Code Optimization

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Code optimization for performance

- A quick look at some techniques that can improve the performance of your code
- Rewrite code to minimize processor cycles
  - But do not mess up the correctness!
  - Reduce number of instructions executed
  - Reduce the “complexity” of instructions
    - In real processors, different arithmetic operations can take different times
- Locality
  - Will improve memory performance

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Recall CPU time model

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

CPU = IC * CPI * Clk

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Summary: Memory Access time optimization

- If each access to memory leads to a cache hit then time to fetch from memory is one cycle
  - Program performance is good!
- If each access to memory leads to a cache miss then time to fetch from memory is much larger than 1 cycle
  - Program performance is bad!
- Design Goal:

How to arrange data/instructions so that we have as few cache misses as possible.

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Who can ‘change’ each parameter

- CPU time = IC * CPI * Clk
- Clock: completely under HW control
- IC: programmer and compiler
- CPI: compiler and HW
- ….so what does a compiler do?

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Compiler Tasks

- 1. Code Translation
  - Source language → target language

    FORTRAN → C

    C → MIPS, x86, PowerPC or Alpha machine code

    MIPS binary → x86 binary

- 2. Code Optimization
  - Code runs faster
  - Match dynamic code behavior to static machine structure

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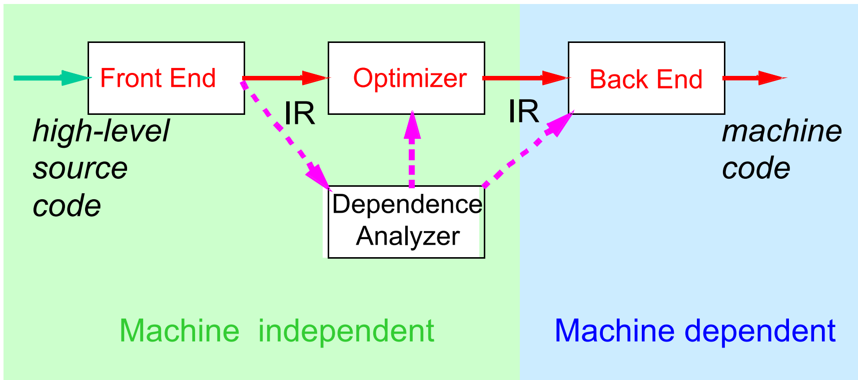
Compiler Structure



(IR= intermediate representation)

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Compiler Front End tasks

- Lexical Analysis
  - Misspelling an identifier, keyword, or operator
    - e.g. lex

  done by a finite state machine (i.e., *deterministic finite automata*)!

- Syntax Analysis
  - Grammar errors, such as mismatched parentheses
  - Define syntax using *Context Free Grammar*…then build parser

  e.g. yacc

- Semantic Analysis
  - Type checking, check formal and actual arguments to function match, etc.
- code generation…*you've been doing this for C to LC3!!*
  - to target ISA or intermediate code, llvm-code

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Code Optimization

- After front end analysis $\Longrightarrow$ an executable program P
- P has some performance $T(P)$
  - $T(P)$ = IC*CPI* Clock
- Goal: Improve $T(P)$
  - Reduce time
  - How ? Reduce CPI and/or IC
- Rewrite/transform P to equivalent program Q such that
  1. $T(Q) < T(P)$ and
  2. Q and P are equivalent, i.e, do exactly the same thing
     - For all inputs, Q and P produce the same result and compute the same function

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Formal Model for Code Optimization ?

- Is it a hack job or is there a formal model underlying the various transformations that can help with designing a tool to optimize code ?
  - *Need to make sure that transformed code is correct and does not change semantics of the original program.*
- Power of abstraction…..
- Graph theory: model program as a graph (Program dependence graph)
  - Model data and control dependencies
  - Code transformation = graph transformation

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The Program Dependence Graph

- How to represent control and data flow of a program ?
- The Program Dependence Graph (PDG) is the intermediate (abstract) representation of a program designed for use in optimizations
- It consists of two important graphs:
  - Control Dependence Graph captures control flow and control dependence
  - Data Dependence Graph captures data dependences
- Analogous to a flow-chart of the program
  - Formal model for flow charts!

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Definition: Control Flow Graph

A control flow graph CFG = $(N_c \,;\, E_c \,;\, T_c)$ consists of

- N_c, a set of nodes. A node represents a straight-line sequence of operations with no intervening control flow i.e. a basic block.
- $E_c \subseteq N_c \times N_c \times \mathit{Labels}$, a set of *labeled* edges.
- Example: the code below has two basic blocks

```
ADD R0, R0, #0
BRn here1
```

```
LDR R1, R0, #0
ADD R2, R1, R2
BRzp here2
```

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Data Dependence Graph

- Within each basic block capture the data dependencies between instructions
  - In RISC processor, follow the data in the registers
  - Value computed in a register is needed by an instruction in the future
  - Ex:
    - o Value computed by LDR is needed by next instruction
    - o But no dependence between AND and the other instructions
- Can capture these dependencies using a graph
  - Nodes are instructions and edges dependencies
- Data dependencies important in
  - Scheduling instructions
  - Parallelizing the code

```
LDR R1, R0, #0

ADD R2, R1, R2
AND R3, R3, #4
BRzp here2
```

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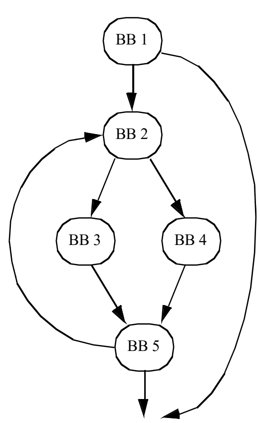
Control Flow Graph




```
main:
      addi r2, r0, A         BB 1
      addi r3, r0, B
      addi r4, r0, C
      addi r5, r0, N
      add  r10,r0, r0
      bge  r10,r5, end
loop:
      lw   r20, 0(r2)        BB 2
      lw   r21, 0(r3)
      bge  r20,r21,T1
      sw   r21, 0(r4)        BB 3
      b    T2
T1:
      sw   r20, 0(r4)        BB 4
T2:
      addi r10,r10,1         BB 5
      addi r2, r2, 4
      addi r3, r3, 4
      addi r4, r4, 4
      blt  r10,r5, loop
end:
```

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Program behaviour ?

- Model as program dependence graph!
- What is a correct execution ?
  - Execution will only follow valid paths in the program dependence graph!
    - **IF code is written correctly, then force the program to only follow paths in the dependence graph!**
- connection to Software security/correctness
  - Only execute along paths in the graph = program cannot execute any malicious code

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Formal Definition/Model: Code Optimization

- Need to make sure that transformed code is correct and does not change semantics of the original program.

- model program as a graph (Program dependence graph)
  - Model data and control dependencies
- Any transformation should give us a homomorphic graph
  - Recall concept of Isomorphism/Homomorphism Discrete Structures courses !!!

- Bad news: checking graph isomorphism is NP-complete !
  - Therefore … ???

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Compiler optimizations

- Use ‘heuristics’ to solve the difficult problem
- All ‘useful’ compilers have code optimizers built into them
  - Optimize time….
  - other metrics: power ? Code size?
    - Why ?
- Machine dependent optimizations
  - Need to know something about the processor details before we can optimize
- Machine independent optimizations
  - These are independent of processor specifics

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Machine Dependent Optimizations

These need some knowledge of the processor

- Register Allocation
- Instruction Scheduling
- Peephole Optimizations

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Peephole Optimizations

- Replacements of assembly instruction through template matching

- Eg. Replacing one addressing mode with another in a CISC

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Instruction Scheduling

- Given a source program P, schedule the instructions so as to minimize the overall execution time on the functional units in the target machine
  - This is where processors with parallelism introduce complexity into the scheduling process
  - Schedule parallel instructions

- Finding a schedule with minimum execution time is an NP-complete problem
  - Need fast and effective heuristics
  - You will cover schedulers in Operating Systems course

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Register Allocation

- Storing and accessing variables from registers is much faster than accessing data from memory.
  - Variables ought to be stored in registers
- It is useful to store variables as long as possible, once they are loaded into registers
- Registers are bounded in number
  - "register-sharing" is needed over time.
  - Some variables have to be 'flushed' to memory
  - Reading from memory takes longer
- how important is Register allocation to performance?
  - **efficient register allocators improved performance 25%**
  - Poor allocation means repeatedly reading variables from memory

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Register Allocation

```
{ …
    i=10;
    x= y +i;
    while (i<100) {
        a = a*100
        b = b + 100
        i++;
    }
```

- Suppose you have 3 registers available…
- should you place a and b into same register ?
- Can you place x and a into same register ?

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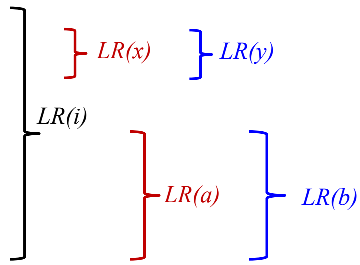
Register Allocation

```
{ …
     i=10;
     x= y +i;
     while (i<100){
          a = a*100
          b = b +100
          i++;
     }
```



- "live range" *LR(j)* for each variable *j* – where is it accessed
- Do live ranges of x and a "interfere" : LR(x) & LR(a) = 0?
- Do live ranges of a and b interfere ? : LR(a) & LR(b) = 0?
- If ranges interfere, then assign to different registers

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Register Allocation: Problem Formulation and Solution

- Determine live ranges for each variable, and determine conflicts/interference between variables/live ranges
  - Using dataflow analysis compute live ranges for each variable
- How do we model the register allocation problem?
  - Power of abstraction!!
- Formulate the problem of assigning variables to registers as a graph problem: The Graph coloring problem !
  - Number of colors = Number of registers;
  - Nodes in graph = number of variables (live ranges)
  - Edges in graph = edge between x,y if live ranges x,y interfere
  - Use application domain (Instruction execution) to define the priority function
- Graph theory & CS – it is every &#@&@ place!
  - My curriculum advice (that nobody takes…except 2): take a graph theory course!

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Machine Dependent Optimizations

•Need thorough knowledge of the architecture AND algorithms

•New architectures introduce new challenges…

- Multi-core, Multi-threaded, Embedded (need to optimize for power consumption), Security (compiler-HW tools to enforce software security)
- Compiling for FPGA co-processors to accelerate (ex: AWS, Microsoft)

• Compiling for Security – leverage FPGAs & extra HW to place verification and encryption circuits

• Compiling for power optimization

- control memory power using compiler….layout the data so we can switch off memory modules

My Research Areas

•Machine dependent optimizations can be done by a compiler writer….Huge demand in industry….

- But few CS students want to study this stuff ☹ …and, this is not our focus for now!

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Our focus: Machine Independent Optimizations

•As SW developers, these should be a 'default' when you write code…

- THIS is what separates you from those who take a single programming course and claim they know CS!!

•How does it work: a large 'menu' of optimization techniques

- Some dependent on general architecture
  - Ex: Pipelined processors and loop unrolling
- We cover a small sample that works on all processors

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Some Machine-Independent Optimizations

- Some easy/obvious ones: Dataflow Analysis and Optimizations
  - Constant folding, Copy propagation etc.
  - Elimination of common subexpression
  - Dead code elimination
- Code motion
- Strength reduction
- Function/Procedure inlining
- Improving memory locality

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Code-Optimizing Transformations

- Constant folding

  (1 + 2) $\Rightarrow$ 3

  (100 > 0) $\Rightarrow$ true

  This save one instruction – reduce IC

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Code-Optimizing Transformations

- Copy propagation

$$x = b + c \qquad\qquad x = b + c$$
$$z = y * x \quad \Rightarrow \quad z = y * (b + c)$$

Why does this make a difference: Recall how code is generated..
(b+c) is stored into a temp register R0 and then STR R0, R5, #-2 to store local var x. Code generated for the 2nd statement z = y*x is:

```
LDR R0, R5, #-2        ; Load x into R0
LDR R1, R5, #-3        ; load y into R1
MUL R2, R0, R1         ; multiply x,y and store into R2
```

Replace above with

```
LDR R1, R5, #-3        ; load y into R1
MUL R2, R0,R1          ; multiply with value (b+c) stored in R0
```

This saves one memory access..reduces IC and CPI

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Code-Optimizing Transformations

- Common subexpression – reduce instruction count

$$x = b * c + 4 \qquad\qquad t = b * c$$
$$z = b * c - 1 \quad \Rightarrow \quad x = t + 4$$
$$z = t - 1$$

- 2 mult, 1 add, 1 sub replaced by
- 1 mult, 1 add, 1 sub

- Reduces IC

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Code-Optimizing Transformations

- Dead code elimination

```
x = 1
x = b + c
```

or if x is not referred to at all

Saves one instruction…reduce IC

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Code Optimization Example

```
x = 1
y = a * b + 3
z = a * b + x + z + 2
x = 3
```

propagation →

```
x = 1
y = a * b + 3
z = a * b + 1 + z + 2
x = 3
```

↓ constant folding

```
x = 1
y = a * b + 3
z = a * b + 3 + z
x = 3
```

← dead code elimination

```
y = a * b + 3
z = a * b + 3 + z
x = 3
```

↓ common subexpression

```
t = a * b + 3
y = t
z = t + z
x = 3
```

Original: 2 Mult, 4 Add, 7 Read/Write Mem

New: 1 Mult, 2 Add, 5 Read/Write

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Code Motion

- Code Motion
  - Reduce frequency with which computation performed
    - If it will always produce same result
    - Especially moving code out of loop
- Move code between blocks
  - eg. move loop invariant computations outside of loops
- What does this reduce ?
  - Number of times x/y is computed…reduce IC

```
while ( i < 100 ) {
        *p  =  x / y + i
        i  =  i + 1
}
```

```
t  =  x / y
while ( i < 100 )  {
        *p  =  t + i
        i  =  i  + 1
}
```

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- Code Motion:
  - Most compilers do a good job with array code + simple loop structures
- Code Generated by GCC

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

```
for (i = 0; i < n; i++)
{
  int ni = n*i;
  int *p = a+ni;
  for (j = 0; j < n;
j++)
    *p++ = b[j];
}
```

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Strength Reduction

- Replace costly operation with simpler one
- Shift, add instead of multiply or divide

```
16*x   -->   x << 4
```

  - Utility is machine dependent
  - Depends on cost of multiply or divide instruction
  - On Pentium x86, integer multiply only requires 4 CPU cycles
- Recognize sequence of products

```
for (i = 0; i < n; i++)
  for (j = 0; j < n; j++)
    a[n*i + j] = b[j];
```

→

```
int ni = 0;
for (i = 0; i < n; i++) {
  for (j = 0; j < n; j++)
    a[ni + j] = b[j];
  ni = ni + n;
}
```

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Strength Reduction

- Replace complex (and costly) expressions with simpler ones
  - What does this reduce ?...the CPI
- E.g.
  a : = b*17 → a: = (b<<4) + b
- E.g.

```
while ( i < 100 ) {
        a[ i ] =  i * 100
        i  =  i + 1
}
```

→

```
p  =  & a[ i ]
t  =  i * 100
while ( i < 100 ) {
        *p  =  t
        t  =  t + 100
        p  =  p  +  4
        i  =  i  + 1
}
```

loop invariant: &a[i]==p, i*100==t

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Function Inlining

- What happens on a function call ?
  - How are function calls implemented on the machine ?
  - Is function call = one subroutine call ?
- Function call in C = number of instructions in machine code
  - Create activation records, allocate memory
  - Manipulate stack and frame pointers
- What happens if we replace function call with body of function
  - i.e., Inline the function

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Function Call/Return

- Instructions to Push arguments to stack
- Instructions to Push frame pointer, return addr.
- Execute instructions of function
- Instructions to Pop return value, reset frame pointer, pop return address
- The bookkeeping instructions are essentially an "overhead"
  - They do not do the work of the function
- What happens if we replace function call with body of function ?
  - **Inline the function**
  - **Remove the function call and return overhead instructions**
  - **…**reduce IC

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Function Inlining

```
…                                      int myfunc(int m,n)
x= myfunc(i,j)          {
…                                           return(m+n);}
```

After inlining:

```
…
x = m+n
…..
```

- Improves performance
  - Removes bookkeeping instructions
- but tradeoff with code readability
  - and code size

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Finally….Memory Locality & Code Performance

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Locality

- Recall Principle of Locality:
  - Programs tend to reuse data and instructions near those they have used recently, or that were recently referenced themselves.
  - Temporal locality: Recently referenced items are likely to be referenced in the near future.
  - Spatial locality: Items with nearby addresses tend to be referenced close together in time.

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Link with Memory organization… . .

- Let's use array data structures to guide our discussions
- Recall: accesses to cache better than accesses to main memory/disk
- Recall: Multidimensional Arrays

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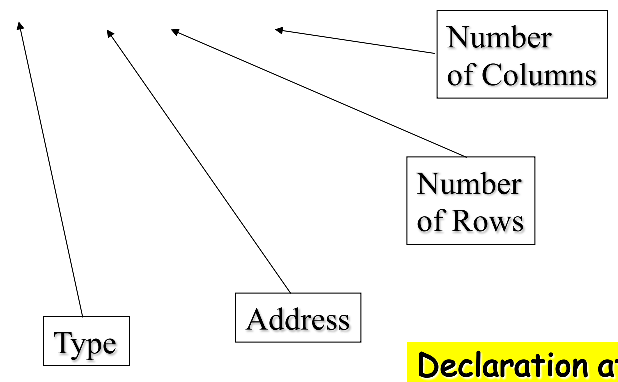
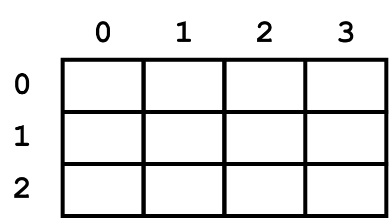
Declaration

```
int ia[3][4];
```

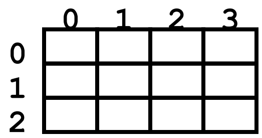


Declaration at compile time i.e. size must be known

How does a two dimensional array work?



How would you store it?



How would you store it?

Column Major Order

0,0	1,0	2,0	0,1	1,1	2,1	0,2	1,2	2,2	0,3	1,3	2,3
Column 0			Column 1			Column 2			Column 3		

Row Major Order

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3
Row 0				Row 1				Row 2			

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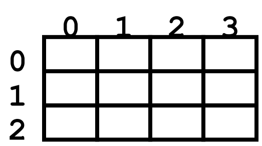

How would you store it?

C stores in row major order

Column Major Order

0,0	1,0	2,0	0,1	1,1	2,1	0,2	1,2	2,2	0,3	1,3	2,3
Column 0			Column 1			Column 2			Column 3		

Row Major Order

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3
Row 0				Row 1				Row 2			

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Locality of Access

- How are elements in the array accessed in your program ?
  - Row major or column major or other ?
  - How would you iterate over the 2-D array to maintain locality ?

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Locality and performance

- Recall: Memory = Cache + Main memory
  - Cache contains small number of bytes
- Recall: cache is arranged as a set of blocks
  - Can only fetch block at a time
- Example:
  - Assume each cache block has 4 words
  - If you fetch a block with addresses {0,1,2,3}
  - If four successive instructions use locations 0,1,2,3 then we only have one cache miss (first time to fetch block into cache)
  - If four successive instructions use locations 0,4,8,12 then each time we have to fetch a new cache block
    - Each memory access is an access to main memory
- Goal: have locality in memory accesses

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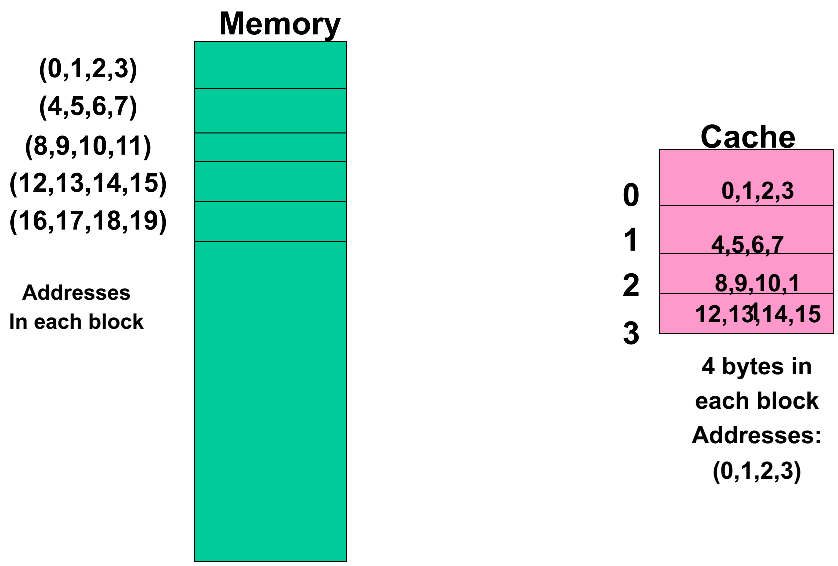
Example



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Locality

- Being able to look at code and get a qualitative sense of its locality is a key skill for a professional software developer.

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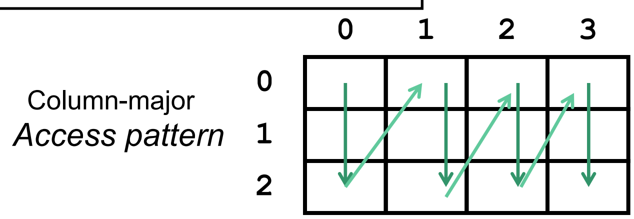
Locality Example

- Question: Does this function have good locality?

```
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
}
```



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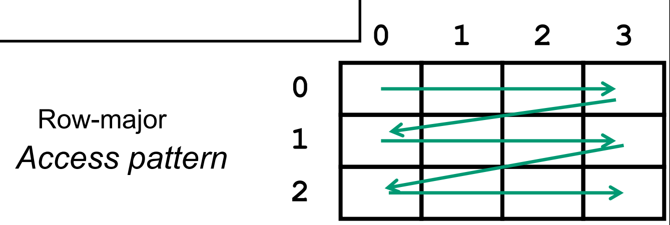
Locality Example

- Question: Does this function have good locality?

```
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
}
```



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Improving Memory Access Times (Cache Performance) by Compiler Optimizations

- McFarling [1989] improve perf. By rewriting the software
- Instructions
  - Reorder procedures in memory so as to reduce cache misses
  - Code Profiling to look at cache misses(using tools they developed)
- Data
  - *Merging Arrays*: improve spatial locality by single array of compound elements vs. 2 arrays
  - *Loop Interchange*: change nesting of loops to access data in order stored in memory
  - *Loop Fusion*: Combine 2 independent loops that have same looping and some variables overlap
  - *Blocking*: Improve temporal locality by accessing "blocks" of data repeatedly vs. going down whole columns or rows

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Compiler optimizations – merging arrays

- This works by improving spatial locality
- For example, some programs may reference multiple arrays of the same size at the same time
  - Could be bad – not enough locality
    - Accesses may interfere with one another in the cache – conflict misses
- A solution: Generate a single, compound array…

```
/* Before:*/
int tag[SIZE]
int byte1[SIZE]
int byte2[SIZE]
int dirty[size]
```

```
/* After */
struct merge {
        int tag;
        int byte1;
        int byte2;
        int dirty;
}
struct merge cache_block_entry[SIZE]
```

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Merging Arrays Example

```
/* Before: 2 sequential arrays */
int val[SIZE];
int key[SIZE];

/* After: 1 array of stuctures */
struct merge {
  int val;
  int key;
};
struct merge merged_array[SIZE];
```

Reducing conflicts between val & key;
improve spatial locality

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Compiler optimizations – loop interchange

- Some programs have nested loops that access memory in non-sequential order
  - Simply changing the order of the loops may make them access the data *in* sequential order…
- What's an example of this?
  - Recall: C stores 2-D arrays in row-major format

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Loop Interchange Example

```
/* Before */
for (k = 0; k < 100; k = k+1)
  for (j = 0; j < 100; j = j+1)
      for (i = 0; i < 5000; i = i+1)
            x[i][j] = 2 * x[i][j];
```

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Loop Interchange Example

```
/* After */
for (k = 0; k < 100; k = k+1)
  for (i = 0; i < 5000; i = i+1)
      for (j = 0; j < 100; j = j+1)
            x[i][j] = 2 * x[i][j];
```

Sequential accesses instead of striding through memory every 100 words; improved spatial locality

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Compiler optimizations – loop fusion

- This one's pretty obvious once you hear what it is…
- Seeks to take advantage of:
  - Programs that have separate sections of code that access the same arrays in different loops
    - Especially when the loops use common data
  - The idea is to "fuse" the loops into one common loop
- What's the target of this optimization?
  - Locality – reduce memory access times
  - IC – by reducing number of branches
    - Important in pipelined processors

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Loop Fusion Example

```
/* Before */
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
      a[i][j] = 1/b[i][j] * c[i][j];

for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
      d[i][j] = a[i][j] + c[i][j];
```

Move inside first loop

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Loop Fusion Example

```
/* After */
for (i = 0; i < N; i = i+1)
  for (j = 0; j < N; j = j+1)
  {   a[i][j] = 1/b[i][j] * c[i][j];
      d[i][j] = a[i][j] + c[i][j];}
```

2 misses per access to `a` & `c` vs. one miss per access; improve spatial locality & temporal locality

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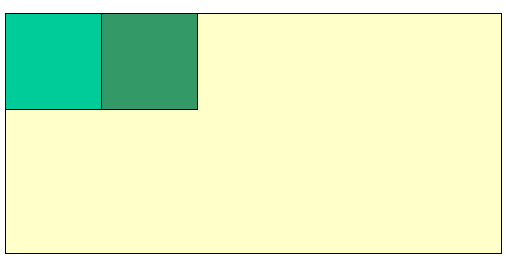
A more general concept: Memory Blocking.

- Can you keep locality in all memory operations
- This is probably the most “famous” of compiler optimizations to improve cache performance
- Another common concept: blocking
  - Rewrite code to process blocks of data at a time
  - Size of block = ???? Size of cache block!!



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Compiler optimizations – blocking

- Tries to reduce misses by improving temporal locality and spatial locality
- To get a handle on this, you have to work through code on your own
- this is used mainly with arrays!
- Simplest case??
  - Row-major access

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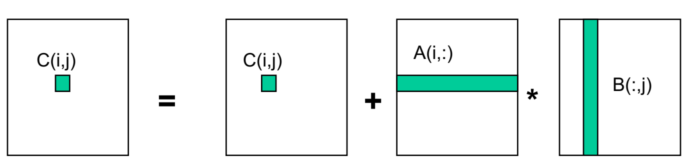
Naïve Matrix Multiply

```
{implements C = C + A*B}
for i = 1 to n
  {read row i of A into fast memory}
   for j = 1 to n
       {read C(i,j) into fast memory}
       {read column j of B into fast memory; note column major access!}
       for k = 1 to n
           C(i,j) = C(i,j) + A(i,k) * B(k,j)
       {write C(i,j) back to slow memory}
```



Good locality in access to matrix A; poor locality in access to B

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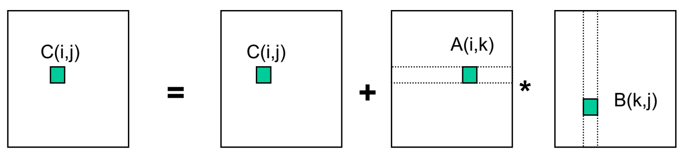
Blocked (Tiled) Matrix Multiply

Consider A,B,C to be N-by-N matrices of b-by-b subblocks where b= N/m is called the block size

```
for i = 1 to N
  for j = 1 to N
    {read block of C(i,j) into fast memory}
    for k = 1 to N
      {read block of A(i,k) into fast memory}
      {read block of B(k,j) into fast memory}
       C(i,j) = C(i,j) + A(i,k) * B(k,j) {do a matrix multiply on blocks}
    {write block C(i,j) back to slow memory}
```



Work these details out….need it for the project!

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Code Optimization and Compilers

- Modern compilers provide a menu of code optimization features
  - Inlining, strength reduction, register allocation, loop optimizations, etc.
- Some provide default optimization levels
  - Example: gcc -03 test.c
- Bottom Line: Everyone wants to run optimized code
  - Being smart with your solution!
- Have we seen everything there is to code optimization?....not by a long shot !!
  - Lots and lots more optimization techniques
    - The “cooler” ones need architecture knowledge

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Example of Code Optimization: (Final) Project 6

- Topic: Code Performance Optimization
  - Given code for Image operations, rewrite the code to make it run faster.
    - Use only techniques covered in class.

- Description will be posted last day of classes and due official final exam date: **Thursday Dec. 17th midnight**.
  Should take you 6-10 hours to complete
- Involves:
  - Code rewriting
  - Report writing: summarize your experiments, explain why the code ran faster (or slower).
- Very Important: Grade will depend on your analysis – simply turning in code (with documentation) that runs faster will only get you up to 50%

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