  - Loops Increment by 1 and start at 0

```
for (int i = 2; i < 100; i+=3) {
  a[i] = c[i + 128];
}
```

```
for (int j = 0; j < 32; j+=1) {
  a[3*j+2] = c[(3*j+2) + 128];
}
```

SMP Parallelism in For Loops

- Given a nest of ***candidate*** *For* loops, determine if we can we make the outer-most loop parallel?
  - Safely
  - efficiently

- Criteria: every iteration of the outer-most loop must be *independent*
  - The loop can execute in any order, and produce the same result

- Such loops are called “DOALL” Loops. The can be flagged and handed off to another pass that can finely tune the parallelism (number of threads, chunking, etc)

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

- How do we check this?
    - If the property doesn't hold then there exists 2 iterations, such that if they are re-ordered, it causes different outcomes for the loop.

    - **Write-Write conflicts**: two distinct iterations write different values to the same location

    - **Read-Write conflicts**: two distinct iterations where one iteration reads from the location written to by another iteration.

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

First example: write-write conflict

```
for (i = 0; i < size; i++) {
   a[index(i)] = loop(i);
}
```

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

First example: write-write conflict

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

Calculate index based on i

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
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First example: write-write conflict

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

Computation to store in the memory location

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
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First example: write-write conflict

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

for two distinct iterations:

`i`$_x$ `!= i`$_y$

Check:

`index(i`$_x$`) != index(i`$_y$`)`

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

First example: write-write conflict

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

for two distinct iterations:

i_x != i_y

Check:

index(i_x) != index(i_y)

Because we start at 0 and increment by 1, we can use i to refer to loop iterations

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

First example: write-write conflict

```
for (i = 0; i < size; i++) {
   a[index(i)] = loop(i);
}
```

for two distinct iterations:

$i_x \mathrel{!=} i_y$

Check:

$\texttt{index}(i_x) \mathrel{!=} \texttt{index}(i_y)$

Why?

Because if

$\texttt{index}(i_x) == \texttt{index}(i_y)$

then:

$\texttt{a[index}(i_x)\texttt{]}$ will equal

either $\texttt{loop}(i_x)$ or $\texttt{loop}(i_y)$

depending on the order

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

Examples:

```
for (i = 0; i < 128; i++) {
    a[i]= i*2;
}
```

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*
- the loop must produce the same result for any order of the iterations

```
for (i = 0; i < size; i++) {
    a[index(i)] = loop(i);
}
```

Examples:

```
for (i = 0; i < 128; i++) {
    a[i]= i*2;
}
```

```
for (i = 0; i < 128; i++) {
    a[i%64]= i*2;
}
```

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {
   a[write_index(i)] = a[read_index(i)] + loop(i);
}
```

Read-write conflicts:

for two distinct iteration variables:

`i`$_x$ `!=` `i`$_y$

Check:

`write_index(i`$_x$`) != read_index(i`$_y$`)`

Safety Criteria

- Criteria: every iteration of the outer-most loop must be *independent*

```
for (i = 0; i < size; i++) {
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}
```

Read-write conflicts:

for two distinct iteration variables:

`i`$_x$ `!= i`$_y$

Check:

`write_index(i`$_x$`) != read_index(i`$_y$`)`

Why?

if `i`$_x$ iteration happens first, then iteration `i`$_y$ reads an updated value.

if `i`$_y$ happens first, then it reads the original value

Examples:

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
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for (i = 0; i < 128; i++) {
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for (i = 0; i < 128; i++) {
   a[i]= a[0]*2;
}
```

Examples:

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for (i = 0; i < 128; i++) {
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}
```

```
for (i = 0; i < 128; i++) {
   a[i]= a[0]*2;
}
```

```
for (i = 1; i < 128; i++) {
   a[i]= a[0]*2;
}
```

Examples:

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for (i = 0; i < 128; i++) {
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   a[i]= a[0]*2;
}
```

```
for (i = 1; i < 128; i++) {
   a[i]= a[0]*2;
}
```

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i]*2;
}
```

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

Automation?

- We have decent intuition about this, but if its going to be in a compiler, then it needs to be automatable

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

two integers: i_x != i_y
i_x >= 0
i_x < 128
i_y >= 0
i_y < 128
write-write conflict write_index(i_x) == write_index(i_y)
read-write conflict write_index(i_x) == read_index(i_y)

Ask if these constraints are satisfiable (if so, it is not safe to parallelize)

Automation?

- We have decent intuition about this, but if its going to be in a compiler, then it needs to be automatable

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

two integers: i_x != i_y

i_x >= 0

i_x < 128

i_y >= 0

i_y < 128

i_x == i_y

i_x == i_y

Automation?

- We have decent intuition about this, but if its going to be in a compiler, then it needs to be automatable

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

two integers: i_x `!=` i_y

$i_x >= 0$

$i_x < 128$

$i_y >= 0$

$i_y < 128$

$i_x == i_y$

$i_x == i_y$

We can feed these constraints to an SMT Solver!

SMT Solver

- Satisfiability Modulo Theories (SMT)
  - Generalized SAT solver

- Solves many types of constraints over many domains
  - Integers
  - Reals
  - Bitvectors
  - Sets

- Complexity bounds are high (and often undecidable). In practice, they work pretty well

Microsoft Z3

- State-of-the-art

- Python bindings

- Tutorials:
  - Python: https://ericpony.github.io/z3py-tutorial/guide-examples.htm
  - SMT LibV2: https://rise4fun.com/z3/tutorial

Automation?

- We have decent intuition about this, but if its going to be in a compiler, then it needs to be automatable

```
for (i = 0; i < 128; i++) {
   a[i]= a[i]*2;
}
```

two integers: i_x != i_y

i_x >= 0

i_x < 128

i_y >= 0

i_y < 128

i_x == i_y

i_x == i_y

We can feed these constraints to an SMT Solver!

Another example:

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

Another example:

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

two integers: i_x != i_y
i_x >= 0
i_x < 128
i_y >= 0
i_y < 128
i_x % 64 == i_y % 64

Another example:

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

two integers: i_x != i_y

i_x >= 0

i_x < 128

i_y >= 0

i_y < 128

i_x % 64 == i_y % 64

what about write-read?

Another example:

```
for (i = 0; i < 128; i++) {
   a[i%64]= a[i+64]*2;
}
```

two integers: i_x != i_y

i_x >= 0

i_x < 128

i_y >= 0

i_y < 128

i_x % 64 == i_y + 64

General formula:

```
for (int i0 = init0; i0 < bound0(); i0++) {

    for (int i1 = init1(i0); i1 < bound1(i0); i1++) {

       ...

       for (int iN = initN(i0, i1, ...); iN < boundN(i0, i1 ...); iN++) {
            write(a, write_index(i0, i1 .. iN))
            read(a, read_index(i0, i1 .. iN));

       }

   }

}
```

General formula:

```
for (int i0 = init0; i0 < bound0(); i0++) {
    for (int i1 = init1(i0); i1 < bound1(i0); i1++) {
        ...
        for (int iN = initN(i0, i1, ...); iN < boundN(i0, i1 ...); iN++) {
             write(a, write_index(i0, i1 .. iN))
             read(a, read_index(i0, i1 .. iN));
        }
    }
}
```

1. Create two variables for each loop variable: $i0_x$, $i0_y$, $i1_x$, $i1_y$ ...
Set outer loop: $i0_x$!= $i0_y$

2. Constrain them to be inside their bounds:
for w in from (0,N): $iw_{x,y}$ >= initw(...), $iw_{x,y}$ < boundN(...)

3. Enumerate all pairs of potential write-write conflicts:
check: write_index($i0_x$,$i1_x$ ...) == write_index ($i0_y$,$i1_y$ ...)

4. Do the same for write-read conflicts

General formula:

```
for (int i0 = init0; i0 < bound0(); i0++) {
    for (int i1 = init1(i0); i1 < bound1(i0); i1++) {
        ...
        for (int iN = initN(i0, i1, ...); iN < boundN(i0, i1 ...); iN++) {
            write(a, write_index(i0, i1 .. iN))
            read(a, read_index(i0, i1 .. iN));
        }
    }
}
```

1. Create two variables for each loop variable: $i0_x$, $i0_y$, $i1_x$, $i1_y$ ...
Set outer loop: $i0_x$!= $i0_y$

2. Constrain them to be inside their bounds:
for w in from (0,N): $iw_{x,y}$ >= initw(...), $iw_{x,y}$ < boundN(...)

3. Enumerate all pairs of potential write-write conflicts:
check: write_index($i0_x$,$i1_x$ ...) == write_index ($i0_y$,$i1_y$ ...)

4. Do the same for write-read conflicts

What if we want to parallelize an inner loop?

Are data races ever okay?

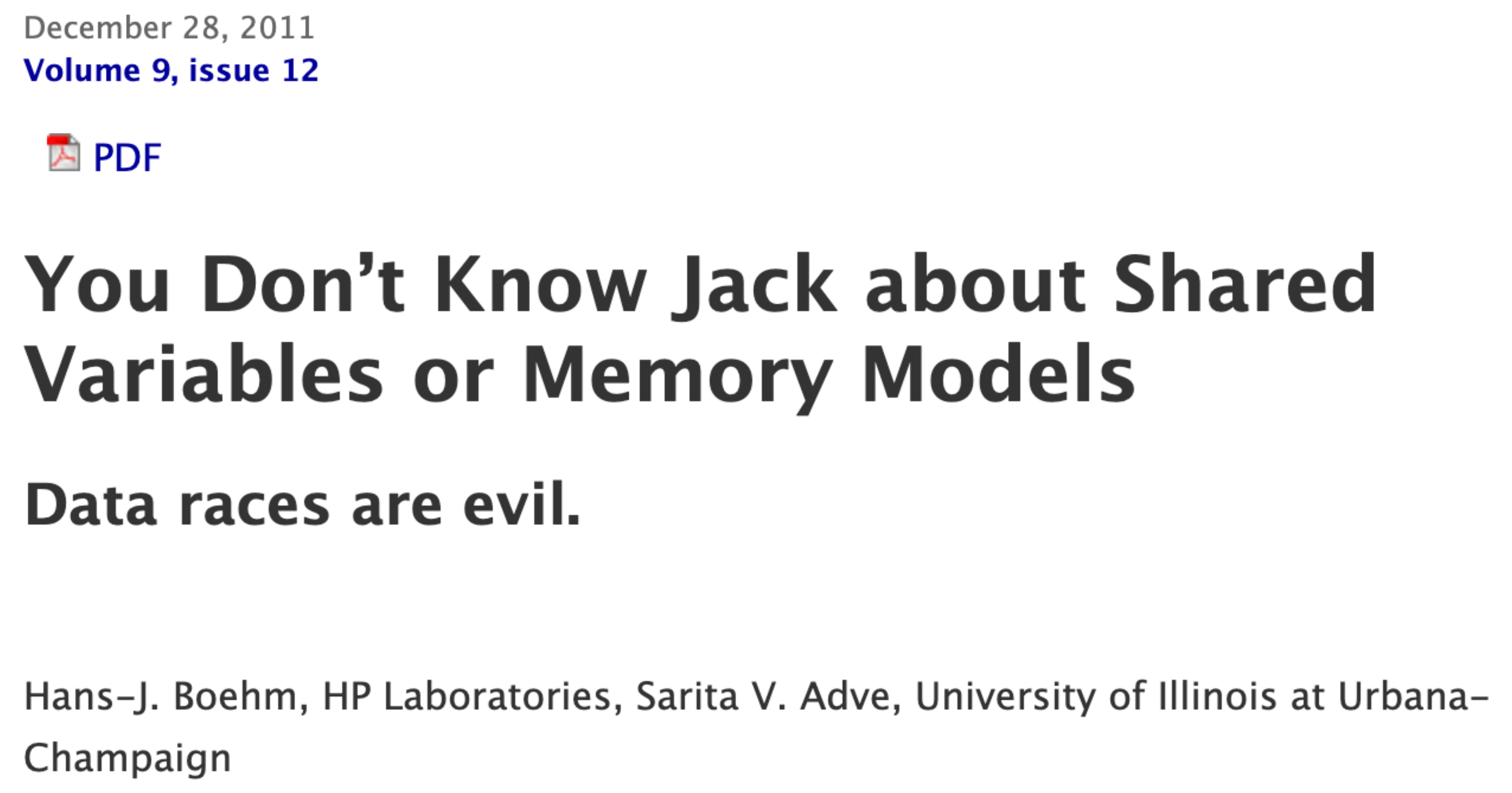
- Thoughts?

Are data races ever okay?

- Consider this program:

```
int x = 0;
for (int i = 0; i < 1024; i++) {
   int tmp = *(&x);
   tmp += 1;
   *(&x) = tmp;
}
```

What can go wrong if we run the loop in parallel?



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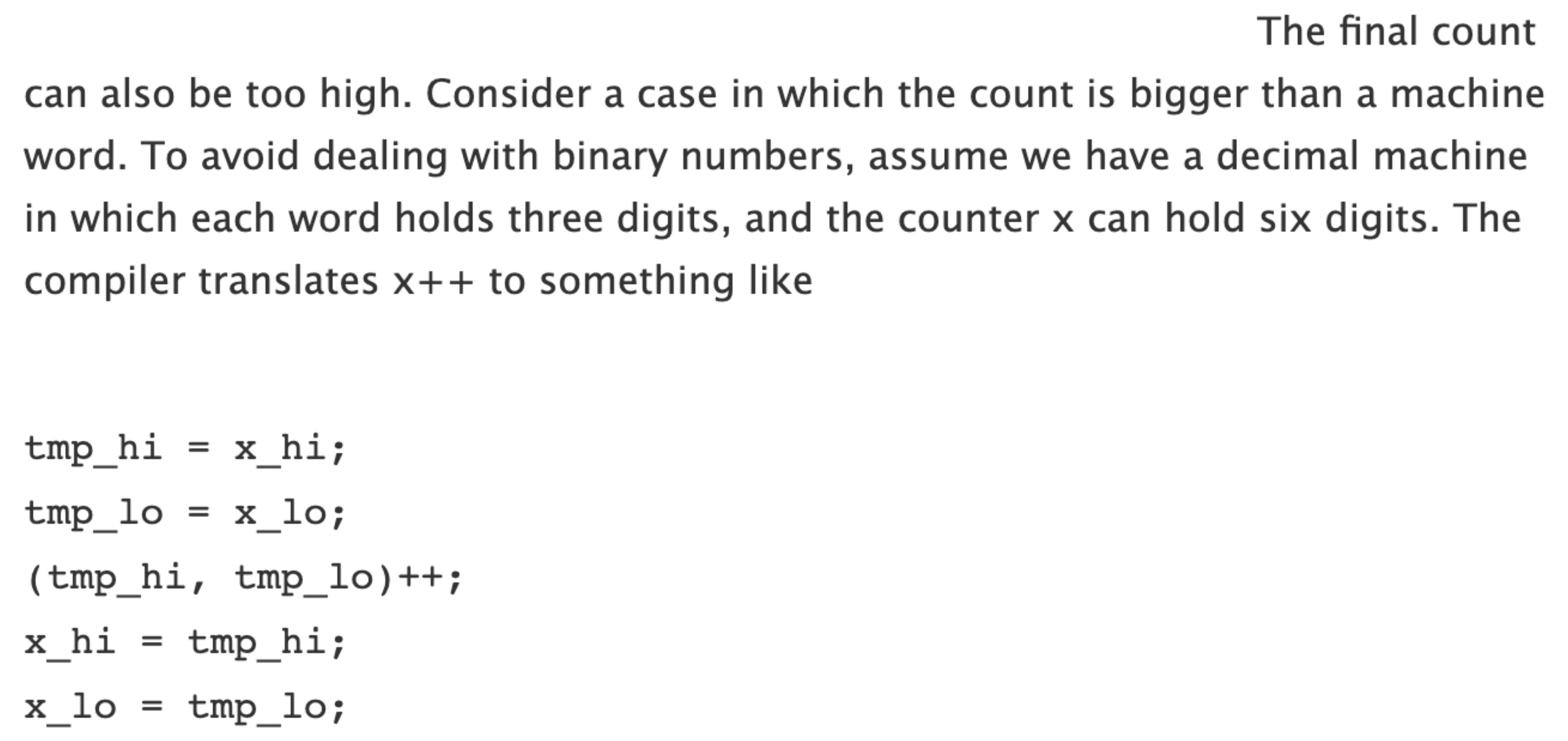
PDF

You Don’t Know Jack about Shared Variables or Memory Models

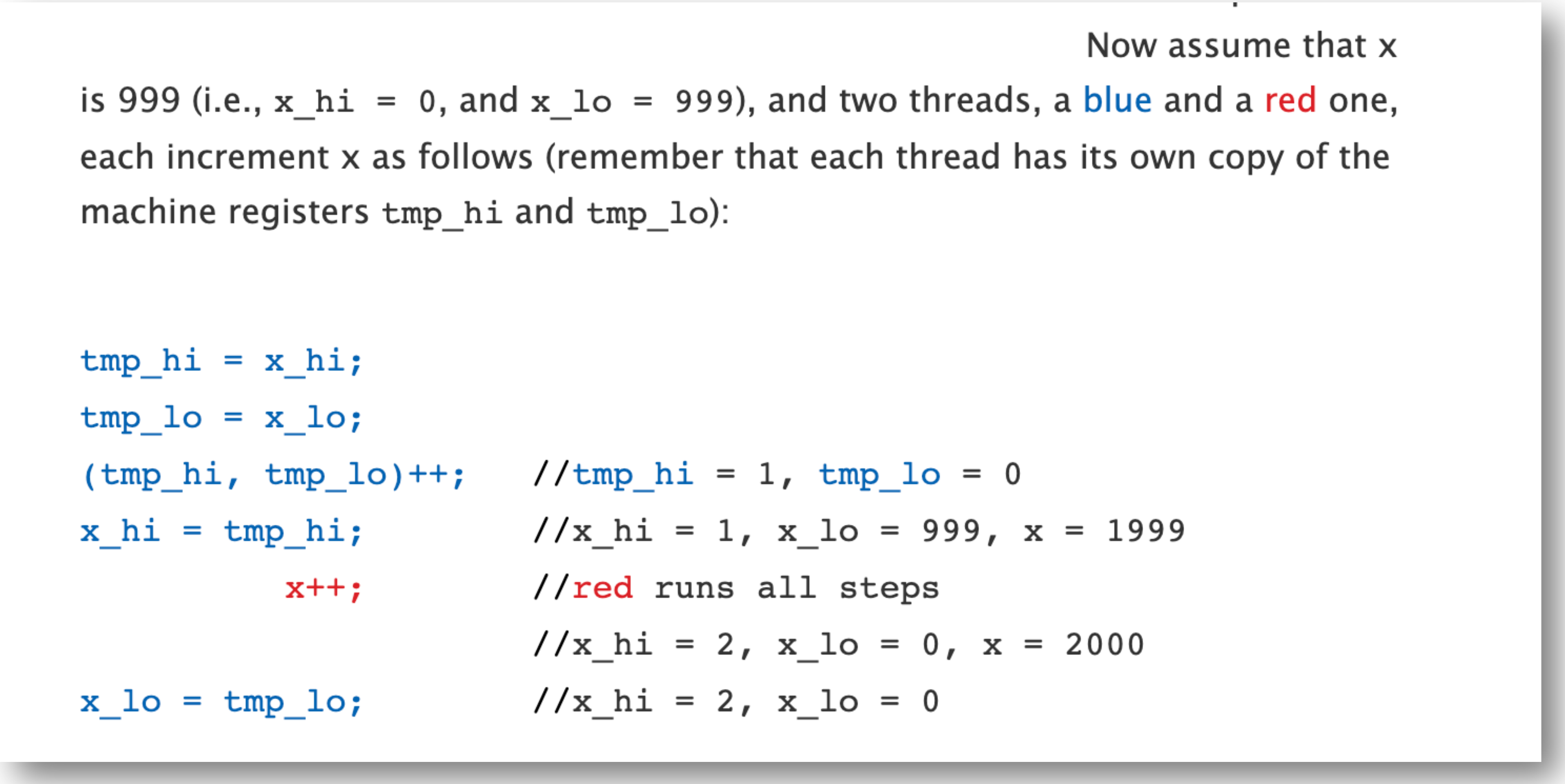
Data races are evil.

Hans-J. Boehm, HP Laboratories, Sarita V. Adve, University of Illinois at Urbana-Champaign



The final count can also be too high. Consider a case in which the count is bigger than a machine word. To avoid dealing with binary numbers, assume we have a decimal machine in which each word holds three digits, and the counter x can hold six digits. The compiler translates x++ to something like

```
tmp_hi = x_hi;
tmp_lo = x_lo;
(tmp_hi, tmp_lo)++;
x_hi = tmp_hi;
x_lo = tmp_lo;
```



Now assume that x is 999 (i.e., `x_hi = 0`, and `x_lo = 999`), and two threads, a blue and a red one, each increment x as follows (remember that each thread has its own copy of the machine registers `tmp_hi` and `tmp_lo`):

```
tmp_hi = x_hi;
tmp_lo = x_lo;
(tmp_hi, tmp_lo)++;    //tmp_hi = 1, tmp_lo = 0
x_hi = tmp_hi;         //x_hi = 1, x_lo = 999, x = 1999
          x++;         //red runs all steps
                       //x_hi = 2, x_lo = 0, x = 2000
x_lo = tmp_lo;         //x_hi = 2, x_lo = 0
```

Horrible data races in the real world

Therac 25: a radiation therapy machine

- Between 1987 and 1989 a software bug caused 6 cases where radiation was massively overdosed

- Patients were seriously injured and even died.

- Bug was root caused to be a data race.

- https://en.wikipedia.org/wiki/Therac-25

Horrible data races in the real world

2003 NE power blackout

- second largest power outage in history: 55 million people were effected
- NYC was without power for 2 days, estimated 100 deaths
- Root cause was a data race
- https://en.wikipedia.org/wiki/Northeast_blackout_of_2003

But checking for data conflicts is hard...

- Tools are here to help (Professor Flanagan is famous in this area)

- My previous group:
    - “Dynamic Race Detection for C++11” Lidbury and Donaldson
    - Scalable (complete) race detection
        - Firefox has ~40 data races
        - Chromium has ~6 data races

Next class

- Topics:
    - Restructuring loops

- Remember:
    - Homework 2 due tomorrow
    - Midterm due on Friday
    - Office hours tomorrow 3-5