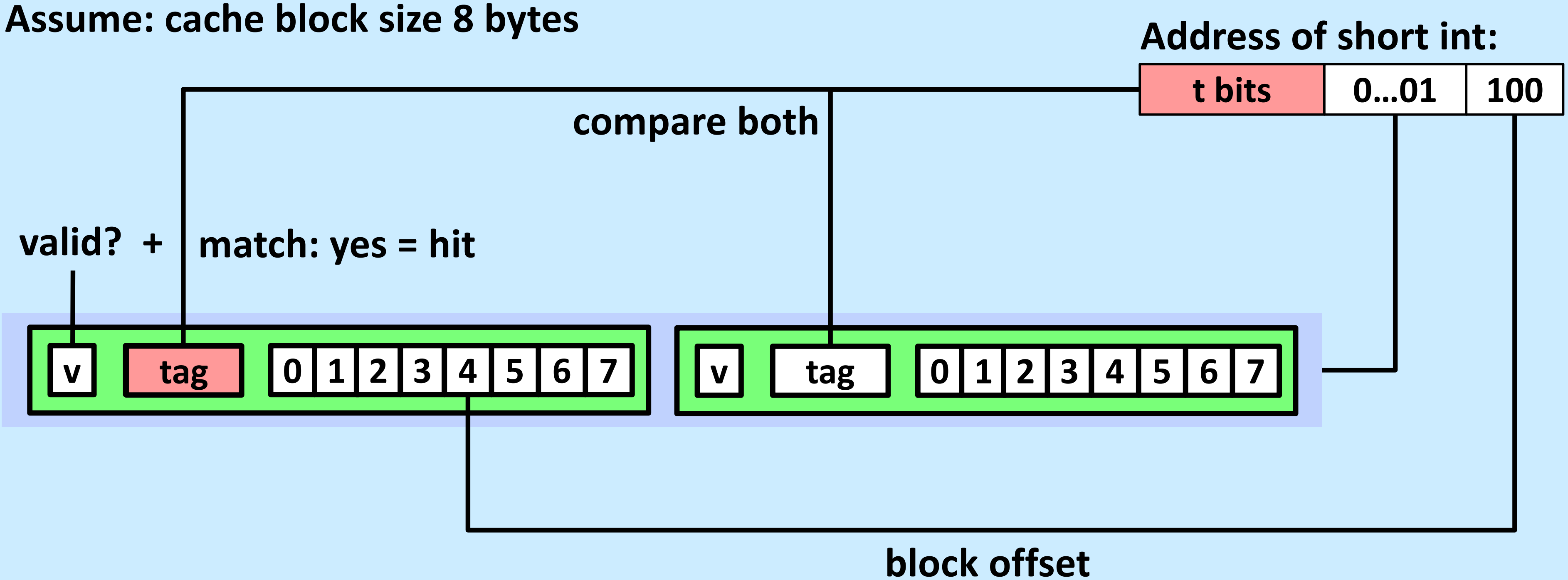
CS 33

Exploiting Caches

E-way Set-Associative Cache (Here: E = 2)

E = 2: two lines per set

Assume: cache block size 8 bytes



E-way Set-Associative Cache (Here: E = 2)

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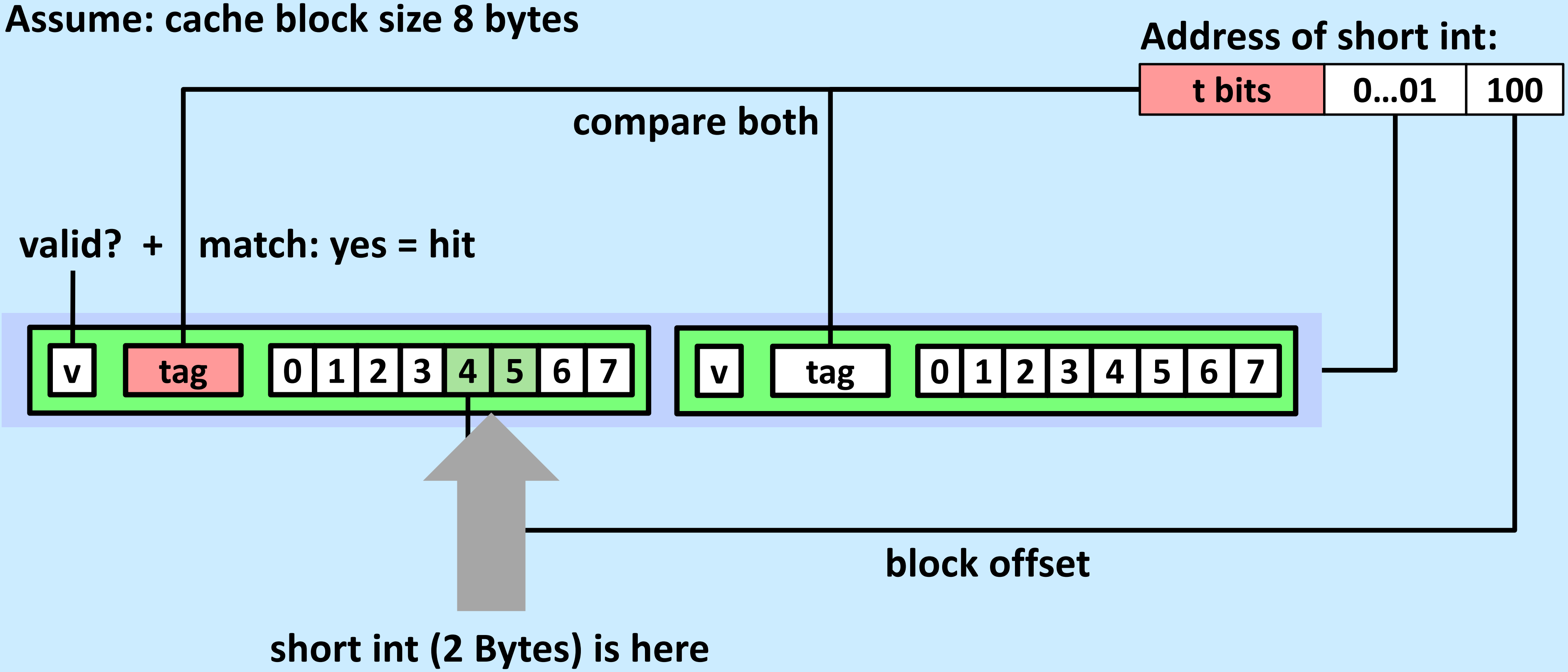

No match:

- One line in set is selected for eviction and replacement
- Replacement policies: random, least recently used (LRU), …

Quiz 1

Address of int:

100	01	100

0	v	tag=0	*0 0 0 0 1 1 1 1*	v	tag=2	*2 2 2 2 3 3 3 3*
1	v	tag=0	*4 4 4 4 5 5 5 5*	v	tag=4	*6 6 6 6 7 7 7 7*
2	v	tag=2	*8 8 8 8 9 9 9 9*	v	tag=3	*a a a a b b b b*
3	v	tag=4	*c c c c d d d d*	v	tag=a	*e e e e f f f f*

Given the address above and the cache contents as shown, what is the value of the *int* at the given address?

a) 1111
b) 3333
c) 4444
d) 7777

2-Way Set-Associative Cache Simulation

t=2	s=1	b=1
xx	x	x

M=16 byte addresses, B=2 bytes/block,
S=2 sets, E=2 blocks/set

Address trace (reads, one byte per read):

0	**$[00\underline{0}0_2]$,**	miss
1	**$[00\underline{0}1_2]$,**	hit
7	**$[01\underline{1}1_2]$,**	miss
8	**$[10\underline{0}0_2]$,**	miss
0	**$[00\underline{0}0_2]$**	hit

	v	**Tag**	**Block**
Set 0	1	00	M[0-1]
	1	10	M[8-9]
Set 1	1	01	M[6-7]
	0		

A Higher-Level Example

Ignore the variables sum, i, j

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

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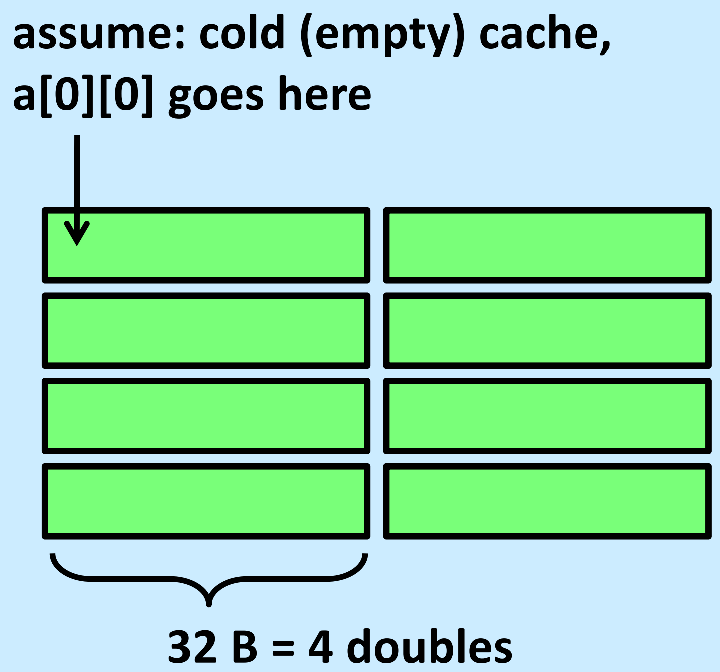
            sum += a[i][j];
    return sum;
}
```



A Higher-Level Example

Ignore the variables sum, i, j

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int sum_array_rows(double a[16][16])
{
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    double sum = 0;

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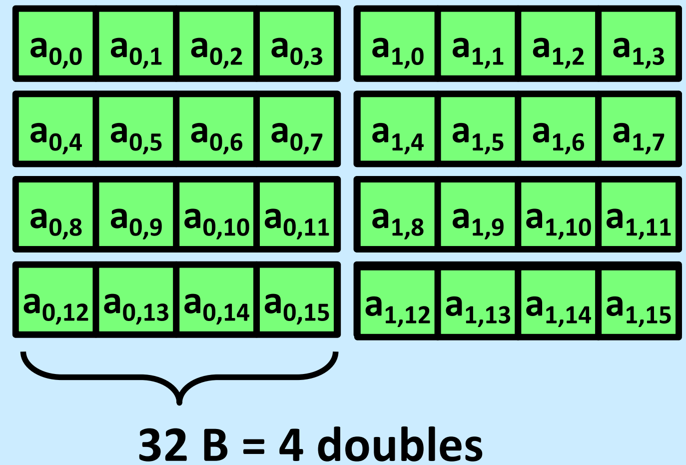
    return sum;
}
```




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

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

A Higher-Level Example

Ignore the variables sum, i, j

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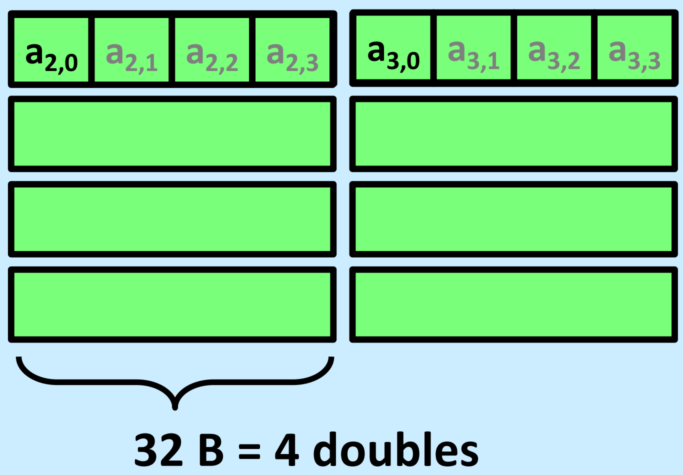
    for (i = 0; i < 16; i++)
        for (j = 0; j < 16; j++)
            sum += a[i][j];
    return sum;
}
```

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

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

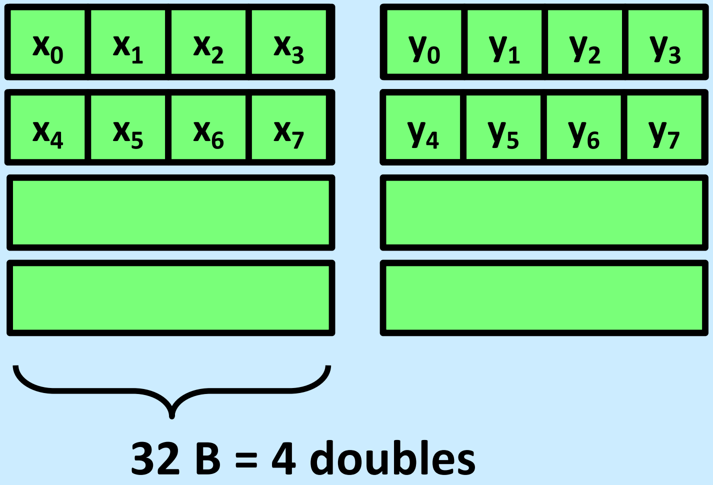


Conflict Misses

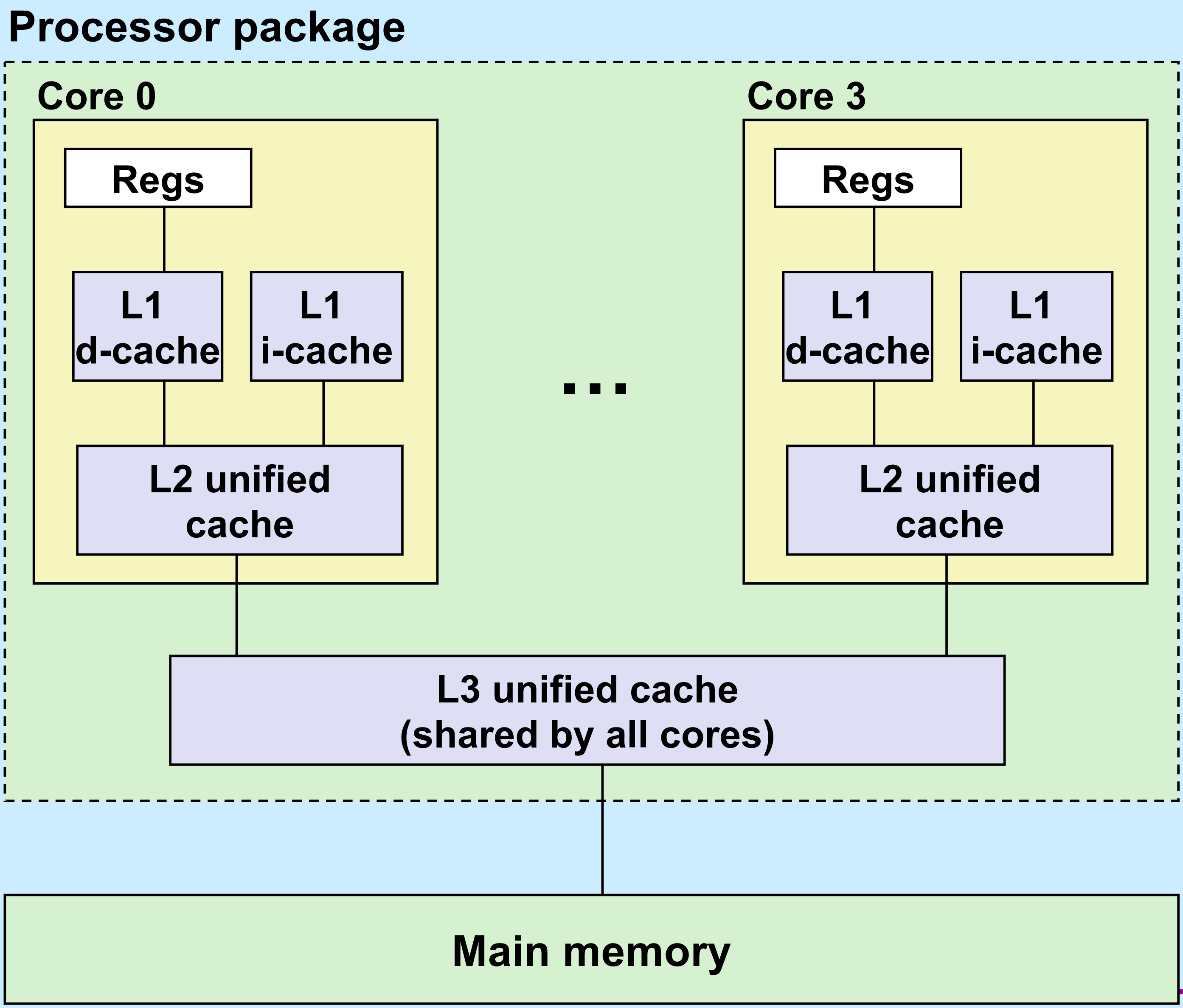
```
double dotprod(double x[8], double y[8]) {
  double sum = 0.0;
  int i;

  for (i=0; i<8; i++)
    sum += x[i] * y[i];

  return sum;
}
```



Intel Core i5 and i7 Cache Hierarchy



L1 i-cache and d-cache:
32 KB, 8-way,
Access: 4 cycles

L2 unified cache:
256 KB, 8-way,
Access: 11 cycles

L3 unified cache:
8 MB, 16-way,
Access: 30-40 cycles

Block size: 64 bytes for all caches

What About Writes?

- Multiple copies of data exist:
  - L1, L2, main memory, disk
- What to do on a write-hit?
  - write-through (write immediately to memory)
  - write-back (defer write to memory until replacement of line)
    - » need a dirty bit (line different from memory or not)
- What to do on a write-miss?
  - write-allocate (load into cache, update line in cache)
    - » good if more writes to the location follow
  - no-write-allocate (writes immediately to memory)
- Typical
  - write-through + no-write-allocate
  - write-back + write-allocate

Accessing Memory

- **Program references memory (load)**
  - if not in cache (*cache miss*), data is requested from RAM
    - » fetched in units of 64 bytes
      - aligned to 64-byte boundaries (low-order 6 bits of address are zeroes)
    - » if memory accessed sequentially, data is pre-fetched
    - » data stored in cache (in 64-byte *cache lines*)
      - stays there until space must be re-used (least recently used is kicked out first)
  - if in cache (*cache hit*) no access to RAM needed
- **Program modifies memory (store)**
  - data modified in cache
  - eventually written to RAM in 64-byte units

Cache Performance Metrics

- **Miss rate**
  - fraction of memory references not found in cache
    (misses / accesses)
    = 1 – hit rate
  - typical numbers (in percentages):
    - » 3-10% for L1
    - » can be quite small (e.g., < 1%) for L2, depending on size, etc.
- **Hit time**
  - time to deliver a line in the cache to the processor
    - » includes time to determine whether the line is in the cache
  - typical numbers:
    - » 1-2 clock cycles for L1
    - » 5-20 clock cycles for L2
- **Miss penalty**
  - additional time required because of a miss
    - » typically 50-200 cycles for main memory (trend: increasing!)

Hits vs. Misses

- Huge difference between hit and miss times
  - could be 100x, if just L1 and main memory
- 99% hit rate is twice as good as 97%!
  - consider:
    cache hit time of 1 cycle
    miss penalty of 100 cycles
  - average access time:

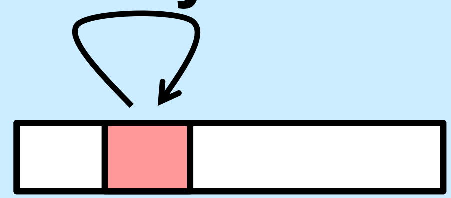
    97% hits: .97 * 1 cycle + 0.03 * 100 cycles ≈ 4 cycles

    99% hits: .99 * 1 cycle + 0.01 * 100 cycles ≈ 2 cycles

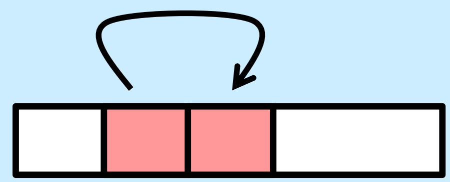
- This is why "miss rate" is used instead of "hit rate"

Locality

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



- **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

Locality Example

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

- **Data references**
  - reference array elements in succession (stride-1 reference pattern) — Spatial locality
  - reference variable `sum` each iteration — Temporal locality
- **Instruction references**
  - reference instructions in sequence. — Spatial locality
  - cycle through loop repeatedly — Temporal locality

Quiz 2

Does this function have good locality with respect to array `a`? The array a is MxN.

a) yes

b) no

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

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

Writing Cache-Friendly Code

- **Make the common case fast**
  - focus on the inner loops of the core functions

- **Minimize the misses in the inner loops**
  - repeated references to variables are good (temporal locality)
  - stride-1 reference patterns are good (spatial locality)

Matrix Multiplication Example

- **Description:**
  - multiply N x N matrices
    - » each element is a double
  - $O(N^3)$ total operations
  - N reads per source element
  - N values summed per destination
    - » but may be able to hold in register

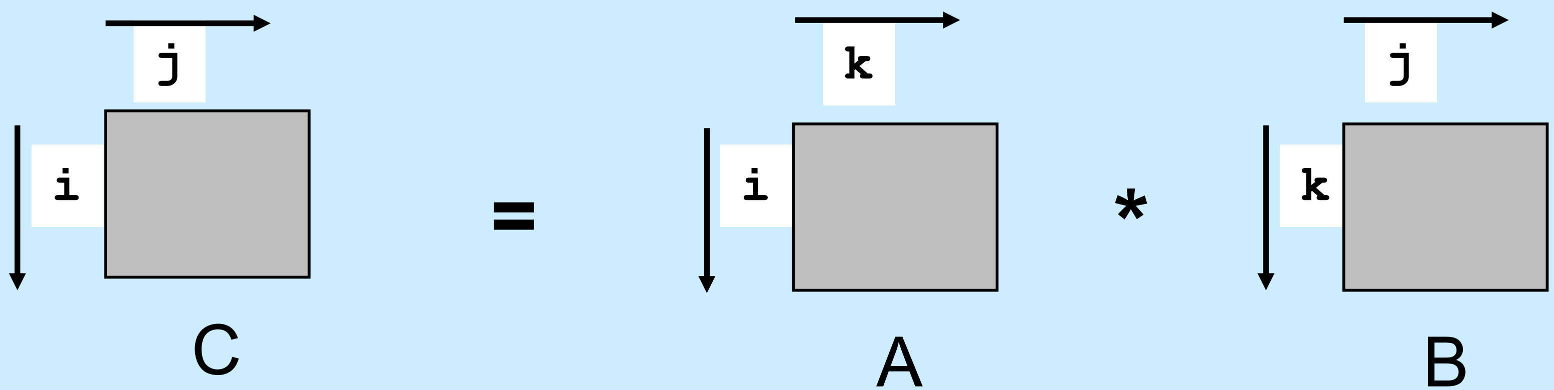
Variable **sum** *held in register*

```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

```
/* ikj */
for (i=0; i<n; i++) {
  for (k=0; k<n; k++) {
    r = a[i][k];
    for (j=0; j<n; j++)
      c[i][j] += r * b[k][j];
  }
}
```

Miss-Rate Analysis for Matrix Multiply

- **Assume:**
  - Block size = 64B (big enough for eight doubles)
  - matrix dimension (N) is very large
  - cache is not big enough to hold multiple rows
- **Analysis method:**
  - look at access pattern of inner loop



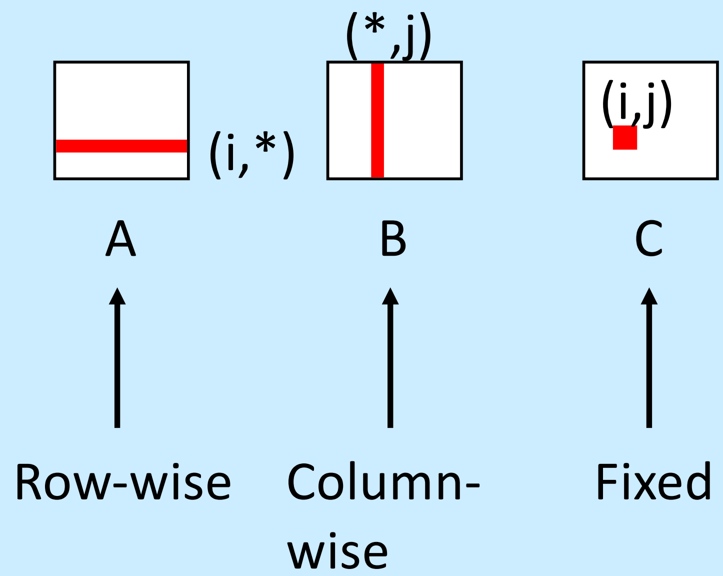
Layout of C Arrays in Memory (review)

- C arrays allocated in row-major order
  - each row in contiguous memory locations
- Stepping through columns in one row:
  - ```
    for (i = 0; i < N; i++)
      sum += a[0][i];
    ```
  - accesses successive elements
  - if block size (B) > 8 bytes, exploit spatial locality
    - » compulsory miss rate = 8 bytes / Block
- Stepping through rows in one column:
  - ```
    for (i = 0; i < n; i++)
      sum += a[i][0];
    ```
  - accesses widely separated elements
  - no spatial locality!
    - » compulsory miss rate = 1 (i.e. 100%)

Matrix Multiplication (ijk)

```
/* ijk */
for (i=0; i<n; i++)  {
  for (j=0; j<n; j++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum;
  }
}
```

Inner loop:



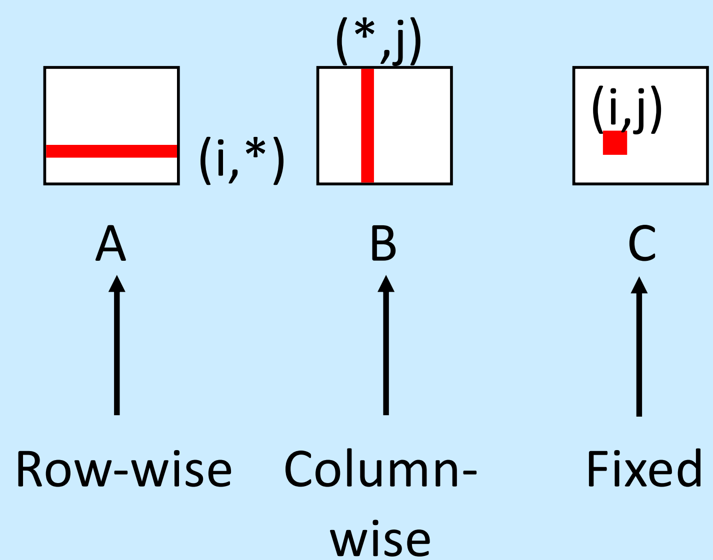
Misses per inner loop iteration:

A	B	C
0.125	1.0	0.0

Matrix Multiplication (jik)

```
/* jik */
for (j=0; j<n; j++) {
  for (i=0; i<n; i++) {
    sum = 0.0;
    for (k=0; k<n; k++)
      sum += a[i][k] * b[k][j];
    c[i][j] = sum
  }
}
```

Inner loop:



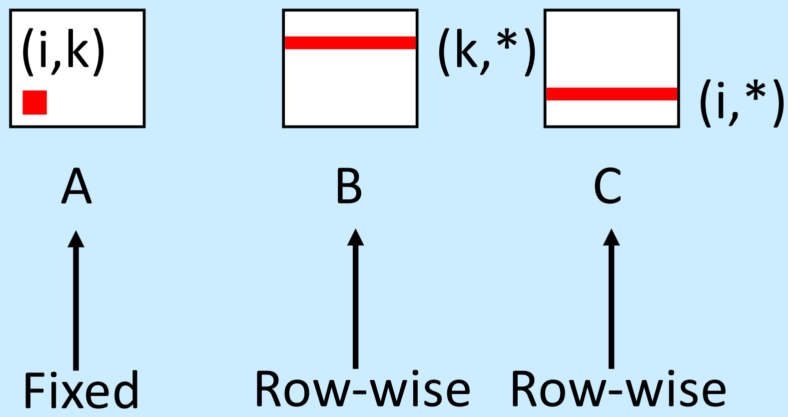
Misses per inner loop iteration:

A	B	C
0.125	1.0	0.0

Matrix Multiplication (kij)

```
/* kij */
for (k=0; k<n; k++) {
  for (i=0; i<n; i++) {
    r = a[i][k];
    for (j=0; j<n; j++)
      c[i][j] += r * b[k][j];
  }
}
```

Inner loop:

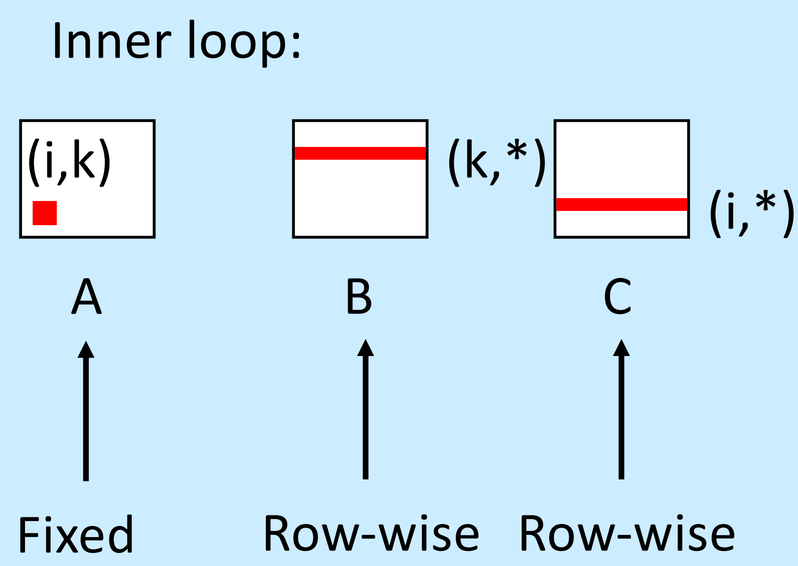


Misses per inner loop iteration:

A	B	C
0.0	0.125	0.125

Matrix Multiplication (ikj)

```
/* ikj */
for (i=0; i<n; i++) {
  for (k=0; k<n; k++) {
    r = a[i][k];
    for (j=0; j<n; j++)
      c[i][j] += r * b[k][j];
  }
}
```



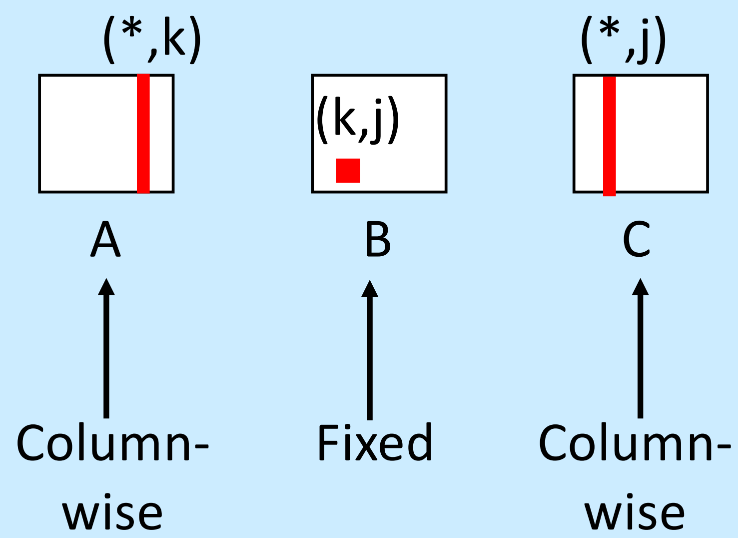
Misses per inner loop iteration:

A	B	C
0.0	0.125	0.125

Matrix Multiplication (jki)

```
/* jki */
for (j=0; j<n; j++) {
  for (k=0; k<n; k++) {
    r = b[k][j];
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * r;
  }
}
```

Inner loop:



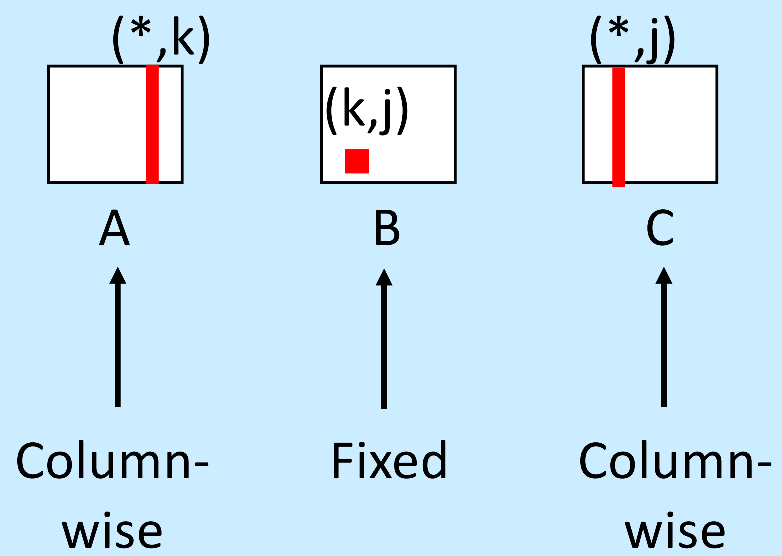
Misses per inner loop iteration:

A	B	C
1.0	0.0	1.0

Matrix Multiplication (kji)

```
/* kji */
for (k=0; k<n; k++) {
  for (j=0; j<n; j++) {
    r = b[k][j];
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * r;
  }
}
```

Inner loop:



Misses per inner loop iteration:

A	B	C
1.0	0.0	1.0

Summary of Matrix Multiplication

```
for (i=0; i<n; i++)
  for (j=0; j<n; j++) {
   sum = 0.0;
   for (k=0; k<n; k++)
     sum += a[i][k] * b[k][j];
   c[i][j] = sum;
  }
```

ijk (& jik):
- 2 loads, 0 stores
- misses/iter = **1.125**

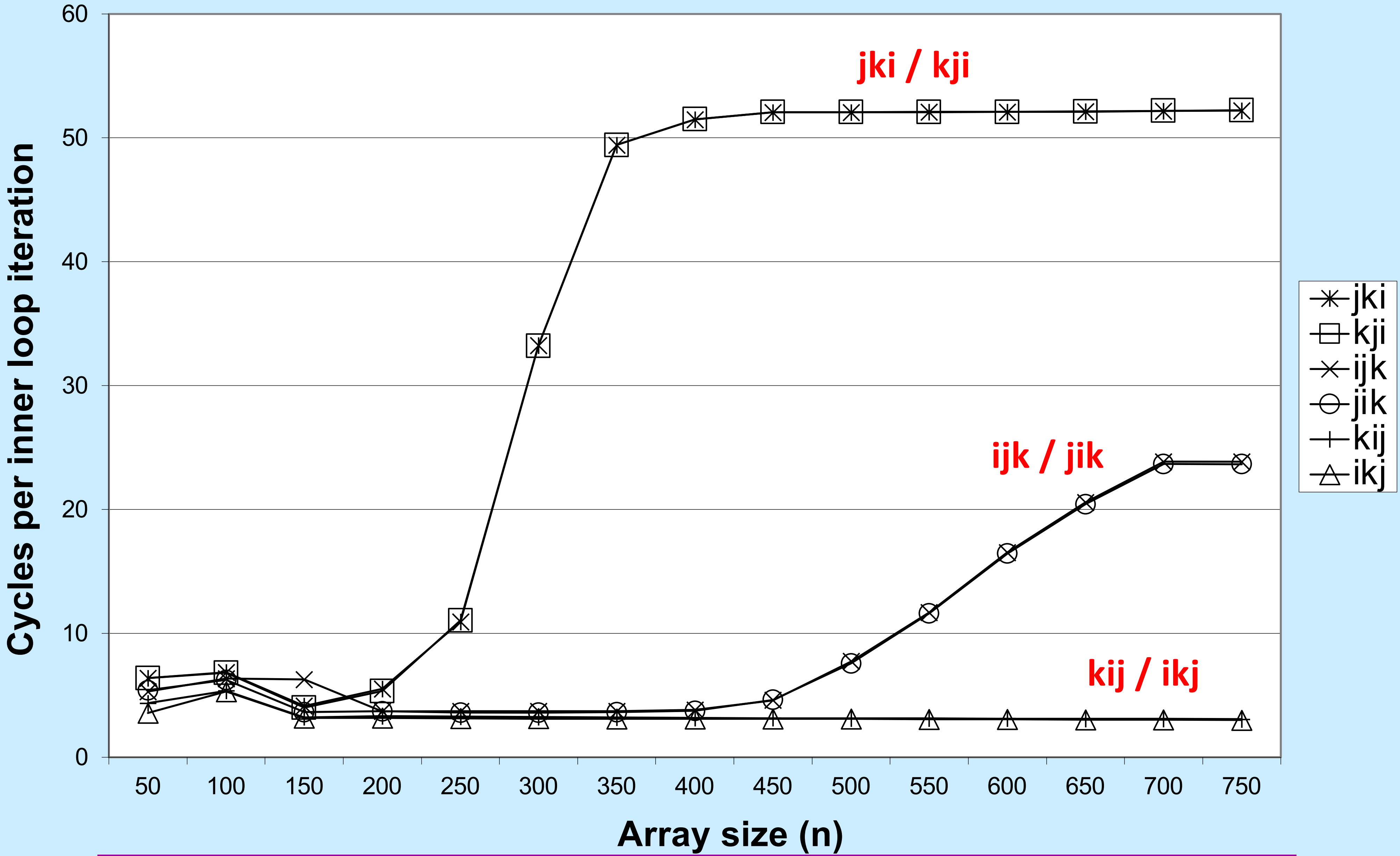
```
for (k=0; k<n; k++)
 for (i=0; i<n; i++) {
  r = a[i][k];
  for (j=0; j<n; j++)
   c[i][j] += r * b[k][j];
  }
```

kij (& ikj):
- 2 loads, 1 store
- misses/iter = **0.25**

```
for (j=0; j<n; j++)
 for (k=0; k<n; k++) {
   r = b[k][j];
   for (i=0; i<n; i++)
    c[i][j] += a[i][k] * r;
 }
```

jki (& kji):
- 2 loads, 1 store
- misses/iter = **2.0**

Core i7 Matrix Multiply Performance



In Real Life ...

- Multiply two 1024x1024 matrices of doubles on sunlab machines
  - ijk
    - » 4.185 seconds
  - kij
    - » 0.798 seconds
  - jki
    - » 11.488 seconds

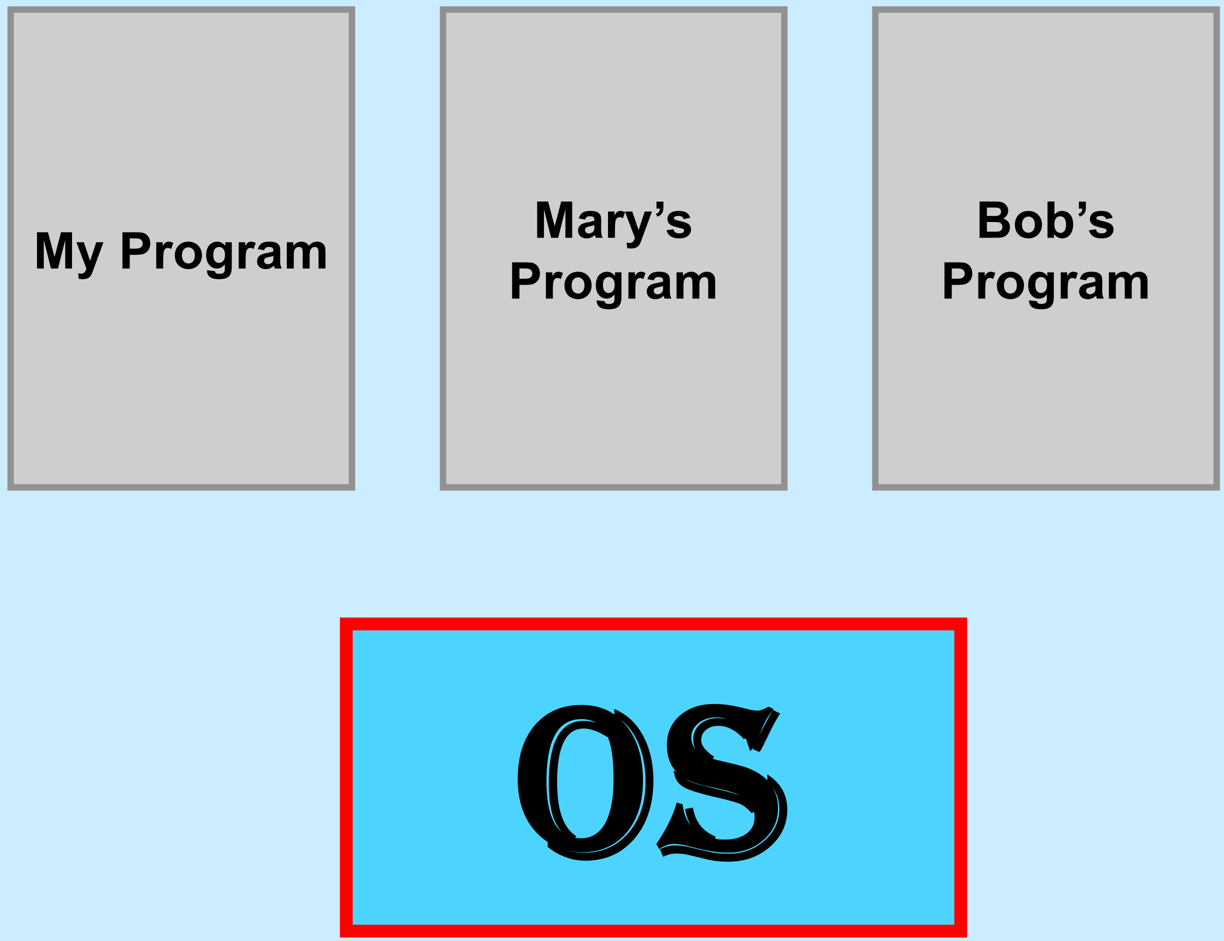
Concluding Observations

- Programmer can optimize for cache performance
  - organize data structures appropriately
- All systems favor "cache-friendly code"
  - getting absolute optimum performance is very platform specific
    - cache sizes, line sizes, associativities, etc.
  - can get most of the advantage with generic code
    - keep working set reasonably small (temporal locality)
    - use small strides (spatial locality)

CS 33

Architecture and the OS

The Operating System



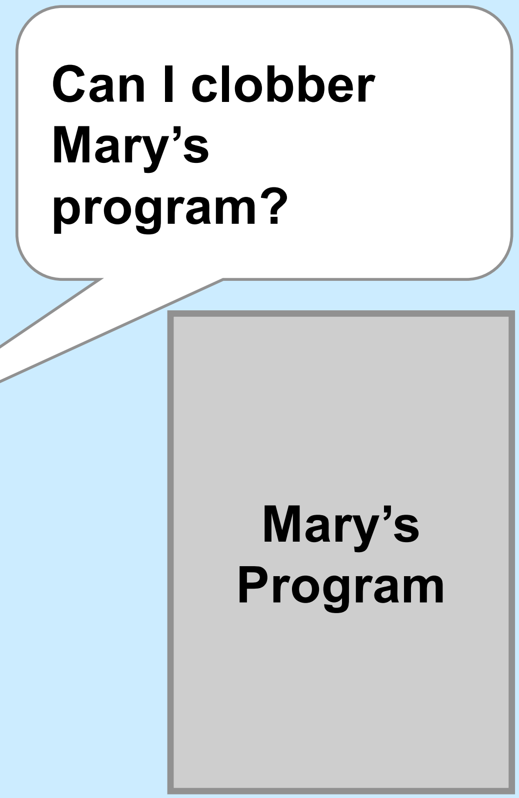
Processes

- Containers for programs
  - virtual memory
    - address space
  - scheduling
    - one or more threads of control
  - file references
    - open files
  - and lots more!

Idiot Proof …

```
int main( ) {
  int i;
  int A[1];

  for (i=0; ; i++)
    A[rand()] = i;
}
```



Fair Share

```
void runforever( ){
  while(1)
    ;
}

int main( ) {
  runforever();
}
```

Can I prevent Bob's program from running?

Bob's Program

Architectural Support for the OS

- Not all instructions are created equal ...
  - non-privileged instructions
    - » can affect only current program
  - privileged instructions
    - » may affect entire system
- Processor mode
  - user mode
    - » can execute only non-privileged instructions
  - privileged mode
    - » can execute all instructions

Which Instructions Should Be Privileged?

- I/O instructions
- Those that affect how memory is mapped
- Halt instruction
- Some others ...

Who Is Privileged?

- No one
  - user code always runs in user mode
- The operating-system kernel runs in privileged mode
  - nothing else does
  - not even super user on Unix or administrator on Windows

Entering Privileged Mode

- How is OS invoked?
  - very carefully ...
  - strictly in response to interrupts and exceptions
  - (booting is a special case)

Interrupts and Exceptions

- Things don’t always go smoothly ...
  - I/O devices demand attention
  - timers expire
  - programs demand OS services
  - programs demand storage be made accessible
  - programs have problems
- Interrupts
  - demand for attention from external sources
- Exceptions
  - executing program requires attention

Exceptions

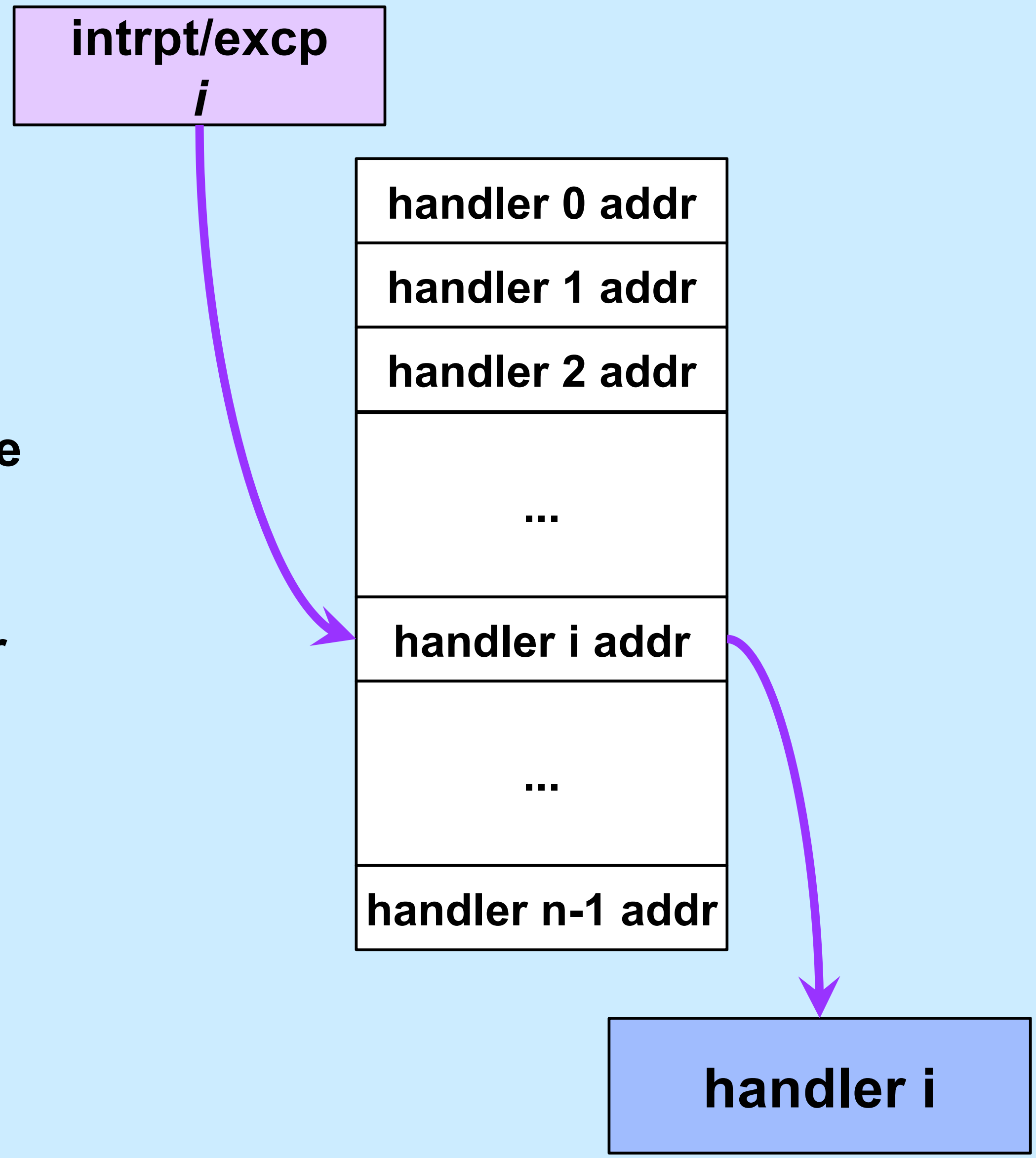
- Traps
  - "intentional" exceptions
    - » execution of special instruction to invoke OS
  - after servicing, execution resumes with next instruction
- Faults
  - a problem condition that is normally corrected
  - after servicing, instruction is re-tried
- Aborts
  - something went dreadfully wrong ...
  - not possible to re-try instruction, nor to go on to next instruction

Actions for Interrupts and Exceptions

- When interrupt or exception occurs
  - processor saves state of current thread/process on stack
  - processor switches to privileged mode (if not already there)
  - invokes handler for interrupt/exception
  - if thread/process is to be resumed (typical action after interrupt)
    - thread/process state is restored from stack
  - if thread/process is to re-execute current instruction
    - thread/process state is restored, after backing up instruction pointer
  - if thread/process is to terminate
    - it's terminated

Interrupt and Exception Handlers

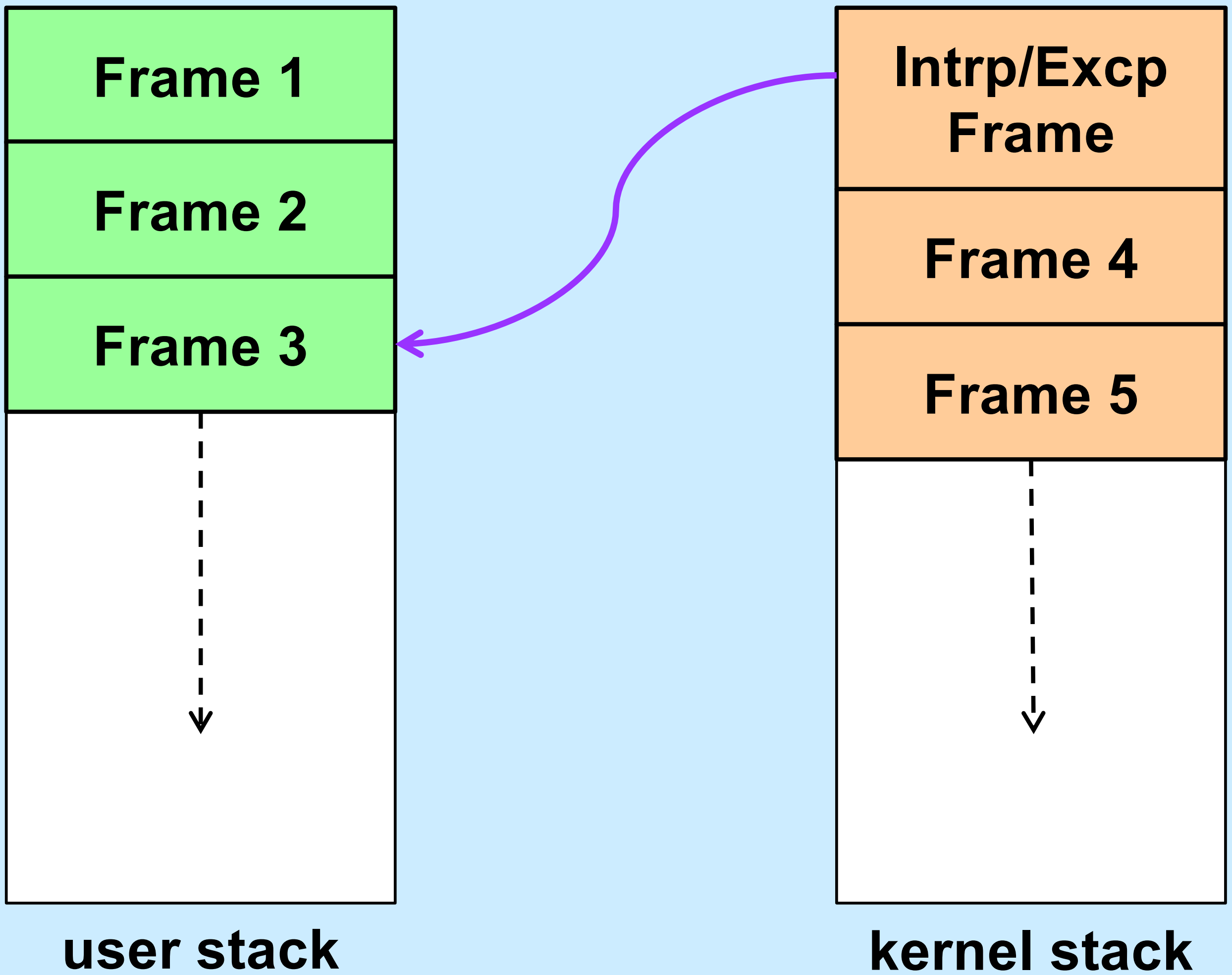
- **Interrupt or exception invokes handler (in OS)**
  - via interrupt and exception vector
    - » one entry for each possible interrupt/exception
      - contains
        - – address of handler
  - code executed in privileged mode
    - » but code is part of the OS



Entering and Exiting

- Entering/exiting interrupt/exception handler more involved than entering/exiting a function
  - must deal with processor mode
    - » switch to privileged mode on entry
    - » switch back to previous mode on exit
  - interrupted process/thread's state is saved on separate kernel stack
  - stack in kernel must be different from stack in user program
    - » why?

One Stack Per Mode



Quiz 3

If an interrupt occurs, which general-purpose registers must be pushed onto the kernel stack?

a) all
b) none
c) callee-save registers
d) caller-save registers