CS 33

Architecture and Optimization (1)

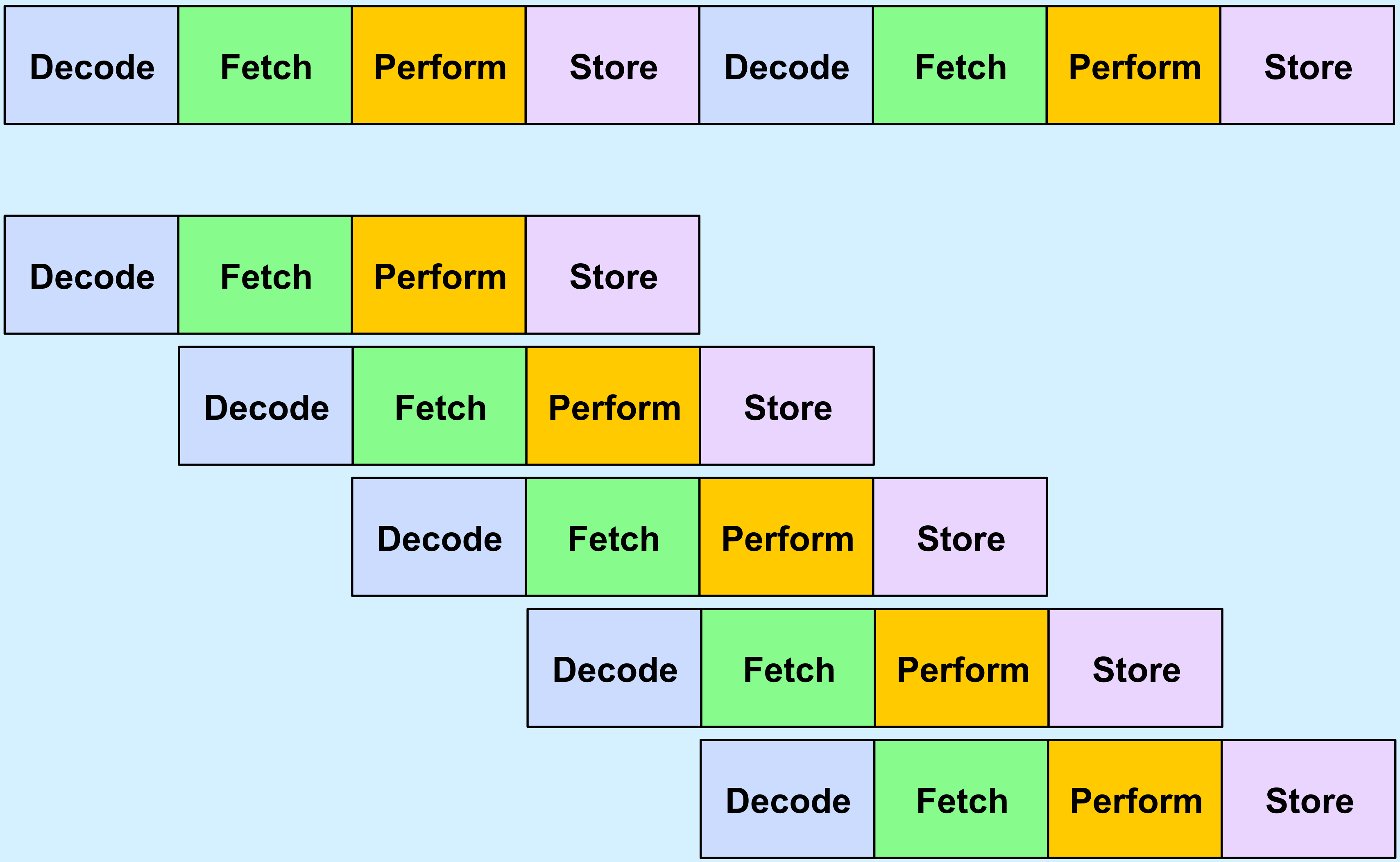
Simplistic View of Processor

```
while (true) {
  instruction = mem[eip];
  execute(instruction);
}
```

Some Details ...

```
void execute(instruction_t instruction) {
  decode(instruction, &opcode, &operands);
  fetch(operands, &in_operands);
  perform(opcode, in_operands, &out_operands);
  store(out_operands);
}
```

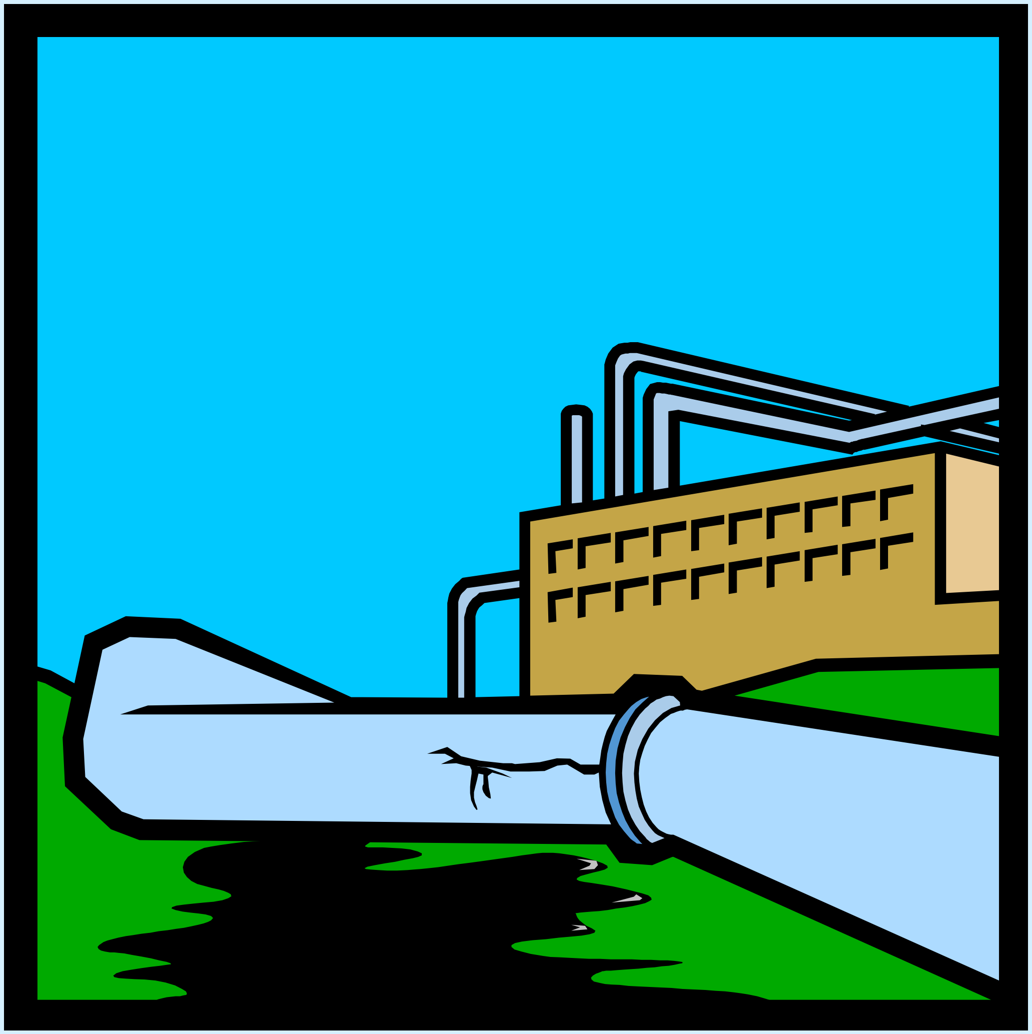
Pipelines


Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store
Decode
Fetch
Perform
Store

Analysis

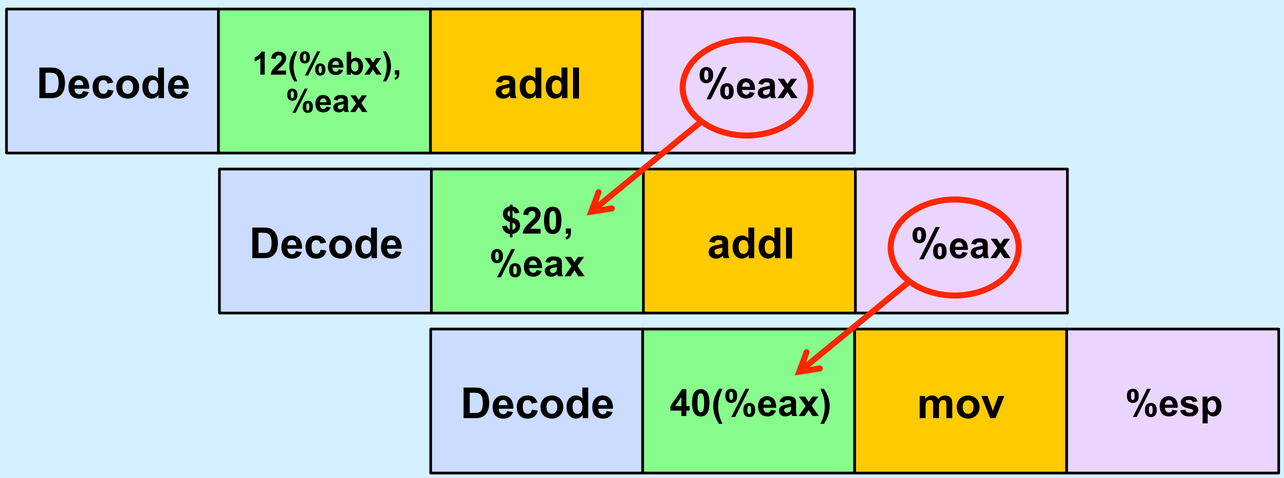
- **Not pipelined**
  - each instruction takes, say, 320 nanoseconds
    - » 320 ns latency
  - 3.125 billion instructions/second (GIPS)
- **Pipelined**
  - each instruction still takes 320 ns
    - » latency still 320 ns
  - an instruction completes every 80 ns
    - » 12.5 GIPS throughput

Hazards ...

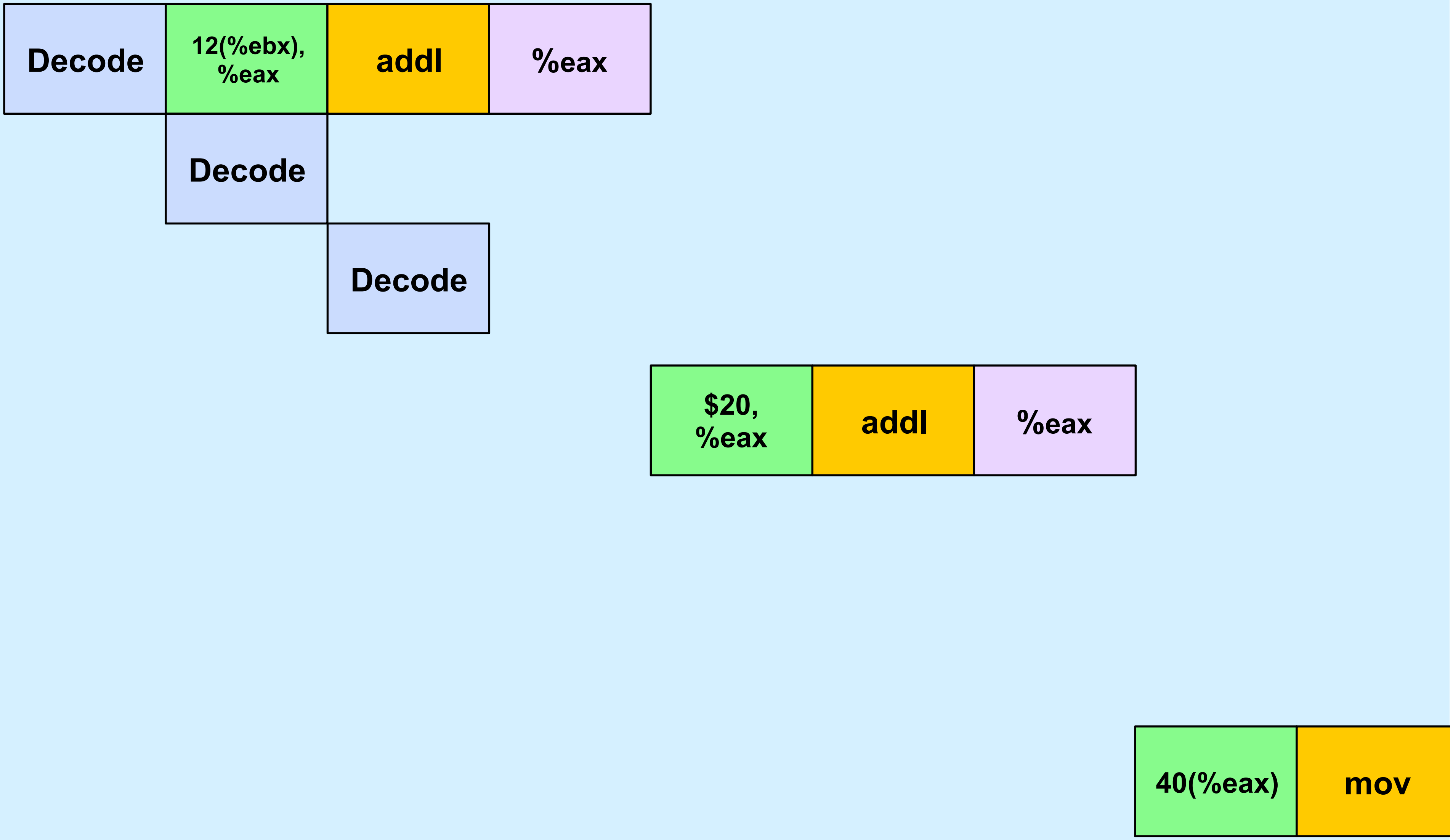


Data Hazards

```
addl 12(%ebx), %eax
addl $20, %eax
movl 40(%eax), %esp
```



Coping


Decode
12(%ebx), %eax
addl
%eax
Decode
Decode
$20, %eax
addl
%eax
40(%eax)
mov

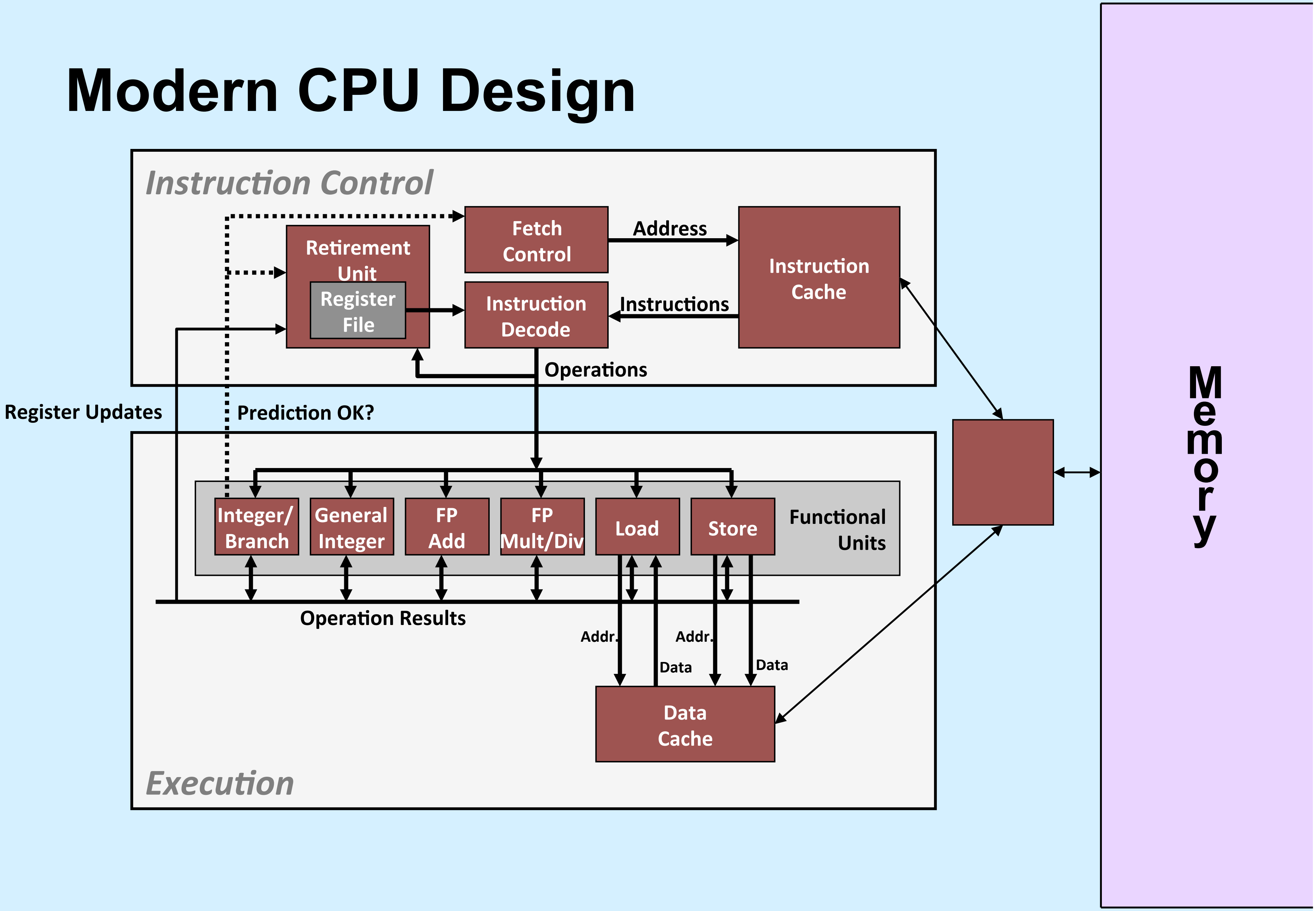
Control Hazards

```
  movl $0, %ecx
.L2:
  movl %edx, %eax
  andl $1, %eax
  addl %eax, %ecx
  shrl $1, %edx
  jne  .L2 # what goes in the pipeline?
  movl %ecx, %eax
  ...
```

Coping: Guess ...

- **Branch prediction**
  - assume, for example, that conditional branches are always taken
  - but don't do anything to registers or memory until you know for sure

Modern CPU Design



Performance Realities

There's more to performance than asymptotic complexity

- **Constant factors matter too!**
  - **easily see 10:1 performance range depending on how code is written**
  - **must optimize at multiple levels:**
    - » **algorithm, data representations, procedures, and loops**
- **Must understand system to optimize performance**
  - **how programs are compiled and executed**
  - **how to measure program performance and identify bottlenecks**
  - **how to improve performance without destroying code modularity and generality**

Optimizing Compilers

- **Provide efficient mapping of program to machine**
  - register allocation
  - code selection and ordering (scheduling)
  - dead code elimination
  - eliminating minor inefficiencies
- **Don’t (usually) improve asymptotic efficiency**
  - up to programmer to select best overall algorithm
  - big-O savings are (often) more important than constant factors
    - » but constant factors also matter
- **Have difficulty overcoming “optimization blockers”**
  - potential memory aliasing
  - potential procedure side-effects

Limitations of Optimizing Compilers

- Operate under fundamental constraint
  - must not cause any change in program behavior
  - often prevents it from making optimizations that would only affect behavior under pathological conditions
- Behavior that may be obvious to the programmer can be obfuscated by languages and coding styles
  - e.g., data ranges may be more limited than variable types suggest
- Most analysis is performed only within procedures
  - whole-program analysis is too expensive in most cases
- Most analysis is based only on *static* information
  - compiler has difficulty anticipating run-time inputs

- When in doubt, the compiler must be conservative

Generally Useful Optimizations

- **Optimizations that you or the compiler should do regardless of processor / compiler**

- **Code Motion**
  - **reduce frequency with which computation performed**
    - » **if it will always produce same result**
    - » **especially moving code out of loop**

```
void set_row(long *a, long *b,
   long i, long n){
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

→

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

Compiler-Generated Code Motion

```
void set_row(long *a, long *b,
   long i, long n){
    long j;
    for (j = 0; j < n; j++)
         a[n*i+j] = b[j];
}
```

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

```
set_row:
        testq   %rcx, %rcx              # Test n
        jle     .L1                     # If 0, goto done
        imulq   %rcx, %rdx              # i *= n
        leaq    (%rdi,%rdx,8), %rdi     # rowp = A + n*i*8
        movl    $0, %eax                # j = 0
.L3:                                  # loop:
        movq    (%rsi,%rax,8), %rdx     # t = b[j]
        movq    %rdx, (%rdi,%rax,8)     # rowp[j] = t
        addq    $1, %rax                # j++
        cmpq    %rcx, %rax              # Compare n:j
        jg      .L3                     # If >, goto loop
.L1:                                  # done:
        rep ; ret
```

Reduction in Strength

- 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 Intel Nehalem, integer multiply requires 3 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 += n;
}
```

Share Common Subexpressions

- **Reuse portions of expressions**
- **Compilers often not very sophisticated in exploiting arithmetic properties**

```
/* Sum neighbors of i,j */
up =    val[(i-1)*n + j  ];
down =  val[(i+1)*n + j  ];
left =  val[i*n     + j-1];
right = val[i*n     + j+1];
sum = up + down + left + right;
```

```
long inj = i*n + j;
up =    val[inj - n];
down =  val[inj + n];
left =  val[inj - 1];
right = val[inj + 1];
sum = up + down + left + right;
```

3 multiplications: i*n, (i–1)*n, (i+1)*n

1 multiplication: i*n

```
leaq   1(%rsi), %rax   # i+1
leaq   -1(%rsi), %r8   # i-1
imulq  %rcx, %rsi      # i*n
imulq  %rcx, %rax      # (i+1)*n
imulq  %rcx, %r8       # (i-1)*n
addq   %rdx, %rsi      # i*n+j
addq   %rdx, %rax      # (i+1)*n+j
addq   %rdx, %r8       # (i-1)*n+j
```

```
imulq    %rcx, %rsi   # i*n
addq     %rdx, %rsi   # i*n+j
movq     %rsi, %rax   # i*n+j
subq     %rcx, %rax   # i*n+j-n
leaq     (%rsi,%rcx), %rcx # i*n+j+n
```

Quiz 1

The fastest means (on the Intel Nehalem) for evaluating

```
n*n + 2*n + 1
```

requires exactly:

a) 2 multiplies and 2 additions

b) one multiply and two additions

c) one multiply and one addition

d) three additions

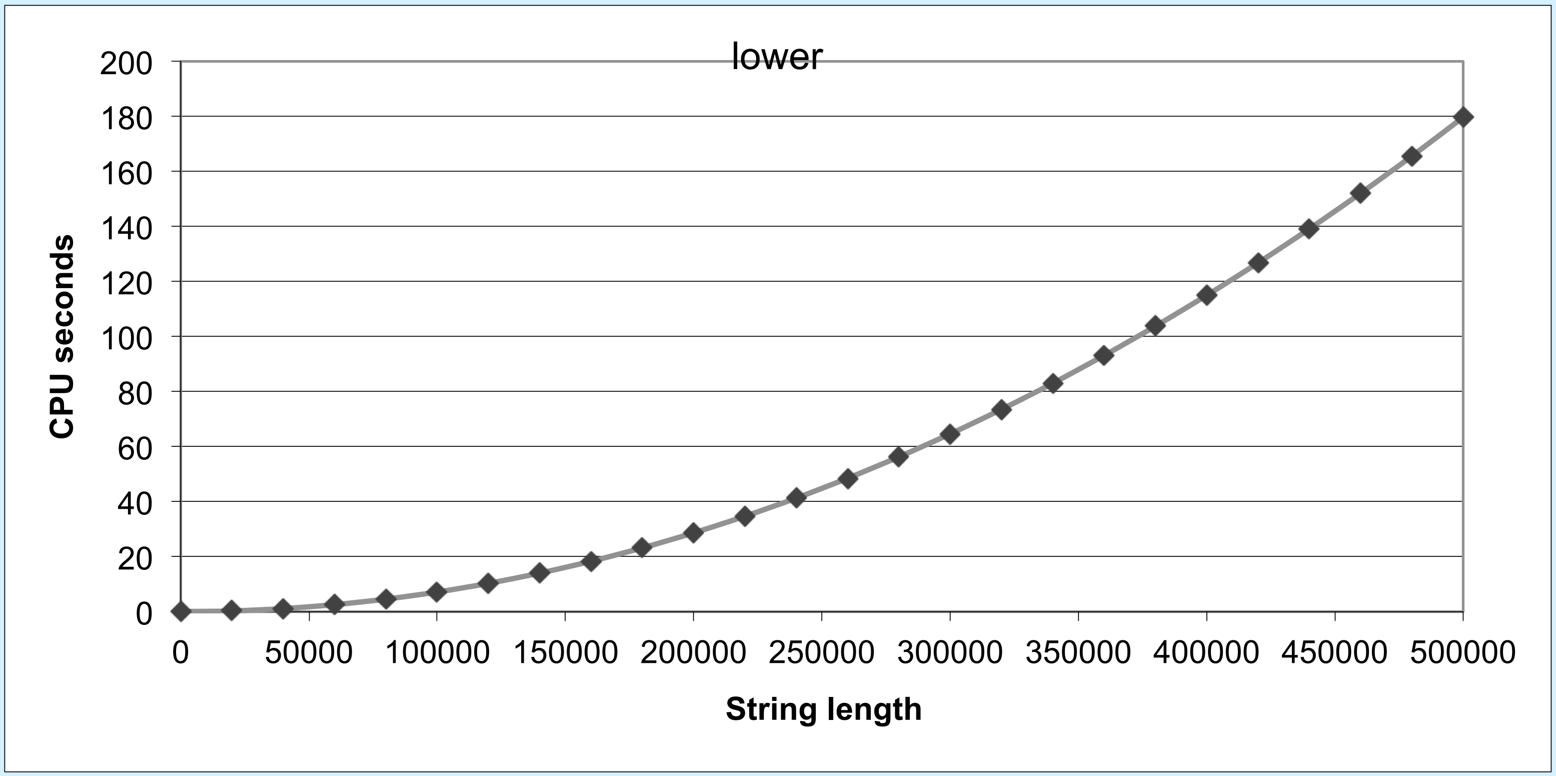
Optimization Blocker #1: Procedure Calls

- **Procedure to convert string to lower case**

```
void lower(char *s){
  int i;
  for (i = 0; i < strlen(s); i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

Lower Case Conversion Performance

- Time quadruples when string length doubles
- Quadratic performance



Convert Loop To Goto Form

```
void lower(char *s){
   int i = 0;
   if (i >= strlen(s))
     goto done;
 loop:
   if (s[i] >= 'A' && s[i] <= 'Z')
       s[i] -= ('A' - 'a');
   i++;
   if (i < strlen(s))
     goto loop;
 done:
}
```

- **`strlen` executed every iteration**

Calling Strlen

```
size_t strlen(const char *s){
    size_t length = 0;
    while (*s != '\0') {
       s++;
       length++;
    }
    return length;
}
```

- **strlen performance**
  - **only way to determine length of string is to scan its entire length, looking for null character**
- **Overall performance, string of length N**
  - **N calls to strlen**
  - **overall O(N^2) performance**

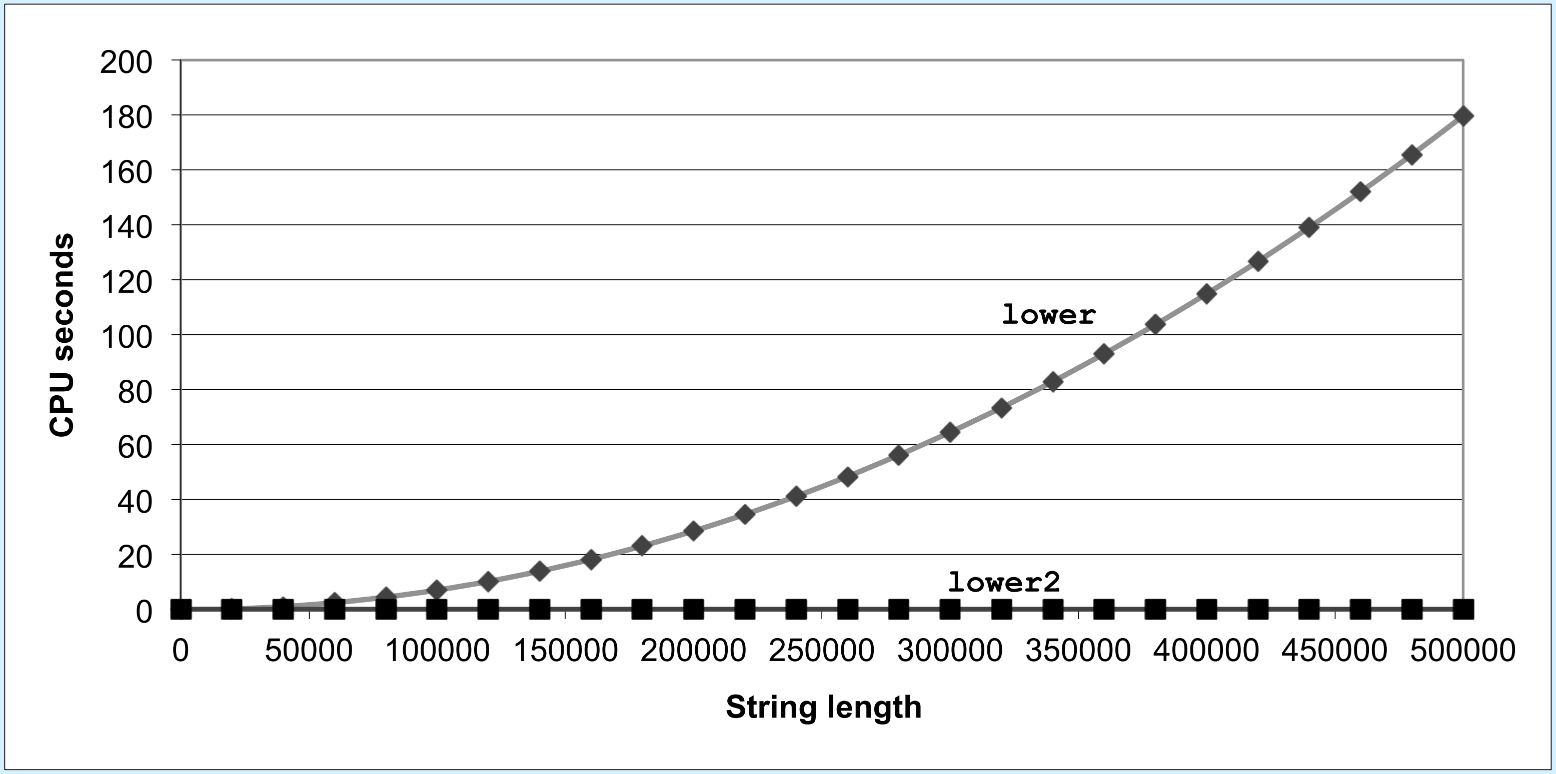
Improving Performance

```
void lower2(char *s){
  int i;
  int len = strlen(s);
  for (i = 0; i < len; i++)
    if (s[i] >= 'A' && s[i] <= 'Z')
      s[i] -= ('A' - 'a');
}
```

- **Move call to `strlen` outside of loop**
  - since result does not change from one iteration to another
  - form of code motion

Lower-Case Conversion Performance

- **Time doubles when string-length doubles**
  - **linear performance of lower2**



Optimization Blocker: Procedure Calls

- ***Why couldn't compiler move `strlen` out of inner loop?***
  - procedure may have side effects
    - » alters global state each time called
  - function may not return same value for given arguments
    - » depends on other parts of global state
    - » procedure `lower` could interact with `strlen`
- **Warning:**
  - compiler treats procedure call as a black box
  - weak optimizations near them
- **Remedies:**
  - use of `inline` functions
    - » gcc does this with –O2
  - do your own code motion

```
int lencnt = 0;
size_t strlen(const char *s){
    size_t length = 0;
    while (*s != '\0') {
        s++; length++;
    }
    lencnt += length;
    return length;
}
```

Memory Matters

```c
/* Sum rows of n X n matrix a
   and store result in vector b  */
void sum_rows1(long *a, long *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
# sum_rows1 inner loop
.L3:
   movq    (%rdi), %rcx         # rcx = *aptr
   addq    %rcx, (%rsi,%rax,8)  # b[i] += rcx
   addq    $8, %rdi             # aptr++
   cmpq    %r8, %rdi
   jne     .L3
```

- **Code updates `b[i]` on every iteration**
- **Why couldn't compiler optimize this away?**

Memory Aliasing

```
/* Sum rows of n X n matrix a
   and store result in vector b  */
void sum_rows1(int *a, int *b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
int A[9] =
  { 0,   1,   2,
    4,   8,  16,
   32,  64, 128};

int *B = &A[3];

sum_rows1(A, B, 3);
```

Value of `B`:

```
init:  [4, 8, 16]
```

```
i = 0: [3, 8, 16]
```

```
i = 1: [3, 22, 16]
```

```
i = 2: [3, 22, 224]
```

- **Code updates `b[i]` on every iteration**
- **Must consider possibility that these updates will affect program behavior**

Removing Aliasing

```
/* Sum rows of n X n matrix a
   and store result in vector b  */
void sum_rows2(int *a, int *b, int n) {
    long i, j;
    for (i = 0; i < n; i++) {
         int val = 0;
         for (j = 0; j < n; j++)
             val += a[i*n + j];
          b[i] = val;
    }
}
```

```
# sum_rows2 inner loop
.L4:
   addq    (%rdi), %rax
   addq    $8, %rdi
   cmpq    %rcx, %rdi
   jne     .L4
```

- **No need to store intermediate results**

Optimization Blocker: Memory Aliasing

- Aliasing
  - two different memory references specify single location
  - easy to have happen in C
    - since allowed to do address arithmetic
    - direct access to storage structures
  - get in habit of introducing local variables
    - accumulating within loops
    - your way of telling compiler not to check for aliasing

C99 to the Rescue

- **New attribute**
  - **restrict**
    - **applied to a pointer, tells the compiler that the object pointed to will be accessed only via this pointer**
    - **compiler thus doesn't have to worry about aliasing**
    - **but the programmer does ...**
    - **syntax**

```
int *restrict pointer;
```

Memory Matters, Fixed

```
/* Sum rows of n X n matrix a
   and store result in vector b  */
void sum_rows3(long *restrict a, long *restrict b, long n) {
    long i, j;
    for (i = 0; i < n; i++) {
        b[i] = 0;
        for (j = 0; j < n; j++)
            b[i] += a[i*n + j];
    }
}
```

```
# sum_rows1 inner loop
.L3:
   addq    (%rdi), %rax
   addq    $8, %rdi
   cmpq    %rcx, %rdi
   jne     .L3
```

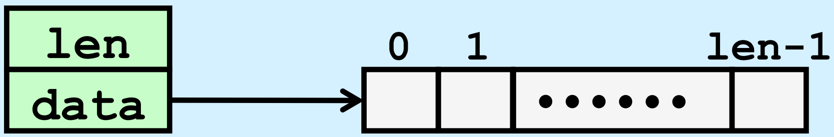
- **Code doesn't update `b[i]` on every iteration**

Exploiting Instruction-Level Parallelism

- Need general understanding of modern processor design
  - hardware can execute multiple instructions in parallel
- Performance limited by data dependencies
- Simple transformations can have dramatic performance improvement
  - compilers often cannot make these transformations
  - lack of associativity and distributivity in floating-point arithmetic

Benchmark Example: Datatype for Vectors

```
/* data structure for vectors */
typedef struct{
    int len;
    data_t *data;
} vec_t, *vec_ptr_t;
```




```
/* retrieve vector element and store at val */
int get_vec_element(vec_ptr_t v, int idx, data_t *val){
    if (idx < 0 || idx >= v->len)
        return 0;
    *val = v->data[idx];
    return 1;
}

/* return length of vector */
int vec_length(vec_ptr_t v) {
     return v->len;
}
```

Benchmark Computation

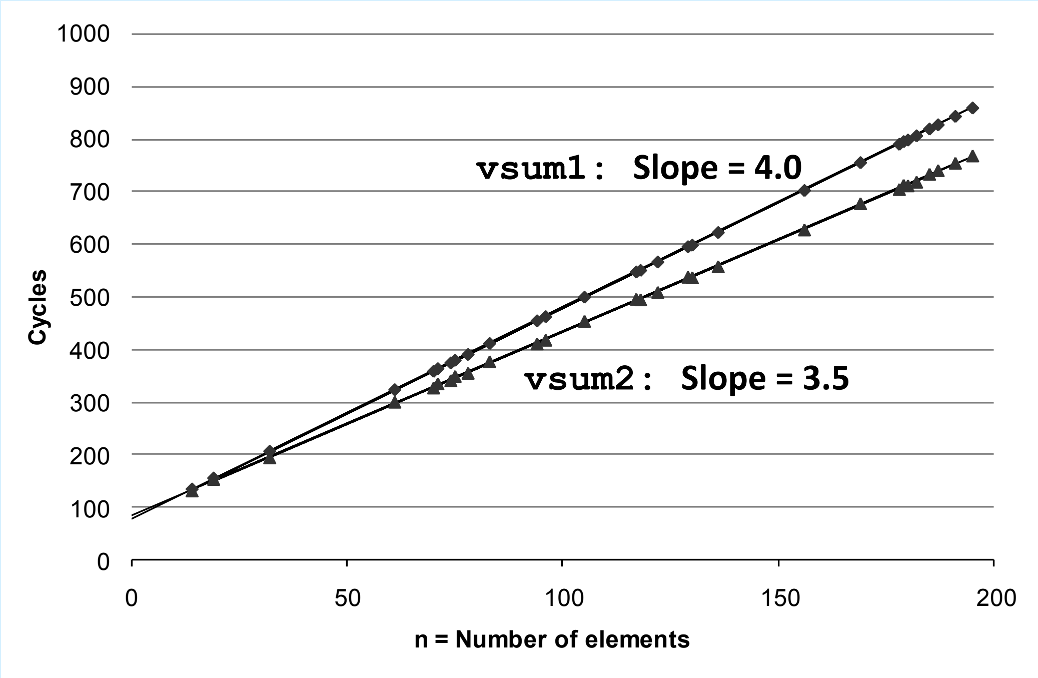
```
void combine1(vec_ptr_t v, data_t *dest){
    long int i;
    *dest = IDENT;
    for (i = 0; i < vec_length(v); i++) {
      data_t val;
      get_vec_element(v, i, &val);
      *dest = *dest OP val;
    }
}
```

Compute sum or product of vector elements

- **Data Types**
  - use different declarations for `data_t`
    - » `int`
    - » `float`
    - » `double`
- **Operations**
  - use different definitions of `OP` and `IDENT`
    - » `+, 0`
    - » `*, 1`

Cycles Per Element (CPE)

- Convenient way to express performance of program that operates on vectors or lists
- Length = n
- T = CPE*n + Overhead
  - CPE is slope of line



Benchmark Performance

```
void combine1(vec_ptr_t v, data_t *dest){
    long int i;
    *dest = IDENT;
    for (i = 0; i < vec_length(v); i++) {
      data_t val;
      get_vec_element(v, i, &val);
      *dest = *dest OP val;
    }
}
```

Compute sum or product of vector elements

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	29.0	29.2	27.4	27.9
Combine1 –O1	12.0	12.0	12.0	13.0

Move vec_length

```
void combine2(vec_ptr_t v, data_t *dest){
    long int i;
    long int length = vec_length(v);
    *dest = IDENT;
    for (i = 0; i < length; i++) {
       data_t val;
       get_vec_element(v, i, &val);
       *dest = *dest OP val;
    }
}
```

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 unoptimized	29.0	29.2	27.4	27.9
Combine1 –O1	12.0	12.0	12.0	13.0
Combine2	8.03	8.09	10.09	12.08

Eliminate Procedure Calls

```
void combine3(vec_ptr_t v, data_t *dest){
    long int i;
    long int length = vec_length(v);
    data_t *data = get_vec_start(v);
    *dest = IDENT;
    for (i = 0; i < length; i++) {
      *dest = *dest OP data[i];
    }
}
```

```
data_t *get_vec_start(
      vec_ptr v) {
   return v->data;
}
```

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine2	8.03	8.09	10.09	12.08
Combine3	6.01	8.01	10.01	12.02

Eliminate Unneeded Memory References

```
void combine4(vec_ptr_t v, data_t *dest){
  int i;
  int length = vec_length(v);
  data_t *d = get_vec_start(v);
  data_t t = IDENT;
  for (i = 0; i < length; i++)
    t = t OP d[i];
  *dest = t;
}
```

Method	Integer		Double FP	
Operation	Add	Mult	Add	Mult
Combine1 –O1	12.0	12.0	12.0	13.0
Combine4	2.0	3.0	3.0	5.0

Quiz 2

Combine4 is pretty fast; we've done all the "obvious" optimizations. How much faster will we be able to make it? (Hint: it involves taking advantage of pipelining and multiple functional units on the chip.)

a) 1× (it's already as fast as possible)
b) 2× – 4×
c) 16× – 64×