Advanced Systems Lab

Spring 2020

Lecture: Memory hierarchy, locality, caches

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Organization

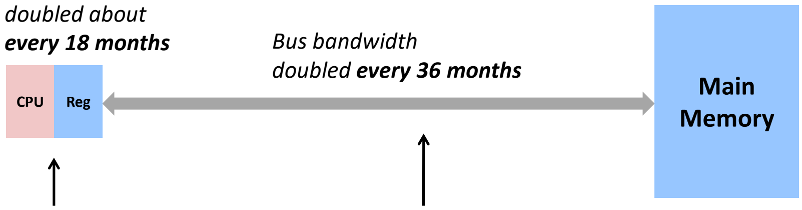
- **Temporal and spatial locality**
- **Memory hierarchy**
- **Caches**

Chapter 5 in ***Computer Systems: A Programmer's Perspective****, 2nd edition,*
Randal E. Bryant and David R. O'Hallaron, Addison Wesley 2010
Part of these slides are adapted from the course associated with this book

Problem: Processor-Memory Bottleneck

Processor performance doubled about ***every 18 months***

Bus bandwidth doubled ***every 36 months***

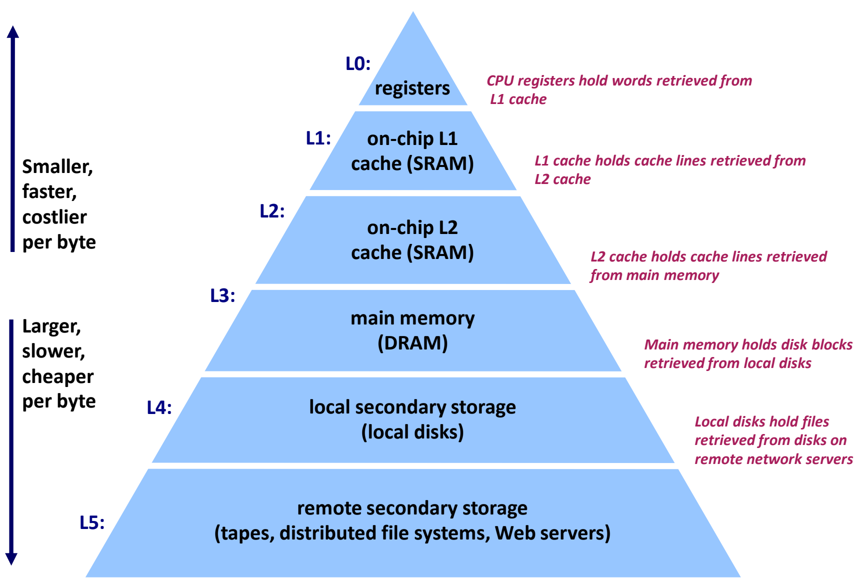


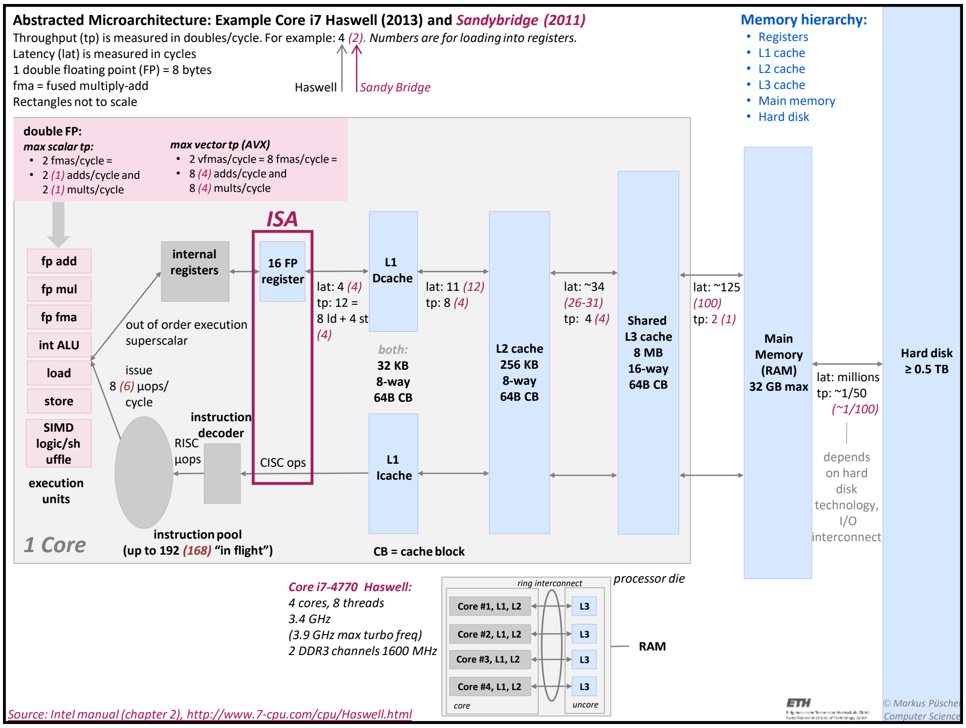
Core i7 Haswell:
Peak performance:
2 AVX three operand (FMA) ops/cycles
consumes up to 192 Bytes/cycle

Core i7 Haswell:
Bandwidth
16 Bytes/cycle

Solution: Caches/Memory hierarchy

Typical Memory Hierarchy

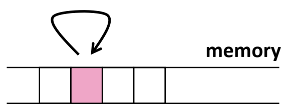




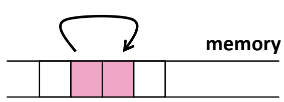
Why Caches Work: Locality

- ***Locality:*** **Programs tend to use data and instructions with addresses near or equal to those they have used recently**
  History of locality

- ***Temporal locality:***
  Recently referenced items are likely
  to be referenced again in the near future



- ***Spatial locality:***
  Items with nearby addresses tend
  to be referenced close together in time



6

Example: Locality?

```
sum = 0;
for (i = 0; i < n; i++)
  sum += a[i];
return sum;
```

- **Data:**
  - Temporal: **sum** referenced in each iteration
  - Spatial: array **a[]** accessed consecutively
- **Instructions:**
  - Temporal: loops cycle through the same instructions
  - Spatial: instructions referenced in sequence

- ***Being able to assess the locality of code is a crucial skill for a performance programmer***

Locality Example #1

```
int sum_array_rows(double a[M][N])
{
  int i, j, sum = 0;

  for (i = 0; i < M; i++)
    for (j = 0; j < N; j++)
      sum += a[i][j];
  return sum;
}
```

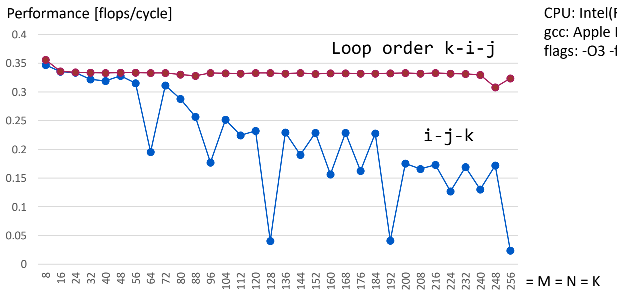
Locality Example #2

```
int sum_array_cols(double a[M][N])
{
  int i, j, sum = 0;

  for (j = 0; j < N; j++)
    for (i = 0; i < M; i++)
      sum += a[i][j];
  return sum;
}
```


Locality Example #3

```
int sum_array_3d(double a[K][M][N])
{
  int i, j, k, sum = 0;

  for (i = 0; i < M; i++)
    for (j = 0; j < N; j++)
      for (k = 0; k < K; k++)
        sum += a[k][i][j];
  return sum;
}
```

How to improve locality?



CPU: Intel(R) Core(TM) i7-4980HQ CPU @ 2.80GHz
gcc: Apple LLVM version 8.0.0 (clang-800.0.42.1)
flags: -O3 -fno-vectorize

Operational Intensity Again

- **Definition: Given a program P, assume cold (empty) cache**

$$\textit{Operational intensity: } I(n) = \frac{W(n)}{Q(n)}$$

W(n): #flops (input size n)

Q(n): #bytes transferred cache ↔ memory (for input size n)

- **Examples: Determine asymptotic bounds on I(n)**
  - Vector sum: y = x + y — **O(1)**
  - Matrix-vector product: y = Ax — **O(1)**
  - Fast Fourier transform — **O(log(n))**
  - Matrix-matrix product: C = AB + C — **O(n)**

11

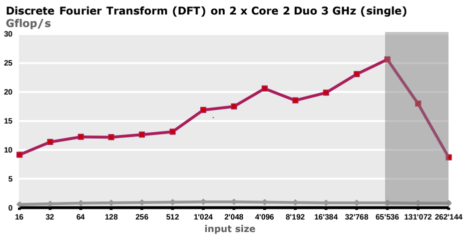
Compute/Memory Bound

- **A function/piece of code is:**
  - ***Compute bound*** if it has high operational intensity
  - ***Memory bound*** if it has low operational intensity
- **Relationship between operational intensity and locality?**
  - They are closely related
  - Operational intensity only describes the boundary last level cache/memory

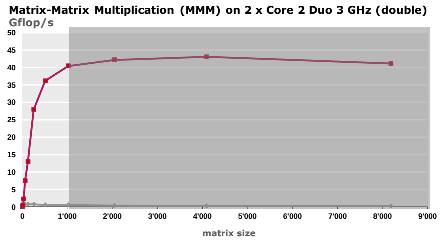
12

Effects

FFT: *I(n) = O(log(n))*



MMM: *I(n) = O(n)*



Up to 40-50% peak
Performance drop outside last level cache (LLC)
Most time spent transferring data

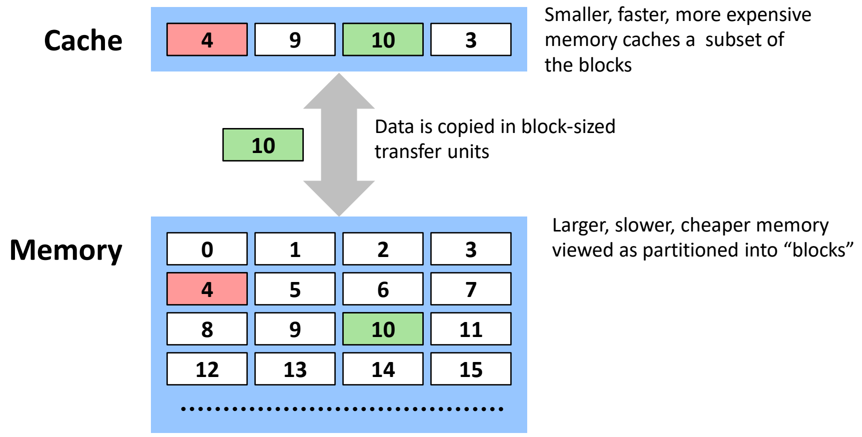
Up to 80-90% peak
Performance can be maintained outside LLC
Cache miss time compensated/hidden by computation

Cache

- ***Definition:*** **Computer memory with short access time used for the storage of frequently or recently used instructions or data**

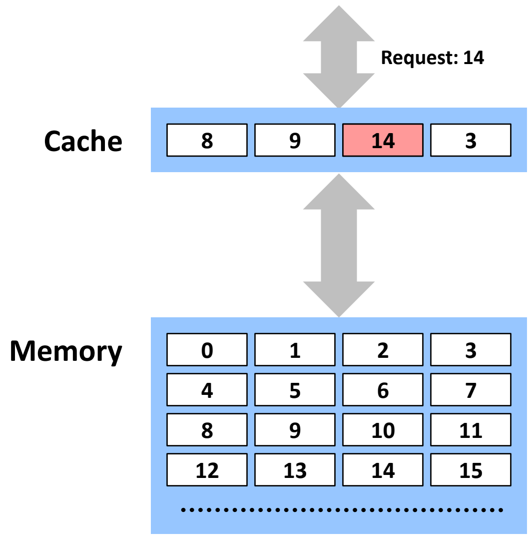
- **Naturally supports *temporal locality***
- ***Spatial locality* is supported by transferring data in blocks**
  - Core family: one block = 64 B = 8 doubles

General Cache Mechanics



15

General Cache Concepts: Hit

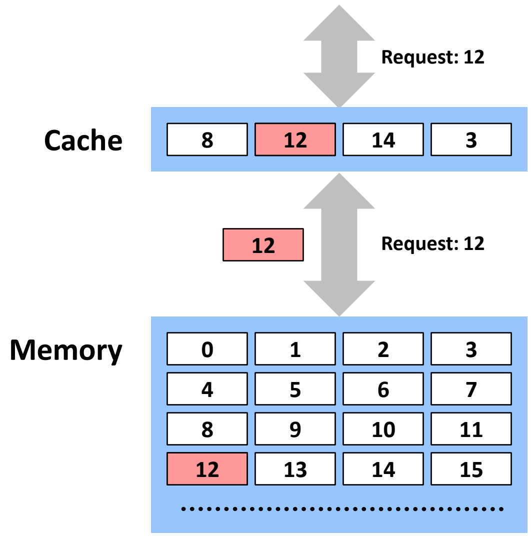


Data in block b is needed

Block b is in cache:
Hit!

16

General Cache Concepts: Miss



Data in block b is needed

Block b is not in cache:
Miss!

Block b is fetched from memory

Block b is stored in cache
- *Placement policy:* determines where b goes
- *Replacement policy:* determines which block gets evicted (victim)

17

Types of Cache Misses (The 3 C's)

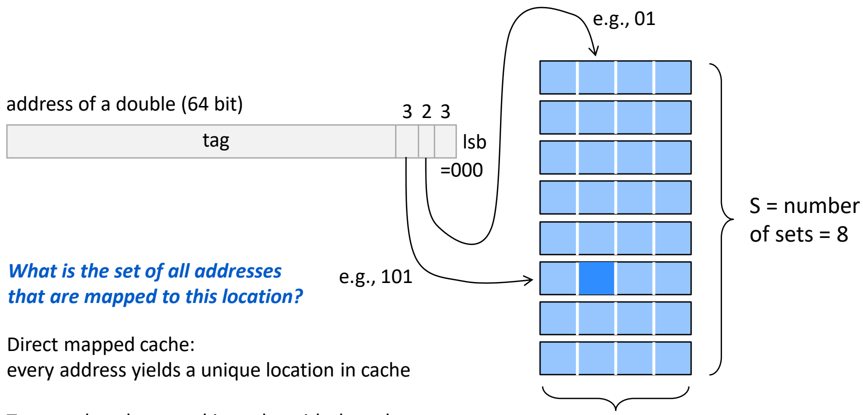
- ***Compulsory (cold)* miss**
  Occurs on first access to a block
- ***Capacity* miss**
  Occurs when working set is larger than the cache
- ***Conflict* miss**
  Conflict misses occur when the cache is large enough, but multiple data objects all map to the same slot

- **Not a clean classification but still useful**

18

Cache Structure

- **Example 1: direct mapped cache (E = 1, B = 4 doubles, S = 8)**



What is the set of all addresses that are mapped to this location?

Direct mapped cache:
every address yields a unique location in cache

Tag: needs to be stored in cache with the value to allow reconstruction of address

Always entire blocks (here 32 bytes) are loaded into cache

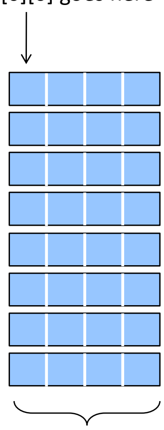
Example (S=8, E=1)

```
int sum_array_rows(double a[16][16])
{
  int i, j;
  double sum = 0;

  for (i = 0; i < 16; i++)
    for (j = 0; j < 16; j++)
      sum += a[i][j];
  return sum;
}
```

```
int sum_array_cols(double a[16][16])
{
  int i, j;
  double sum = 0;

  for (j = 0; j < 16; j++)
    for (i = 0; i < 16; i++)
      sum += a[i][j];
  return sum;
}
```

Ignore the variables sum, i, j

assume: cold (empty) cache,
a[0][0] goes here

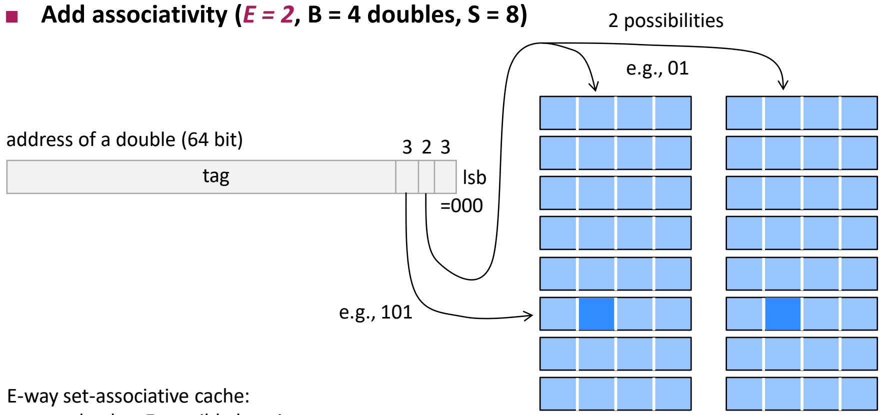


B = 32 byte = 4 doubles

How is the cache filled?

Cache Structure

- **Add associativity (*E = 2*, B = 4 doubles, S = 8)**



E-way set-associative cache:
every value has E possible locations

Usually, least recently used (LRU) is replaced

Always entire blocks (here 32 bytes) are loaded into cache

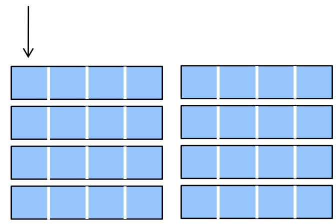
Example (S=4, E=2)

```
int sum_array_rows(double a[16][16])
{
  int i, j;
  double sum = 0;

  for (i = 0; i < 16; i++)
    for (j = 0; j < 16; j++)
      sum += a[i][j];
  return sum;
}
```

```
int sum_array_cols(double a[16][16])
{
  int i, j;
  double sum = 0;

  for (j = 0; j < 16; j++)
    for (i = 0; i < 16; i++)
      sum += a[i][j];
  return sum;
}
```

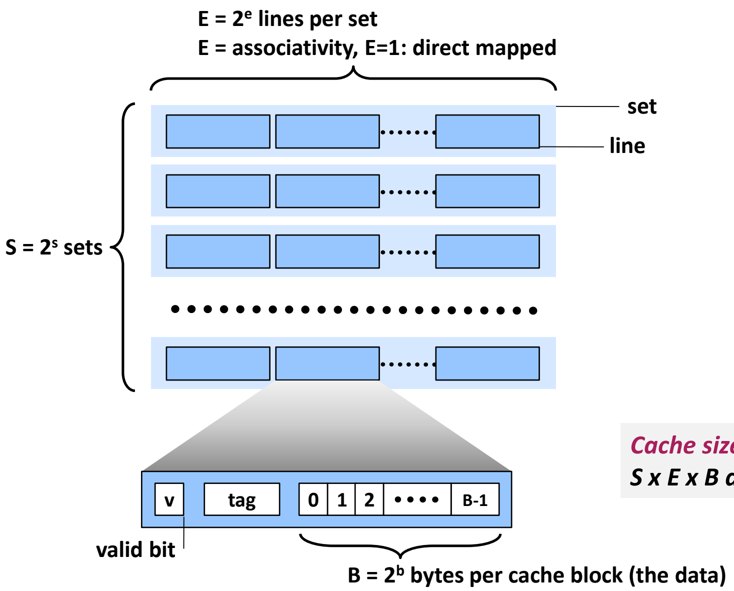
Ignore the variables sum, i, j

assume: cold (empty) cache,
a[0][0] goes here



How is the cache filled?

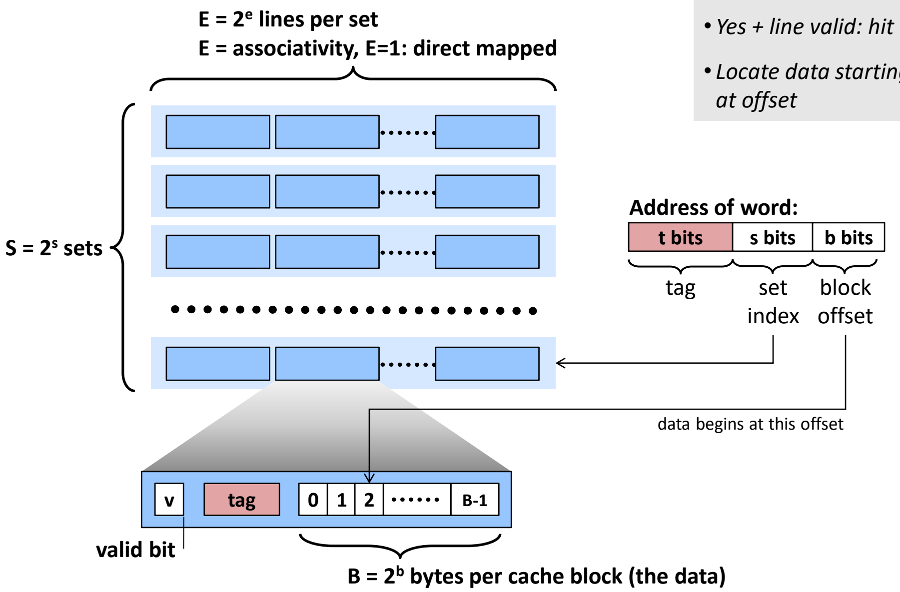
General Cache Organization (S, E, B)



Cache size:
S x E x B data bytes

Cache Read

- *Locate set*
- *Check if any line in set has matching tag*
- *Yes + line valid: hit*
- *Locate data starting at offset*



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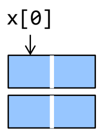
Terminology

- **Direct mapped cache:**
  - Cache with E = 1
  - Means every block from memory has a unique location in cache
- **Fully associative cache**
  - Cache with S = 1 (i.e., maximal E)
  - Means every block from memory can be mapped to any location in cache
  - In practice to expensive to build
  - One can view the register file as a fully associative cache
- **LRU (least recently used) replacement**
  - when selecting which block should be replaced (happens only for E > 1), the least recently used one is chosen

Small Example, Part 1



Cache:
E = 1 (direct mapped)
S = 2
B = 16 (2 doubles)

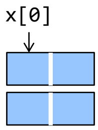
Array (accessed twice in example)
`x = x[0], …, x[7]`

```
% Matlab style code
for j = 0:1
  for i = 0:7
    access(x[i])
```

Access pattern: 0123456701234567
Hit/Miss: MHMHMHMHMHMHMHMH

Result: 8 misses, 8 hits
Spatial locality: yes
Temporal locality: no

Small Example, Part 2



Cache:
E = 1 (direct mapped)
S = 2
B = 16 (2 doubles)

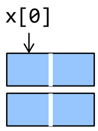
Array (accessed twice in example)
`x = x[0], …, x[7]`

```
% Matlab style code
for j = 0:1
  for i = 0:2:7
    access(x[i])
  for i = 1:2:7
    access(x[i])
```

Access pattern: 0246135702461357
Hit/Miss: MMMMMMMMMMMMMMMM

Result: 16 misses
Spatial locality: no
Temporal locality: no

Small Example, Part 3



Cache:
E = 1 (direct mapped)
S = 2
B = 16 (2 doubles)

Array (accessed twice in example)
`x = x[0], …, x[7]`

```
% Matlab style code
for j = 0:1
  for k = 0:1
    for i = 0:3
      access(x[i+4j])
```

Access pattern: 0123012345674567
Hit/Miss: MHMHHHHHMHMHHHHH

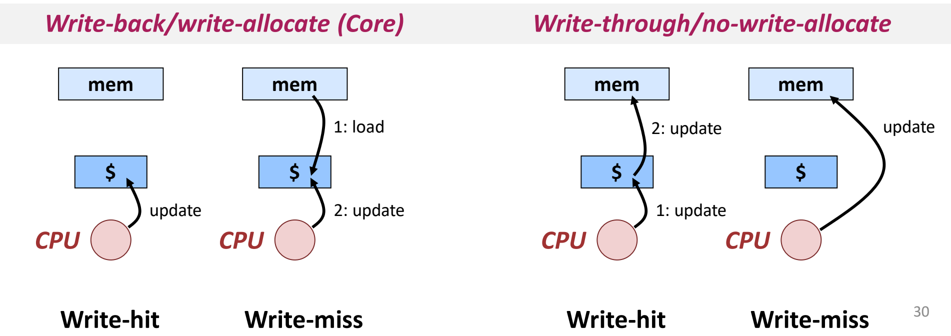
Result: 4 misses, 12 hits (is optimal, why?)
Spatial locality: yes
Temporal locality: yes

Cache Performance Metrics

- **Miss Rate**
  - Fraction of memory references not found in cache: misses / accesses
    = 1 – hit rate
- **Hit Time**
  - Time to deliver a block in the cache to the processor
  - Haswell:
    4 clock cycles for L1
    11 clock cycles for L2
- **Miss Penalty**
  - Additional time required because of a miss
  - Haswell: about 100 cycles for L3 miss

What about writes?

- **What to do on a write-hit?**
  - ***Write-through:*** write immediately to memory
  - ***Write-back:*** defer write to memory until replacement of line
- **What to do on a write-miss?**
  - ***Write-allocate:*** load into cache, update line in cache
  - ***No-write-allocate:*** writes immediately to memory



Example:

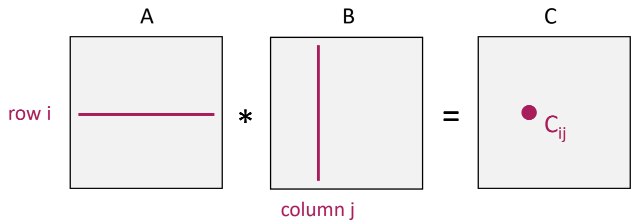
- **z = x + y, x, y, z vector of length n**
- **assume they fit jointly in cache + cold cache**
- **memory traffic Q(n):** 4n doubles = 32n bytes
- **operational intensity I(n)?** W(n) = n flops, so I(n) = W(n)/Q(n) = 1/32

Locality Optimization: Blocking

- **Example: MMM**

```
void mmm(double *A, double *B, double *C, int n) {

  for( int i = 0; i < n; i++ )
    for( int j = 0; j < n; j++ )
      for( int k = 0; k < n; k++ )
        C[n*i + j] = C[n*i + j] + A[n*i + k] * B[n*k + j]; }
```

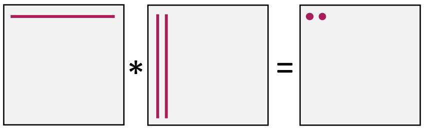


Cache Miss Analysis MMM

C = A*B, all n x n

Assumptions: cache size γ << n, cache block: 8 doubles, only 1 cache

Triple loop:

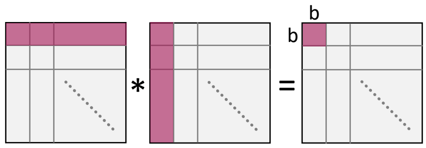


1. entry: n/8 + n = 9n/8 cache misses

2. entry: same

Total: $n^2 * 9n/8 = 9n^3/8$

Blocked (six-fold loop): block size b, 8 divides b



1. block: nb/8 + nb/8 = nb/4 cache misses

2. block: same

Total: $(n/b)^2 * nb/4 = n^3/(4b)$

How to choose b?
The above analysis assumes that the multiplication of b x b blocks can be done with only compulsory misses. This requires $3b^2 \le \gamma$.

b = sqrt(γ/3) which yields about sqrt(3)/(4*sqrt(γ)) * n^3 cache misses, a gain of ≈ 2.6*sqrt(γ)

On Previous Slide

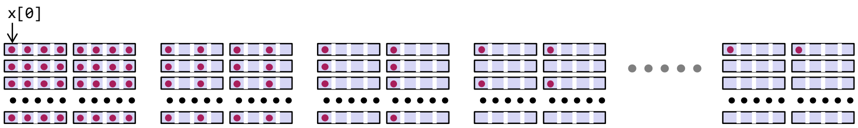
- **Refine the analysis by including the misses incurred by C**
- **Compute the operational intensity in both cases**
- **Try an analogous analysis for matrix-vector multiplication**

The Killer: Two-Power Strided Working Sets

```
% t = 1,2,4,8,… a 2-power
% size W of working set: W = n/t
for (i = 0; i < n; i += t)
  access(x[i])
for (i = 0; i < n; i += t)
  access(x[i])
```

Cache: E = 2, B = 4 doubles

t = 1: **t = 2:** **t = 4:** **t = 8:** **t ≥ 4S:**



t = 1	t = 2	t = 4	t = 8	t ≥ 4S
Spatial locality Temporal locality: if W ≤ C	Some spatial locality Temporal locality: if W ≤ C/2	No spatial locality Temporal locality: if W ≤ C/4	No spatial locality Temporal locality: if W ≤ C/8	No spatial locality Temporal locality: if W ≤ 2

Working with a two-power-strided working set is like having a smaller cache

The Killer: Where Can It Occur?

- **Accessing two-power size 2D arrays (e.g., images) columnwise**
  - 2d Transforms
  - Stencil computations
  - Correlations
- **Various transform algorithms**
  - Fast Fourier transform
  - Wavelet transforms
  - Filter banks

Summary

- **It is important to assess temporal and spatial locality in the code**
- **Cache structure is determined by three parameters**
  - block size
  - number of sets
  - associativity
- **You should be able to roughly simulate a computation on paper**
- **Blocking to improve locality**
- **Two-power strides are problematic (conflict misses)**