JDEP 284H
Foundations of Computer Systems

Cache Memories

Dr. Steve Goddard
goddard@cse.unl.edu

http://cse.unl.edu/~goddard/Courses/JDEP284

Giving credit where credit is due

- **Most of slides for this lecture are based on slides created by Drs. Bryant and O'Hallaron, Carnegie Mellon University.**
- **I have modified them and added new slides.**

2

Topics

- **Generic cache memory organization**
- **Direct mapped caches**
- **Set associative caches**
- **Impact of caches on performance**

3

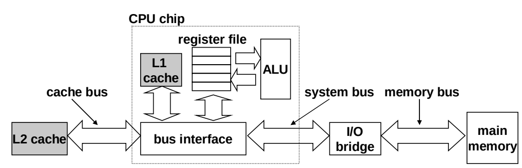
Cache Memories

Cache memories are small, fast SRAM-based memories managed automatically in hardware.

- **Hold frequently accessed blocks of main memory**

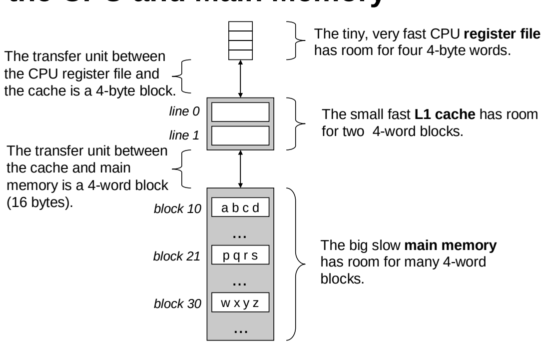
CPU looks first for data in L1, then in L2, then in main memory.

Typical bus structure:



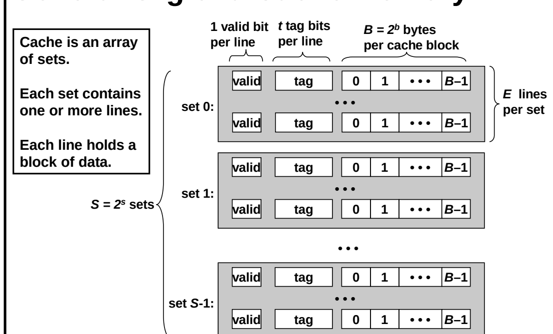
4

Inserting an L1 Cache Between the CPU and Main Memory



5

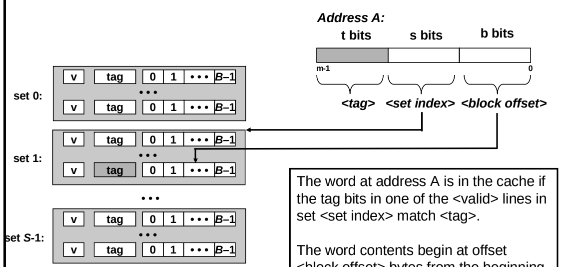
General Org of a Cache Memory



Cache size: $C = B \times E \times S$ data bytes

6

Addressing Caches



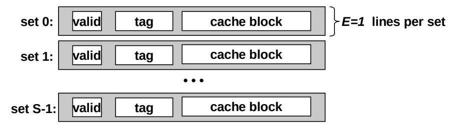
The word at address A is in the cache if the tag bits in one of the <valid> lines in set <set index> match <tag>.

The word contents begin at offset <block offset> bytes from the beginning of the block.

Direct-Mapped Cache

Simplest kind of cache

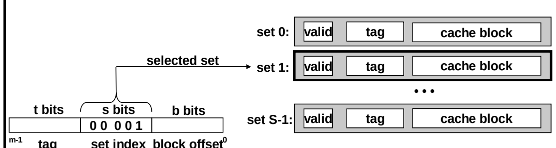
Characterized by exactly one line per set.



Accessing Direct-Mapped Caches

Set selection

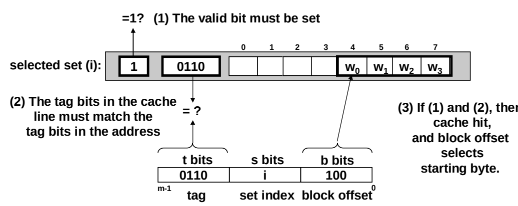
- **Use the set index bits to determine the set of interest.**



Accessing Direct-Mapped Caches

Line matching and word selection

- **Line matching: Find a valid line in the selected set with a matching tag**
- **Word selection: Then extract the word**



Direct-Mapped Cache Simulation

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

M=16 byte addresses, B=2 bytes/block, S=4 sets, E=1 entry/set

Address trace (reads):
0 [0000_2], 1 [0001_2], 13 [1101_2], 8 [1000_2], 0 [0000_2]

(1) 0 [0000_2] *(miss)*

v	tag	data
1	0	M[0-1]

(3) 13 [1101_2] *(miss)*

v	tag	data
1	0	M[0-1]
1	1	M[12-13]

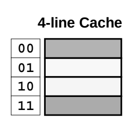
(4) 8 [1000_2] *(miss)*

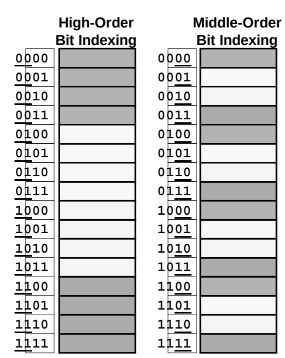
v	tag	data
1	1	M[8-9]
1	1	M[12-13]

(5) 0 [0000_2] *(miss)*

v	tag	data
1	0	M[0-1]
1	1	M[12-13]

Why Use Middle Bits as Index?





High-Order Bit Indexing

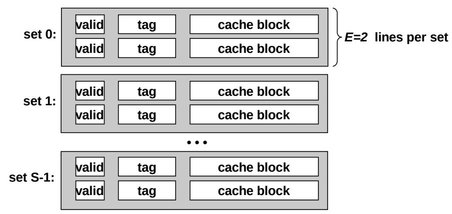
- **Adjacent memory lines would map to same cache entry**
- **Poor use of spatial locality**

Middle-Order Bit Indexing

- **Consecutive memory lines map to different cache lines**
- **Can hold C-byte region of address space in cache at one time**

Set Associative Caches

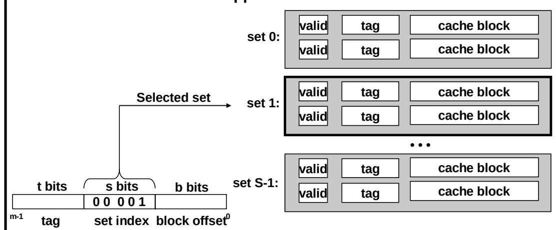
Characterized by more than one line per set



Accessing Set Associative Caches

Set selection

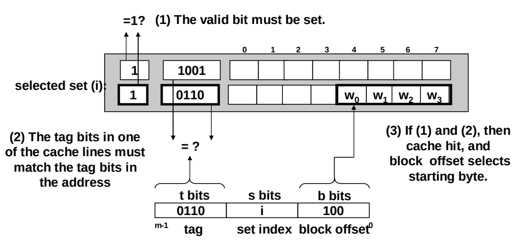
- **identical to direct-mapped cache**



Accessing Set Associative Caches

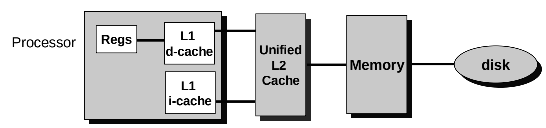
Line matching and word selection

- **must compare the tag in each valid line in the selected set.**



Multi-Level Caches

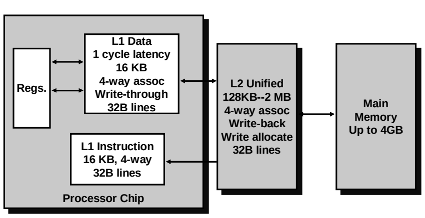
Options: separate data and instruction caches, or a unified cache



size:	200 B	8-64 KB	1-4MB SRAM	128 MB DRAM	30 GB
speed:	3 ns	3 ns	6 ns	60 ns	8 ms
$/Mbyte:			$100/MB	$1.50/MB	$0.05/MB
line size:	8 B	32 B	32 B	8 KB	

larger, slower, cheaper →

Intel Pentium Cache Hierarchy



Cache Performance Metrics

Miss Rate

- **Fraction of memory references not found in cache (misses/references)**
- **Typical numbers:**
  - **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 clock cycle for L1**
  - **3-8 clock cycles for L2**

Miss Penalty

- **Additional time required because of a miss**
  - **Typically 25-100 cycles for main memory**

Writing Cache Friendly Code

Repeated references to variables are good (temporal locality)

Stride-1 reference patterns are good (spatial locality)

Examples:

- **cold cache, 4-byte words, 4-word cache blocks**

```
int sumarrayrows(int 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;
}
```

Miss rate = 1/4 = 25%

```
int sumarraycols(int 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;
}
```

Miss rate = 100%

The Memory Mountain

Read throughput (read bandwidth)

- **Number of bytes read from memory per second (MB/s)**

Memory mountain

- **Measured read throughput as a function of spatial and temporal locality.**
- **Compact way to characterize memory system performance.**

Memory Mountain Test Function

```
/* The test function */
void test(int elems, int stride) {
    int i, result = 0;
    volatile int sink;

    for (i = 0; i < elems; i += stride)
        result += data[i];
    sink = result; /* So compiler doesn't optimize away the loop */
}

/* Run test(elems, stride) and return read throughput (MB/s) */
double run(int size, int stride, double Mhz)
{
    double cycles;
    int elems = size / sizeof(int);

    test(elems, stride);                       /* warm up the cache */
    cycles = fcyc2(test, elems, stride, 0);  /* call test(elems,stride) */
    return (size / stride) / (cycles / Mhz); /* convert cycles to MB/s */
}
```


Memory Mountain Main Routine

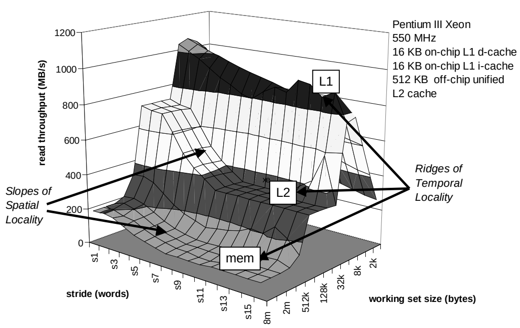
```
/* mountain.c - Generate the memory mountain. */
#define MINBYTES (1 << 10)  /* Working set size ranges from 1 KB */
#define MAXBYTES (1 << 23)  /* ... up to 8 MB */
#define MAXSTRIDE 16        /* Strides range from 1 to 16 */
#define MAXELEMS MAXBYTES/sizeof(int)

int data[MAXELEMS];         /* The array we'll be traversing */

int main()
{
    int size;        /* Working set size (in bytes) */
    int stride;      /* Stride (in array elements) */
    double Mhz;      /* Clock frequency */

    init_data(data, MAXELEMS); /* Initialize each element in data to 1 */
    Mhz = mhz(0);              /* Estimate the clock frequency */
    for (size = MAXBYTES; size >= MINBYTES; size >>= 1) {
        for (stride = 1; stride <= MAXSTRIDE; stride++)
            printf("%.1f\t", run(size, stride, Mhz));
        printf("\n");
    }
    exit(0);
}
```

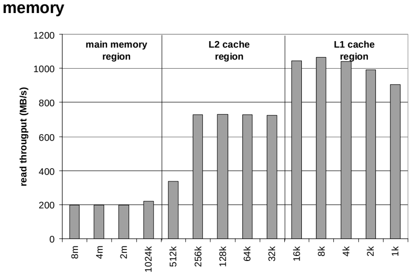

The Memory Mountain



Ridges of Temporal Locality

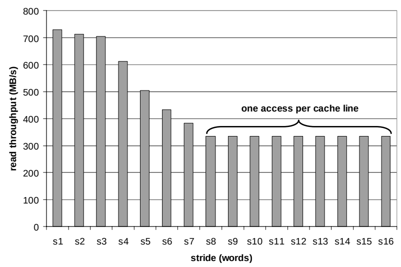
Slice through the memory mountain with stride=1

- **illuminates read throughputs of different caches and memory**



A Slope of Spatial Locality

Slice through memory mountain with size=256KB
- shows cache block size.



25

Matrix Multiplication Example

Major Cache Effects to Consider
- Total cache size
  - Exploit temporal locality and keep the working set small (e.g., by using blocking)
- Block size
  - Exploit spatial locality

```
/* 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;
  }
}
```

Variable **sum** *held in register*

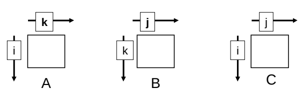
Description:
- Multiply N x N matrices
- O(N^3) total operations
- Accesses
  - N reads per source element
  - N values summed per destination
    - » but may be able to hold in register

26

Miss Rate Analysis for Matrix Multiply

Assume:
- Line size = 32B (big enough for 4 64-bit words)
- Matrix dimension (N) is very large
  - Approximate 1/N as 0.0
- Cache is not even big enough to hold multiple rows

Analysis Method:
- Look at access pattern of inner loop



27

Layout of C Arrays in Memory (review)

C arrays allocated in row-major order
- each row in contiguous memory locations

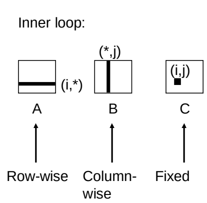
Stepping through columns in one row:
- `for (i = 0; i < N; i++)`
  `sum += a[0][i];`
- accesses successive elements
- if block size (B) > 4 bytes, exploit spatial locality
  - compulsory miss rate = 4 bytes / B

Stepping through rows in one column:
- `for (i = 0; i < n; i++)`
  `sum += a[i][0];`
- accesses distant elements
- no spatial locality!
  - compulsory miss rate = 1 (i.e. 100%)

28

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;
  }
}
```



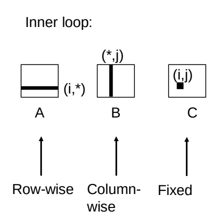
Misses per Inner Loop Iteration:

A	B	C
0.25	1.0	0.0

29

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
  }
}
```



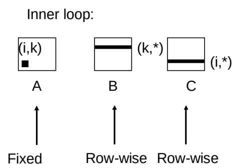
Misses per Inner Loop Iteration:

A	B	C
0.25	1.0	0.0

30

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];
  }
}
```



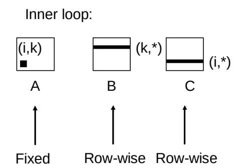
Misses per Inner Loop Iteration:

A	B	C
0.0	0.25	0.25

31

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];
  }
}
```



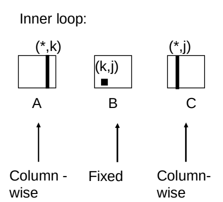
Misses per Inner Loop Iteration:

A	B	C
0.0	0.25	0.25

32

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;
  }
}
```



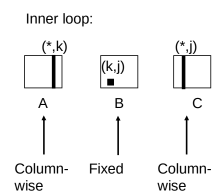
Misses per Inner Loop Iteration:

A	B	C
1.0	0.0	1.0

33

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;
  }
}
```



Misses per Inner Loop Iteration:

A	B	C
1.0	0.0	1.0

34

Summary of Matrix Multiplication

ijk (& jik):
- 2 loads, 0 stores
- misses/iter = **1.25**

```
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;
  }
}
```

kij (& ikj):
- 2 loads, 1 store
- misses/iter = **0.5**

```
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];
  }
}
```

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

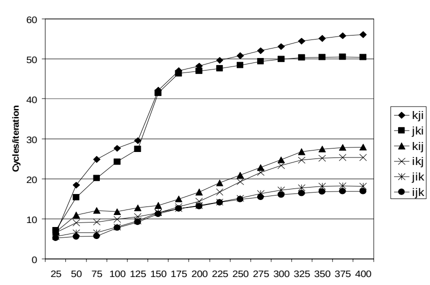
```
for (j=0; j<n; j++) {
  for (k=0; k<n; k++) {
    r = b[k][j];
    for (i=0; i<n; i++)
      c[i][j] += a[i][k] * r;
  }
}
```

35

Pentium Matrix Multiply Performance

Miss rates are helpful but not perfect predictors.

- **Code scheduling matters, too.**



36

Improving Temporal Locality by Blocking

Example: Blocked matrix multiplication

- **"block" (in this context) does not mean "cache block".**
- **Instead, it means a sub-block within the matrix.**
- **Example: N = 8; sub-block size = 4**

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \times \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}$$

Key idea: Sub-blocks (i.e., $\mathbf{A}_{xy}$) can be treated just like scalars.

$C_{11} = A_{11}B_{11} + A_{12}B_{21}$ $\quad$ $C_{12} = A_{11}B_{12} + A_{12}B_{22}$

$C_{21} = A_{21}B_{11} + A_{22}B_{21}$ $\quad$ $C_{22} = A_{21}B_{12} + A_{22}B_{22}$

37

Blocked Matrix Multiply (bijk)

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

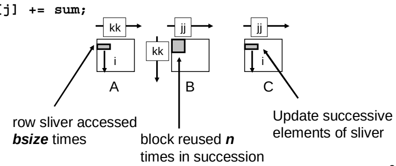
38

Blocked Matrix Multiply Analysis

- **Innermost loop pair multiplies a *1 X bsize* sliver of *A* by a *bsize X bsize* block of *B* and accumulates into *1 X bsize* sliver of *C***
- **Loop over *i* steps through *n* row slivers of *A* & *C*, using same *B***

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

Innermost Loop Pair

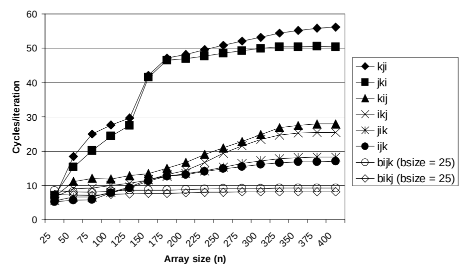


39

Pentium Blocked Matrix Multiply Performance

Blocking (bijk and bikj) improves performance by a factor of two over unblocked versions (ijk and jik)

- **relatively insensitive to array size.**



40

Concluding Observations

Programmer can optimize for cache performance

- **How data structures are organized**
- **How data are accessed**
  - **Nested loop structure**
  - **Blocking is a general technique**

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)**

41