Memory Prefetching

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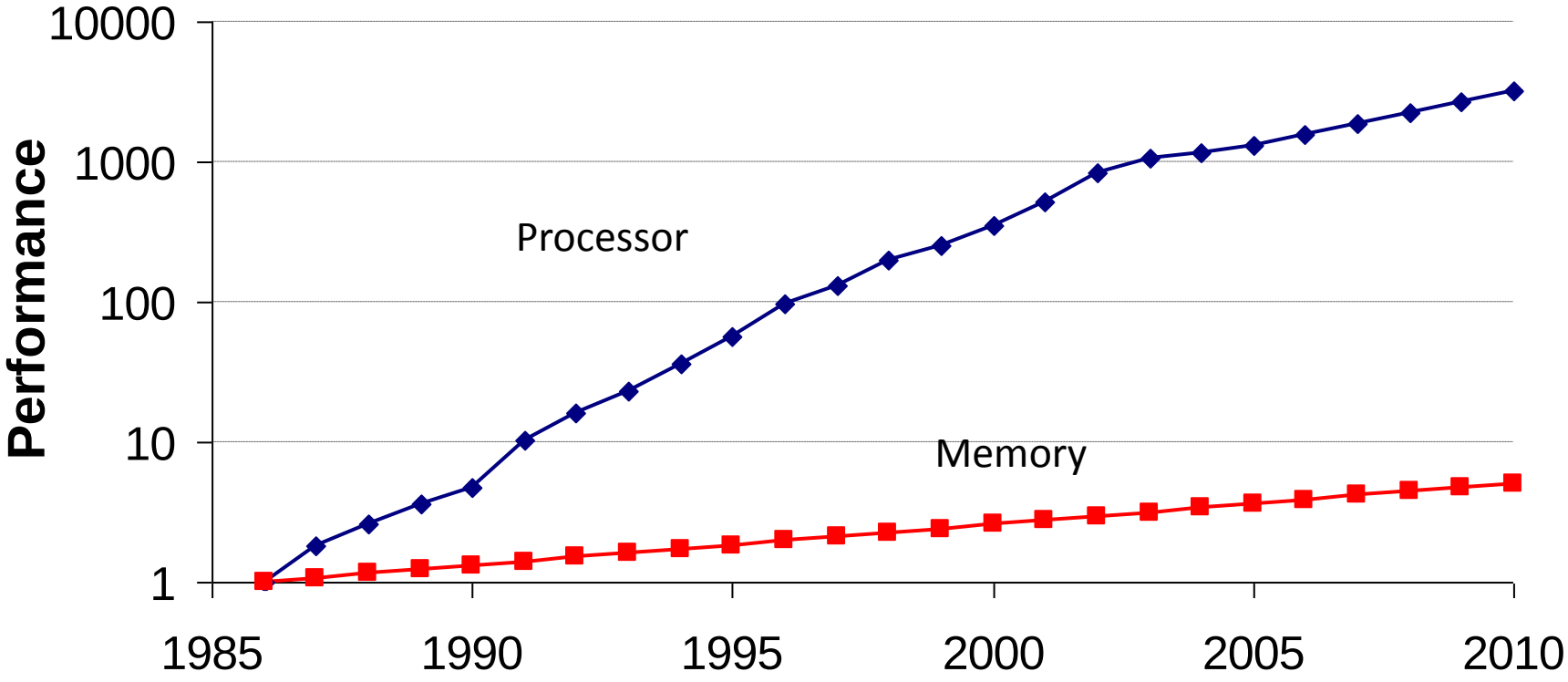
The memory wall



Source: Hennessy & Patterson, Computer Architecture: A Quantitative Approach, 4th ed.

Today: 1 mem access ≈ 500 arithmetic ops

How to reduce memory stalls for existing SW?

Techniques We've Seen So Far

- Use Caching
- Use wide out-of-order execution to hide memory latency
  - By overlapping misses with other execution
  - Cannot efficiently go much wider than several instructions
- Neither is enough for server applications
  - Not much spatial locality (mostly accessing linked data structures)
  - Not much ILP and MLP

  → Server apps spend 50-66% of their time stalled on memory

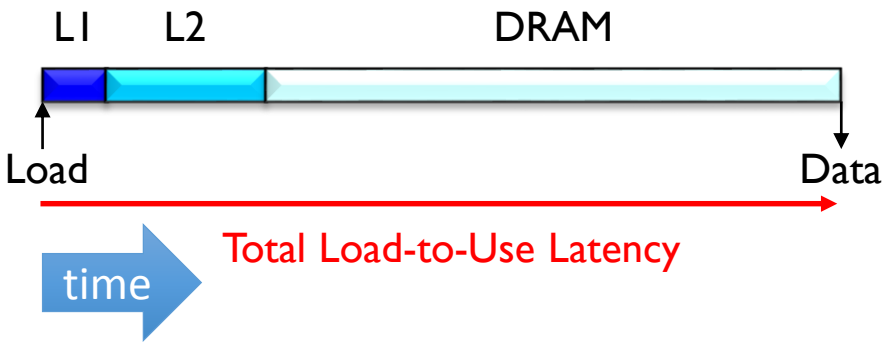
Need a different strategy

Prefetching (1/3)

- Fetch data ahead of ***demand***
- Big challenges:
  - Knowing "what" to fetch
    - Fetching useless blocks wastes resources
  - Knowing "when" to fetch
    - Too early → clutters storage (or gets thrown out before use)
    - Fetching too late → defeats purpose of "pre"-fetching

Prefetching (2/3)

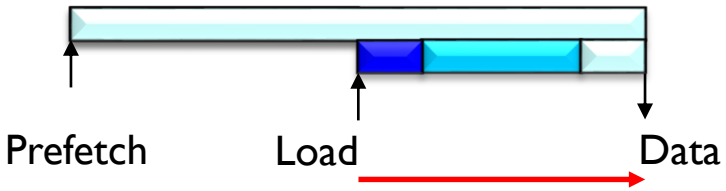
- Without prefetching:



- With prefetching:

Much improved Load-to-Use Latency

- Or:



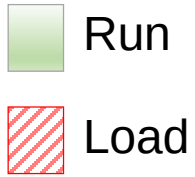
Somewhat improved Latency

Prefetching must be *accurate* and *timely*

Prefetching (3/3)

- Without prefetching:

- With prefetching:



Prefetching removes loads from critical path

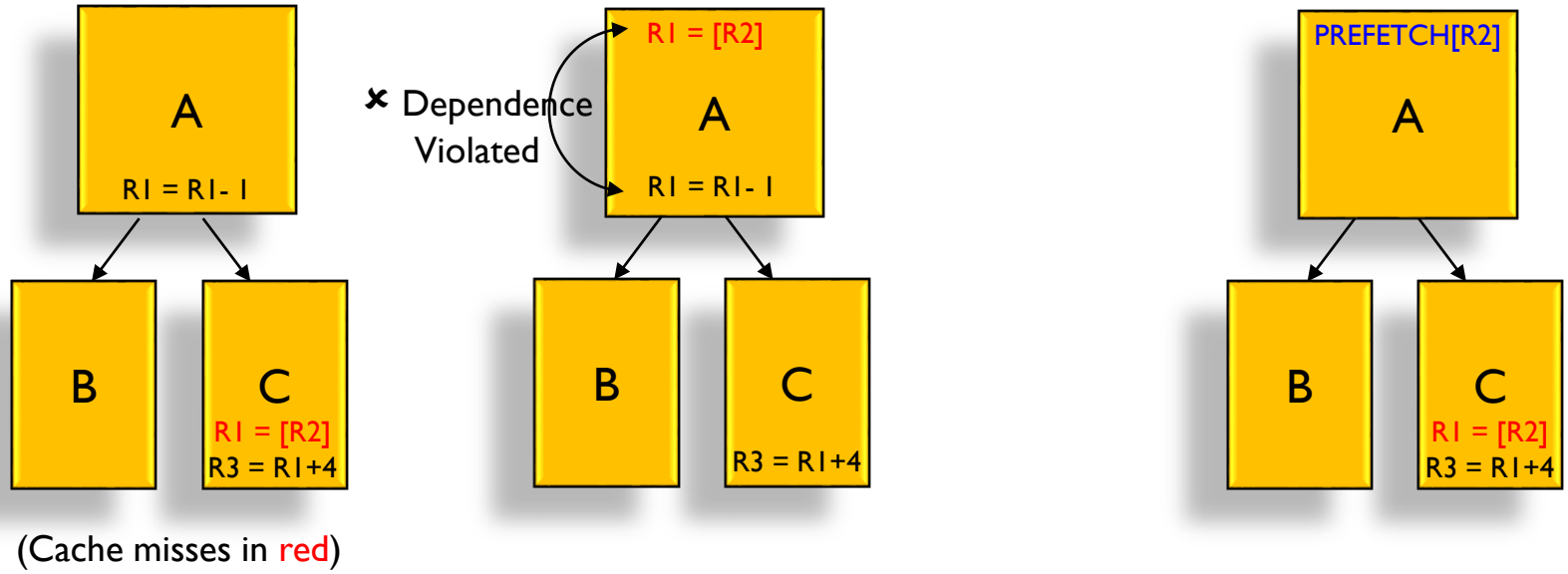
Common "Types" of Prefetching

- Software
  - By compiler
  - By programmer
- Hardware
  - Next-Line, Adjacent-Line
  - Next-N-Line
  - Stream Buffers
  - Stride
  - "Localized" (PC-based)
  - Pointer
  - Correlation

Software Prefetching (1/4)

- Prefetch data using explicit instructions
  - Inserted by compiler and/or programmer
- Put prefetched value into…
  - Register (binding, also called "*hoisting*")
    - Basically, just moving the load instruction up in the program
  - Cache (non-binding)
    - Requires ISA support
    - May get evicted from cache before demand

Software Prefetching (2/4)



(Cache misses in red)

- Hoisting is prone to many problems:
  - May prevent earlier instructions from committing
  - Must be aware of dependences
  - Must not cause exceptions not possible in the original execution
- Using a ***prefetch instruction*** can avoid all these problems

Software Prefetching (3/4)

```
for (I = 1; I < rows; I++)
{
    for (J = 1; J < columns; J++)
    {
        prefetch(&x[I+1,J]);
        sum = sum + x[I,J];
    }
}
```

Software Prefetching (4/4)

- Pros:
  - Gives programmer control and flexibility
  - Allows for complex (compiler) analysis
  - No (major) hardware modifications needed
- Cons:
  - Prefetch instructions increase code footprint
    - May cause more I$ misses, code alignment issues
  - Hard to perform timely prefetches
    - At IPC=2 and 100-cycle memory → move load 200 inst. earlier
    - Might not even have 200 inst. in current function
  - Prefetching earlier and more often leads to low accuracy
    - Program may go down a different path (block B in prev. slides)

Hardware Prefetching

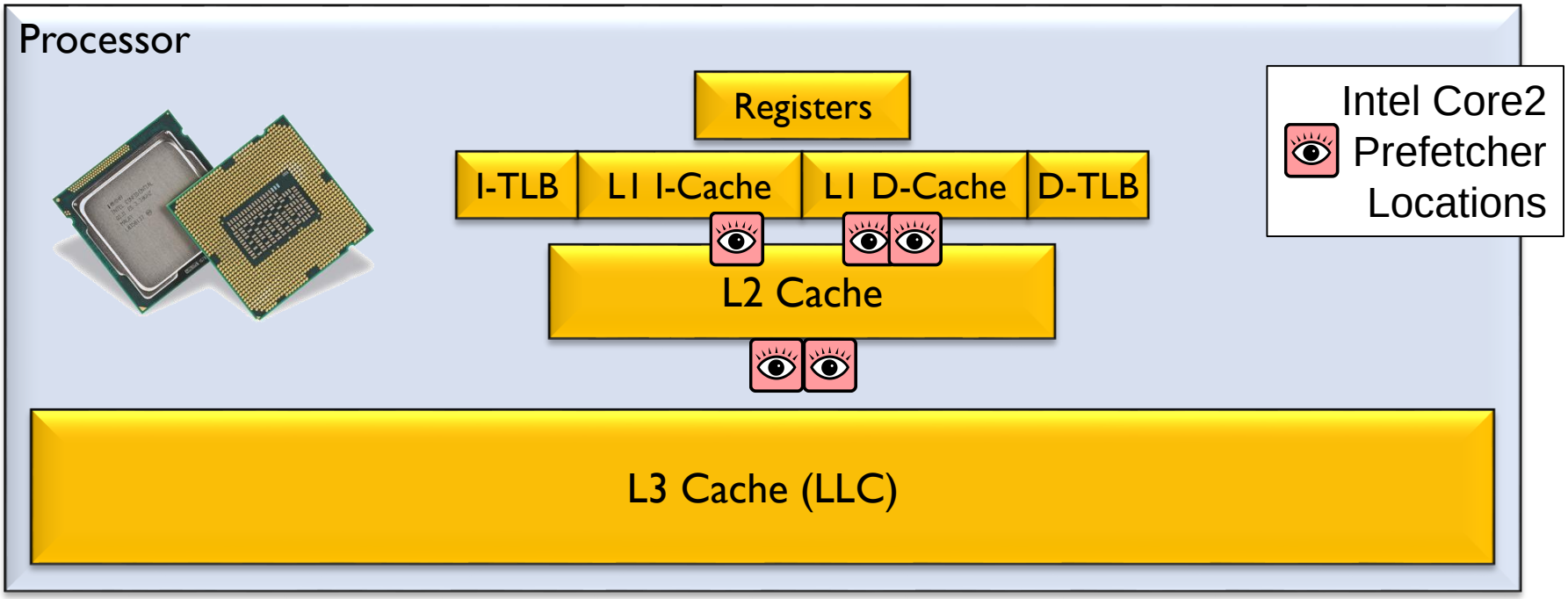
- Hardware monitors memory accesses
  - Looks for common patterns
- Guessed addresses are placed into ***prefetch queue***
  - Queue is checked when no demand accesses waiting
- Prefetchers look like READ requests to the mem. hierarchy
- Prefetchers trade bandwidth for latency
  - Extra bandwidth used ***only*** when guessing incorrectly
  - Latency reduced ***only*** when guessing correctly

No need to change software

Hardware Prefetcher Design Space

- What to prefetch?
  - Predictors regular patterns (x, x+8, x+16, …)
  - Predicted correlated patterns (A…B->C, B..C->J, A..C->K, …)
- When to prefetch?
  - On every reference → lots of lookup/prefetcher overhead
  - On every miss → patterns filtered by caches
  - On prefetched-data hits (positive feedback)
- Where to put prefetched data?
  - *Prefetch buffers*
  - Caches

Prefetching at Different Levels



- Real CPUs have multiple prefetchers w/ different strategies
  - Usually closer to the core (easier to detect patterns)
  - Prefetching at LLC is hard (cache is banked and hashed)

Next-Line (or Adjacent-Line) Prefetching

- On request for line X, prefetch X+1
  - Assumes spatial locality
    - Often a good assumption
  - Should stop at physical (OS) page boundaries (why?)
- Can often be done efficiently
  - Adjacent-line is convenient when next-level $ block is bigger
  - Prefetch from DRAM can use bursts and row-buffer hits
- Works for I$ and D$
  - Instructions execute sequentially
  - Large data structures often span multiple blocks

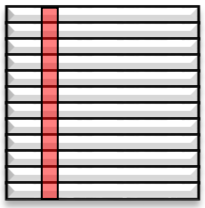
Simple, but usually not timely

Next-N-Line Prefetching

- On request for line X, prefetch X+1, X+2, …, X+N
  - N is called *"prefetch depth"* or *"prefetch degree"*
- Must carefully tune depth N. Large N is …
  - More likely to be useful (timely)
  - More aggressive → more likely to make a mistake
    - Might evict something useful
  - More expensive → need storage for prefetched lines
    - Might delay useful request on interconnect or port

Still simple, but more timely than Next-Line

Stride Prefetching (1/2)



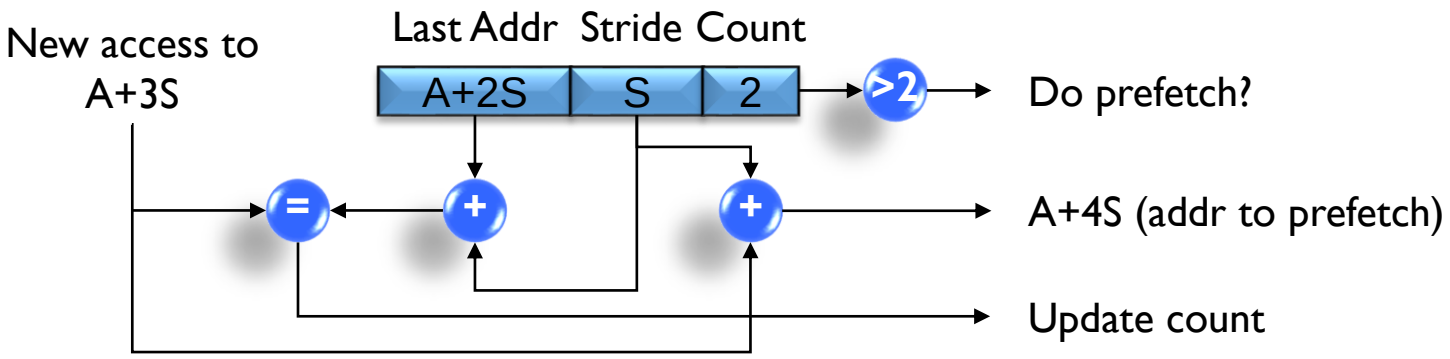
Column in matrix

Elements in array of `structs`

- Access patterns often follow a *stride*
  - Accessing column of elements in a matrix
  - Accessing elements in array of `structs`
- Detect stride S, prefetch depth N
  - Prefetch X+1·S, X+2·S, …, X+N·S

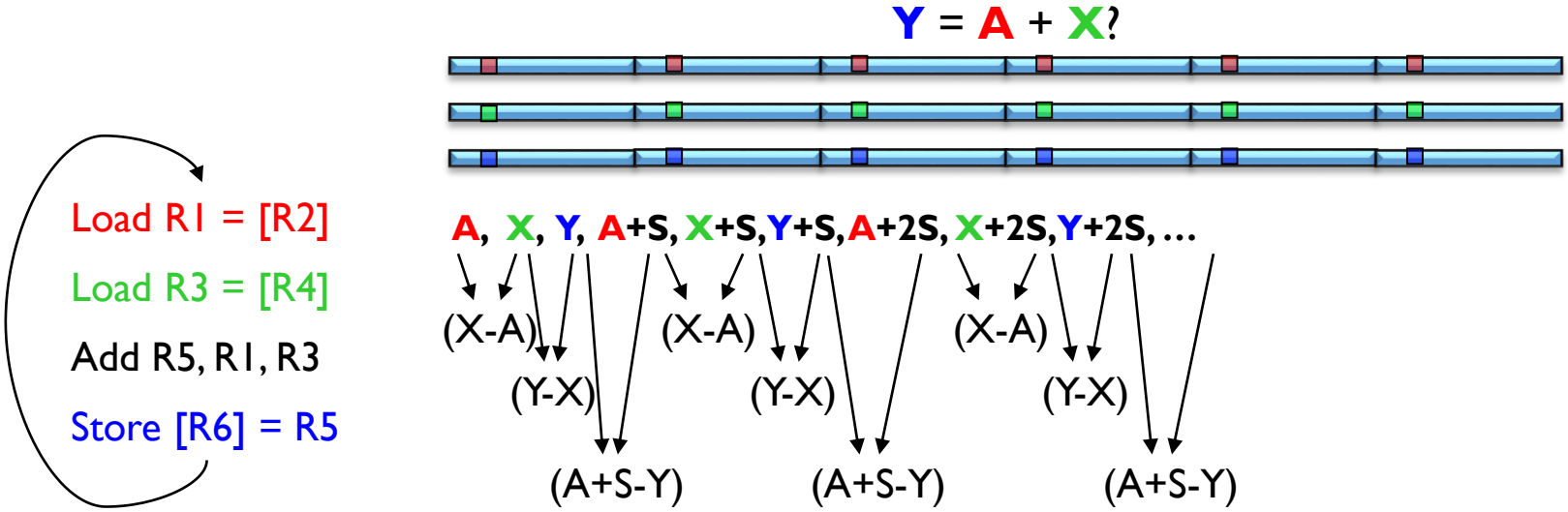
Stride Prefetching (2/2)

- Must carefully select depth N
  - Same constraints as Next-N-Line prefetcher
- How to tell the diff. between A[i] → A[i+1] and X → Y ?
  - Wait until you see the *same stride* a few times
  - Can vary prefetch depth based on confidence
    - More consecutive strided accesses → higher confidence



"Localized" Stride Prefetchers (1/2)

- What if multiple strides are interleaved?
  - No clearly-discernible stride

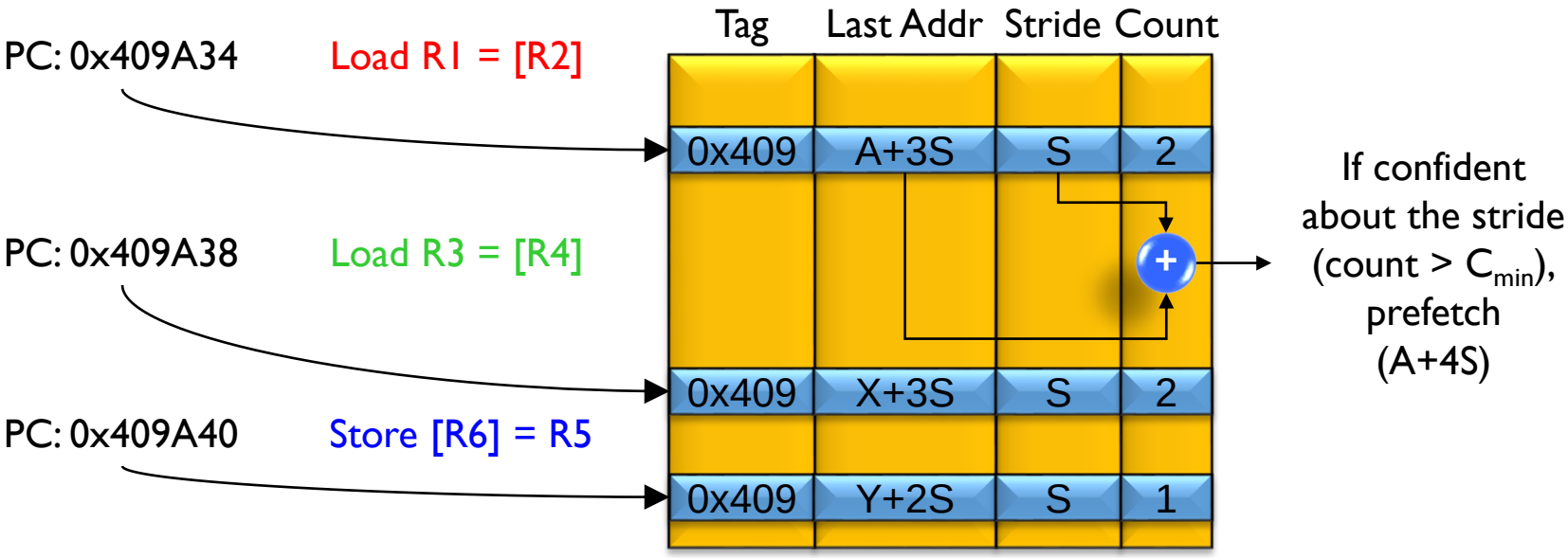


- Accesses to structures usually *localized* to an instruction

Use an array of strides, indexed by PC

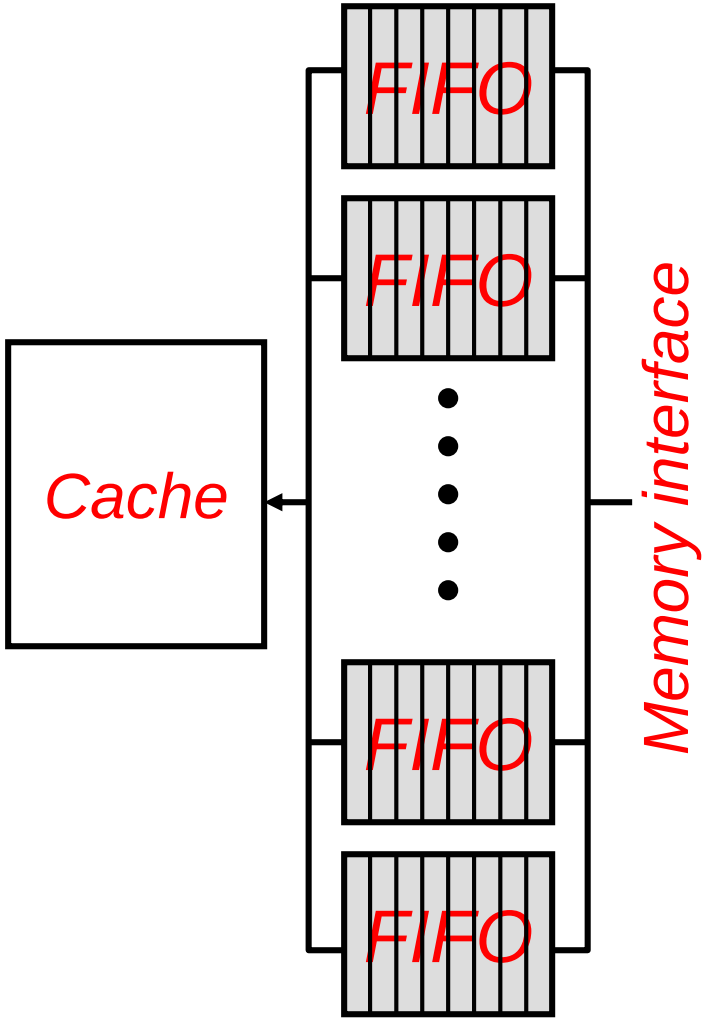
"Localized" Stride Prefetchers (2/2)

- Store PC, last address, last stride, and count in RPT
- On access, check *RPT (Reference Prediction Table)*
  - Same stride? → count++ if yes, count-- or count=0 if no
  - If count is high, prefetch (last address + stride)



Stream Buffers (1/2)

- Used to avoid cache pollution caused by deep prefetching
- Each SB holds one stream of sequentially prefetched lines
  - Keep next-N available in buffer
- On a load miss, check the head of all buffers
  - if match, pop the entry from FIFO, fetch the N+1st line into the buffer
  - if miss, allocate a new stream buffer (use LRU for recycling)

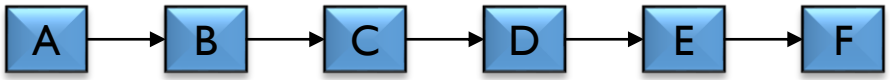


Stream Buffers (2/2)

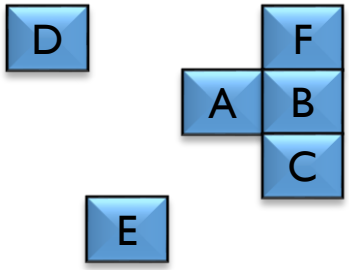
- FIFOs are continuously topped-off with subsequent cache lines
  - whenever there is room and the bus is not busy
- Can incorporate stride prediction mechanisms to support non-unit-stride streams
- Can extend to "quasi-sequential" stream buffer
  - On request Y in [X…X+N], advance by Y-X+1
  - Allows buffer to work when items are skipped
  - Requires expensive (associative) comparison

Other Patterns

- Sometimes accesses are regular, but no strides
  - Linked data structures (e.g., lists or trees)



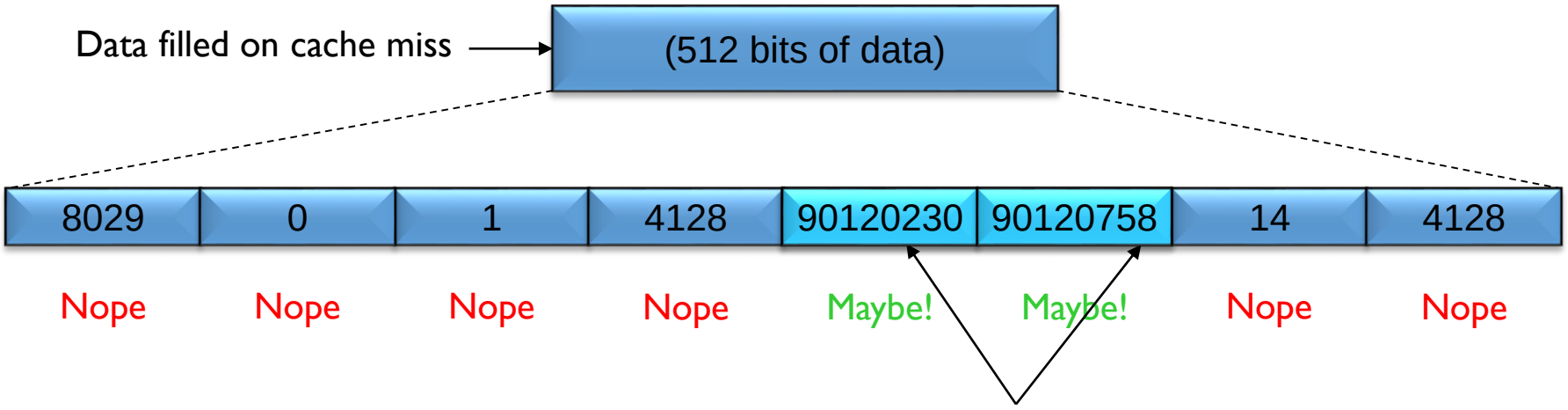
Linked-list traversal



Actual memory layout

(no chance to detect a stride)

Pointer Prefetching (1/2)



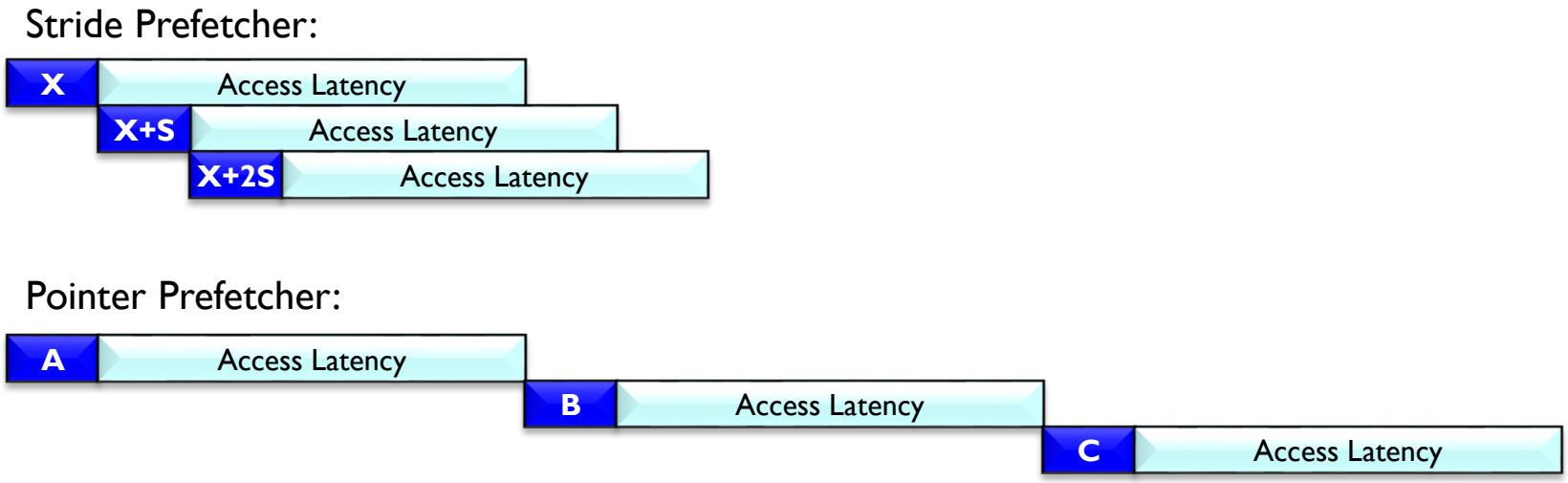

```
struct bintree_node_t {
    int data1;
    int data2;
    struct bintree_node_t * left;
    struct bintree_node_t * right;
};
```

This allows you to walk the tree
(or other pointer-based data structures
which are typically hard to prefetch)

Pointers usually "look different"

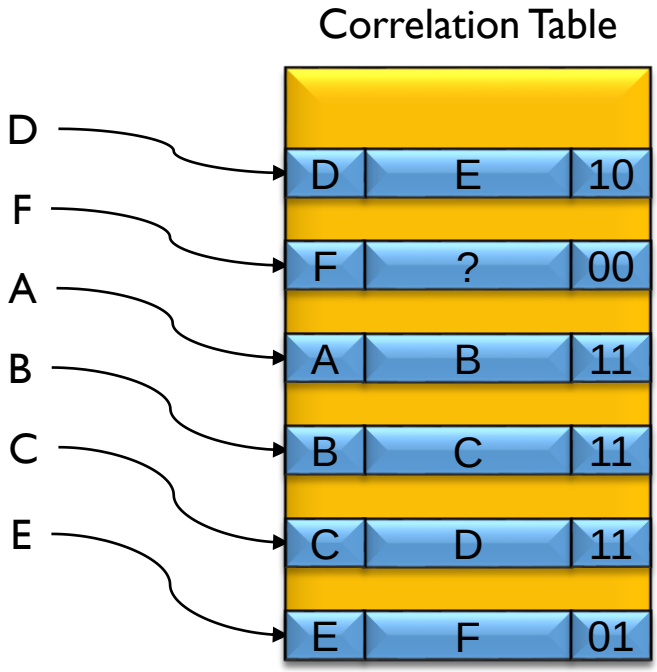
Pointer Prefetching (2/2)

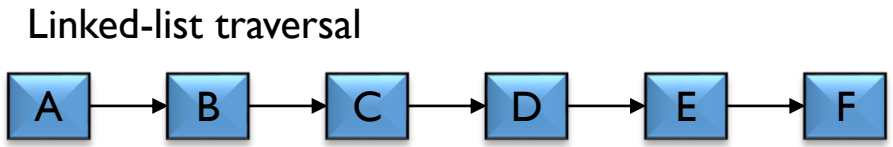
- Relatively cheap to implement
  - Don't need extra hardware to store patterns
- Limited *lookahead* makes timely prefetches hard
  - Can't get next pointer until fetched data block

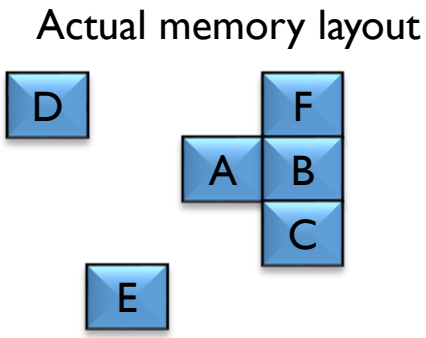


Pair-wise Temporal Correlation (1/2)

- Accesses exhibit *temporal correlation*
  - If E followed D in the past → if we see D, prefetch E
  - Somewhat similar to history-based branch prediction



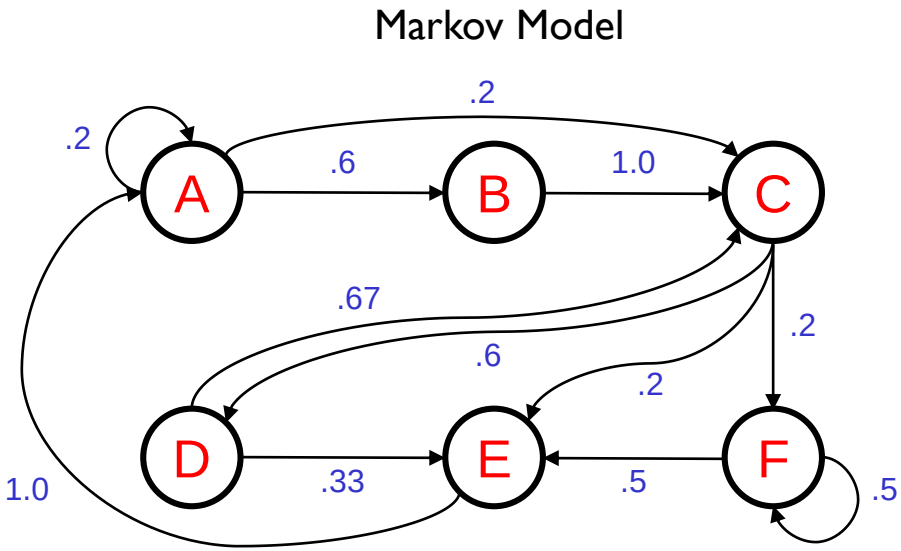


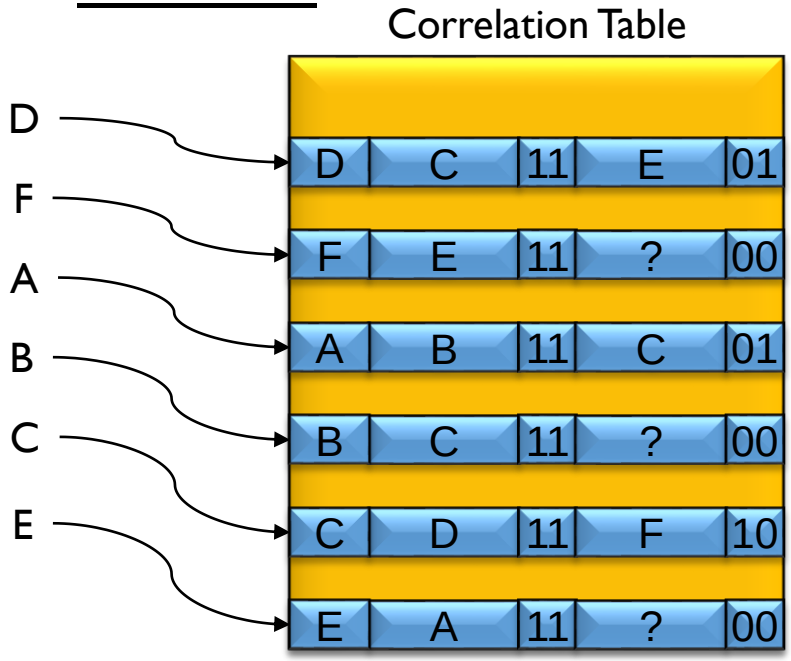


Can use recursively to get more lookahead ☺

Pair-wise Temporal Correlation (2/2)

- Many patterns more complex than linked lists
  - Can be represented by a "*Markov Model*"
  - Required tracking ***multiple*** potential successors
- Number of candidates is called *breadth*



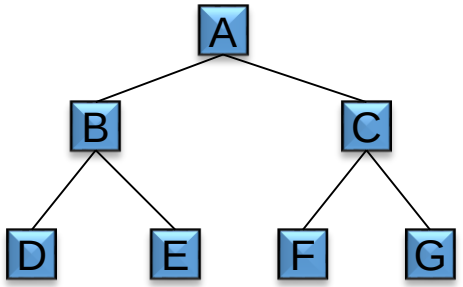


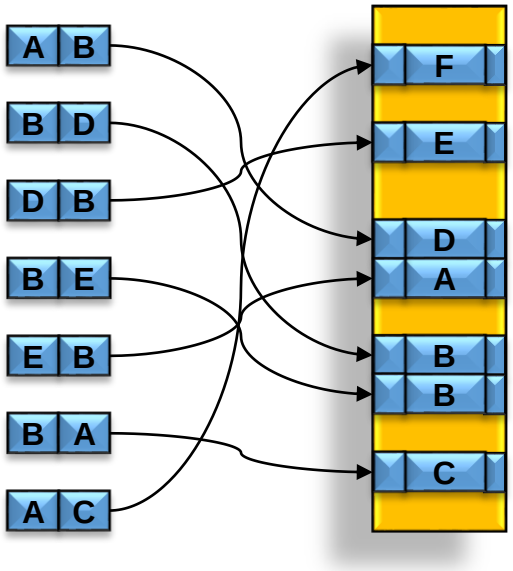
Recursive breadth & depth grows exponentially ☹

Increasing Correlation History Length

- Like branch prediction, longer history can provide more accuracy
  - And increases training time
- Use history hash for lookup
  - E.g., XOR the bits of the addrs of the last K accesses

DFS traversal: ABDBEBACFCGCA





Better accuracy ☺, larger storage cost ☹

Evaluating Prefetchers

- Compare against larger caches
  - Complex prefetcher vs. simple prefetcher + larger cache
- Primary metrics
  - *Coverage*: prefetched hits / base misses
  - *Accuracy*: prefetched hits / total prefetches
  - *Timeliness*: latency of prefetched blocks / hit latency
- Secondary metrics
  - *Pollution*: misses / (prefetched hits + base misses)
  - Bandwidth: total prefetches + misses / base misses
  - Power, Energy, Area...

What's Inside Today's Chips

- Data L1
  - PC-localized stride predictors
  - Short-stride predictors within block → prefetch next block
- Instruction L1
  - Predict future PC → prefetch
- L2
  - Stream buffers
  - Adjacent-line prefetch