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Lecture 1. Introduction

- **What is ‘computer science?’**

    1. **The science of manipulating ‘information’**
    2. **Designing and building systems that do (1); e.g., computers, software, networks, …**

- **What does COS 126 cover?**

    Science (the elegant ideas):

    algorithms and algorithm design (recursion, efficiency, data structures)

    theory of computation (what is computable, instrinsically ‘hard’ problems)

    Engineering (the nuts and bolts):

    programming (the C programming language, machine language)

    basic computer architecture (instruction sets)

    software systems (operating systems, virtual memory, compilers)

- **A better name for ‘Computer Science’ might be ‘Computing’**

    “*Any field that calls itself a science probably isn’t one.*”

    — anonymous?

What You'll Learn

- **Just enough to make you dangerous…**
- **Science:**

  how to design algorithms to solve specific problems

  how to choose efficient data structures and algorithms

  how and when to use recursion

  how to recognize hard problems
- **Engineering:**

  how to write small applications in the C programming language

  how to use C pointers to build dynamic data structures

  how to build a program from smaller subprograms

  how to write assembly language programs

  how programs in high-level languages are translated into machine language

  how to use the UNIX operating system and its tools

  how to browse the World Wide Web
- **COS 126 is about computer science, *not* about getting a job, but 126 will help…**

Survival Tips

- **Attend lectures and classes**
- **Go to a ‘Getting Started’ session**
- **Do the reading; cruise the books on reserve (at the Engineering Library, EQuad)**
- **Do the exercises; understand the solutions**
- **Visit the COS 126 Help! Web page when you have questions**
- **Browse the COS 126 Web often; visit ‘What’s New’ perhaps daily**
- **Do the programming assignments**
- **Digest programming assignments as soon as they appear on the COS 126 Web**
- **Start on programming assignments *early***
- **Think before you write code; compose first, then write code**
- **Use the lab undergraduate teaching assistants**
- **Ask for help — as soon as you need it!**

Course Information

- Nearly *all* COS 126 material is available *only* on the World Wide Web

  detailed course information (grading, policies, etc.)
  lecture slides (buy the paper copy, too)
  course schedule
  programming assignments
  exercises
  helpful information
  frequently asked questions
  etc.

  Exceptions: first handout (how to browse the Web)
  exams (two *evening* midterms, final)
  perhaps a few ‘crib’ sheets

- You will submit all assignments electronically; timestamps will tell us when
- *You* are responsible for getting the necessary material and meeting deadlines
- Save trees — don’t print Web pages unnecessarily

Surfing the Web

- **use `netscape` (or another Web browser) to access course materials**

  `%` *`netscape http://www.cs.princeton.edu/courses/cs126/ &`*↵

  slanted font indicates what you type; ↵ denotes the 'enter' or 'new-line' key

- **The course URL — universal resource locator — is**

  `http://www.cs.princeton.edu/courses/cs126/`

  You can browse the course Web from *anywhere*, if you have computer and Internet access (e.g. America Online)

Lecture 2. An Introduction to C

- **Everyone's first C program: `hello.c`**

```
/* Everyone's first
    C program. */
#include <stdio.h>

int main(void) {
    printf("Hello world!\n");
    return 0;
}
```

- **To compile, load, and execute `hello.c`:**

```
% lcc hello.c
% a.out
Hello world!
%
```

slanted font indicates what you type

- **Writing and running C programs involves at least 3 steps:**

1. **Using an *editor* (`emacs`) to create a *file* that contains the program (`hello.c`)**
2. **Using a *compiler* (`lcc`) to translate the program from C to 'machine language'**
3. **Issuing a *command* (`a.out`) to execute the machine-language program**

Usually — *OK, always* — you iterate these steps until step 3 is 'correct'

Dissecting hello.c

```
/* Everyone's first
    C program. */
```

`/*` and `*/` enclose *comments*, which document your program or parts of it. The compiler treats a comment as a single space

```
#include <stdio.h>
```

`#include` is a *preprocessor* directive, which causes the compiler to read in standard declarations from the *header file* `stdio.h`

```
int main(void) {
```

Introduces the `main` function, which is where execution begins. `int` is the type of the value returned by `main`, `void` indicates that `main` has no arguments, and the `{` begins the body of the function

```
printf("Hello world!\n");
```

Calls the *standard library* function `printf`, which prints the characters in its *string* argument. `\n` is an *escape sequence* for a new-line character

```
return 0;
```

`main` returns the integer 0, indicating that the program completed successfully

```
}
```

Ends the function `main`

Computing the Sum from 1 to n

```
/*
Compute the sum of the integers
from 1 to n, for a given n.
*/
#include <stdio.h>

int main(void) {
    int i, n, sum;

    sum = 0;
    printf("Enter n:\n");
    scanf("%d", &n);
    i = 1;
    while (i <= n) {
        sum = sum + i;
        i = i + 1;
    }
    printf("Sum from 1 to %d = %d\n", n, sum);
    return 0;
}
```

```
% lcc sum.c
% a.out
Enter n:
100
Sum from 1 to 100 = 5050
%
```

Dissecting sum.c

```
int i, n, sum;
```

This *declaration* introduces three *variables* that can store integers — values of type `int`

```
sum = 0;
```

This *assignment expression* changes the value stored in sum to 0

```
scanf("%d", &n);
```

Calls the *standard library* function `scanf` to read an integer (%d) and store it in n

```
i = 1;
```

Changes the value stored in i to 1

```
while (i <= n) {
    sum = sum + i;
    i = i + 1;
}
```

This *while loop* executes the loop body — the two statements between { and } — repeatedly as long as the value of `i` is less than or equal to the value of n

Expression Evaluation

```
sum = sum + i;
```

This assignment expression means:

> **add the value of `sum` to the value of `i`, then**
> **store that result *back* into the variable `sum`**

The meaning of this assignment — its *semantics* — might be clearer if written as

```
sum + i --> sum;
```

but that's not C (or any other language)

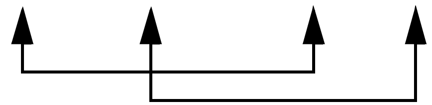
```
i = i + 1;
```

Stores the sum of `i` and 1 back into `i` — increments `i` by 1

```
printf("Sum from 1 to %d = %d\n", n, sum);
```

Calls `printf` to output its first argument; each *conversion specifier* %d causes the value of the corresponding following `int` argument to be printed instead

```
printf("Sum from 1 to %d = %d\n", n, sum);
```



Another Example: Printing a Random Pattern

```
/*
Print a NxN random pattern.
*/
#include <stdlib.h>
#include <stdio.h>

int main(void) {
    int i, j, n, bit;

    scanf("%d", &n);
    for (i = 0; i < n; i = i + 1) {
        for (j = 0; j < n; j = j + 1) {
            bit = (rand()>>14)%2;
            if (bit == 0)
                printf(" ");
            else
                printf("*");
        }
        printf("\n");
    }
    return 0;
}
```

```
% lcc pattern.c
% a.out
20
*  ** *       ******
* *  ** ********   *
  *  ** ***  * * *
 ** *     *     **
*     * * *** *** **
   **   * ** *  ****
     ***  *    *** *
*  * *  ** * ******
  * *   * *    *  *
* *  * * ****** **
*   *     ** * ****
** ***** ***    **
  *** *   * ** * **
 *** *       * **
* **      *****
  ****   **     ** *
    *** ** **  *****
* ** * **    ** ****
   ** *   * **** **
*   * * *       ***
%
```

Dissecting pattern.c

```
for (i = 0; i < n; i = i + 1) {
    …
}
```

This ***for loop*** executes its body (…) n times; it is equivalent to

```
    i = 0;
    while (i < n) {
        …
        i = i + 1;
    }
```

```
for (i = 0; i < n; i = i + 1) {
    for (j = 0; j < n; j = j + 1) {
        …
    }
}
```

These two ***nested for loops*** execute the body of the inner loop $n \times n = n^2$ times

Dissecting pattern.c, cont'd

```
bit = (rand()>>14)%2;
```

This assignment expression

calls the standard function `rand`, which returns a 15-bit *random number*, *shifts* that number right by 14 bits, computes the *remainder* of dividing that number by 2;

so, `bit` is assigned 0 or 1

```
if (bit == 0)
    printf(" ");
else
    printf("*");
```

This *if-else statement* compares `bit` with 0;
it prints a space if `bit` is equal to 0, or an asterisk if `bit` is not equal to 0

For More Information

- **Check out the other texts on C programming (on reserve in the Eng. Library):**

  Kelley and Pohl, *C by Dissection: The Essentials of C Programming*, 3/e

  Kelley and Pohl, *A Book on C: Programming in C*, 3/e

  Roberts, *The Art and Science of C: An Introduction to Computer Science*

- **Check out the reference books (on reserve):**

  Harbison and Steele, *C: A Reference Manual*, 4/e

  Kernighan and Ritchie, *The C Programming Language*, 2/e

- **Cruise the sample programs on the COS 126 Help! Web page:**

  follow the 'Sample Programs' link to `hello.c`, `sum.c`, etc.

Lecture 3. More About C

- **Programming languages have their lingo**
- **Programming *language***

Types	are 'categories' of values	`int`, `float`, `char`
Constants	are values of basic types	`0`, `123.6`, `"Hello"`
Variables	name locations that hold values	`i`, `sum`
Expressions	compute values/change variables	`sum = sum + i`
Statements	control a program's *flow of control*	`while`, `for`, `if-else`
Functions	encapsulate statements	`main`
Modules	collections of related variables & functions	

a.k.a. 'compilation units'

- **Programming *environment***

  Text editor (`emacs`, `vi`, `sam`)

  Compiler (`lcc`, `cc`, `gcc`)

  Linker/loader (`ld`); used rarely, because `lcc` runs it

  Debugger (gdb)

Types

- A ***type*** determines

  a set of ***values***, and

  what ***operations*** can be performed on those values

- ***Scalar*** types

`char`	a 'character'; typically a 'byte' — 8 bits
`int`	a signed integer; typically values from –2147483648 to 2147483647
`unsigned`	an unsigned integer; typically values from 0 to 4294967295
`float`	single-precision floating point
`double`	double-precision floating point

- ***Pointer*** types: *much* more later…

- ***Aggregate*** types: values that have ***elements*** or ***fields***, e.g., arrays, structures

Constants

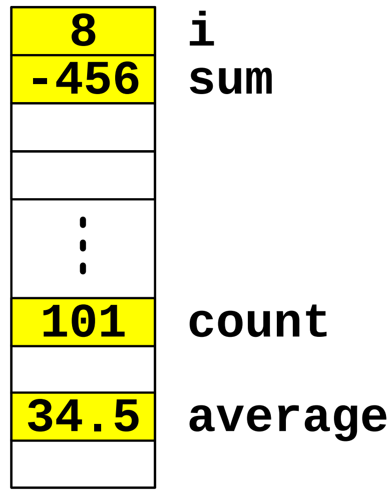
- **Constant values of the scalar types**

`char`	`'a'`	character constant (use single quotes)
	`'\035'`	character code 35 octal, or base 8
	`'\x29'`	character code 29 hexadecimal, or base 16
	`'\t'`	tab (`'\011'`, do '`man ascii`' for details)
	`'\n'`	newline (`'\012'`)
	`'\\'`	backslash
	`'\''`	single quote
	`'\b'`	backspace (`'\010'`)
	`'\0'`	null character; i.e., the character with code 0
`int`	`156`	decimal (base 10) constant
	`0234`	octal (base 8)
	`0x9c`	hexadecimal (base 16)
`unsigned`	`156U`	decimal
	`0234U`	octal
	`0x9cU`	hexadecimal
`float`	`15.6F`	
	`1.56e1F`	
`double`	`15.6`	'plain' floating point constants are `doubles`
	`1.56E1L`	

Variables

- **A variable is the name of a *location in memory* that can hold values**

```
int i, sum;
float average;
unsigned count;

i = 8;
sum = -456;
count = 101U;
average = 34.5;
```



- **A variable has a *type*; it can hold only values of that type**

- **Assignments *change* the values of variables**

```
sum = sum + i;
```

changes the value of `sum` **to -448**

- **Variables must be *initialized* before they are used**

```
#include <stdio.h>

int main(void) {
    int x;

    printf("x = %d\n", x);
    return 0;
}
```

output is *undefined*!

Expressions

- **Expressions use the values of variables and constants to compute new values**
- **Binary arithmetic operators take two operands produce one result**

`+`	`-`	**addition, subtraction**
`*`	`/`	**multiplication, division**
`%`		**remainder (a.k.a. modulus)**

- **Type of result depends on type of operands**

```
int i; unsigned u; float f;
```

+	i	u	f
i	int	unsigned	float
u	?	unsigned	float
f	?	?	float

`i + i` **specifies** `int` **addition and yields an** `int` **result**

`int` **and** `unsigned` **division _truncate_: 7/2 is 3, but 7.0/2 is 3.5**

- **Unary operators take one operand and produce one result**

`-`	`+`	**negation, 'affirmation' (just returns its operand's value)**

Precedence and Associativity

- Operator precedence and associativity dictate the ***order of expression evaluation***
- ***Precedence*** dictates which subexpressions get evaluated first

  highest — unary `-` `+`

  binary `*` `/` `%`

  lowest — binary `+` `-`

  `-2*a + b` is evaluated as if written as `(((-2)*a) + b)`

- ***Associativity*** dictates the evaluation order for expressions with several operators of the same precedence

  all arithmetic operators have ***left-to-right*** associativity

  `a + b + c` is evaluated as if written as `((a + b) + c)`

- Use ***parentheses*** to force a specific order of evaluation

  `-2*(a + b)` computes `-2`
`a + b`
the product of these two values

Assignments

- Assignment expressions ***store*** values in variables

  variable* = *expression

  the type of *expression* must be

  the same as the type of *variable*
  convertible to the type of *variable*

  `int i; unsigned u; float f;`

=	i	u	f
i	int	int	int
u	unsigned	unsigned	unsigned
f	float	float	float

- Augmented assignments combine a binary operator with assignment

  variable* += *expression
  variable* -= *expression
  ...

  `sum += i` **is the same as** `sum = sum + i`

Increment/Decrement

- **Prefix and postfix operators `++` `--` increment and decrement operand by 1**

  `++n` adds 1 to n

  `--n` subtracts 1 from n

- ***Prefix*** **operator increments operand** ***before*** **returning the** ***new*** **value**

```
n = 5;
x = ++n;
```

  x is 6, n is 6

- ***Postfix*** **operator increments operand** ***after*** **returning the** ***old*** **value**

```
n = 5;
x = n++;
```

  x is 5, n is 6

- **Operands of `++` and `--` must be** ***variables***

```
++1
2 + 3++
```

  are illegal

Idiomatic C

- **`sum.c` (in `sum2.c`) rewritten using common idioms involving += and ++**

```
/*
Compute the sum of the integers
from 1 to n, for a given n.
*/
#include <stdio.h>

int main(void) {
	int i, n, sum = 0;

	printf("Enter n:\n");
	scanf("%d", &n);
	for (i = 1; i <= n; i++)
		sum += i;
	printf("Sum from 1 to %d = %d\n", n, sum);
	return 0;
}
```

- **`scanf` is a form of assignment; it _**changes**_ n**

Statements

- **Expression statements**

  expression$_{opt}$ **;**

```
sum += i;
printf("Sum from 1 to %d = %d\n", n, sum);
```

- **Selection statements**

  if (***conditional*** **)** ***statement***
  if (***conditional*** **)** ***statement*** **else** ***statement***

```
if (x > max) max = x;
if (bit == 0) printf(" "); else printf("*");
```

  switch (***expression*** **) { case** ***constant*** **:** ***statement***... **default :** ***statement*** **}**

- **Iteration statements (loops)**

  while (***conditional*** **)** ***statement***

```
while (i <= n) { sum += i; i++; }
```

  for (***expression***$_{opt}$ **;** ***conditional***$_{opt}$ **;** ***expression***$_{opt}$ **)** ***statement***

```
for (i = 1; i <= n; i++) sum += i;
for (;;) printf("Help! I'm looping\n");
```

  do ***statement*** **while (** ***expression*** **) ;**

```
do { sum += i; ++i; } while (i <= n);
```

Statements, cont'd

- **Compound statements**

  { *declaration*$_{opt}$... *statement*... }

```
for (j = 0; j < n; j = j + 1) {
    int bit = (rand()>>14)%2;
    if (bit == 0)
        printf(" ");
    else
        printf("*");
}
```

- **Others**

  `return` *expression*$_{opt}$ `;`

```
return;
return 0;
return -2*(a + b);
```

  `break ;`
  `continue ;`

- **Keywords (`if else while do for switch case` ...) *cannot* be used as variables**

Conditional Expressions

- **A *conditional* expression is *any* expression that evaluates to zero or nonzero**
- **There is no 'Boolean' type; nonzero is true, zero is false**
- **Relational operators compare two arithmetic values (or pointers) and yield 0 or 1**

`<`	`<=`	**less than, less than or equal to**
`==`	`!=`	**equal to, not equal to**
`>`	`>=`	**greater than, greater than or equal to**

- **Logical connectives**

***conditional*$_1$ `&&` *conditional*$_2$**	**1 if both *conditionals* are nonzero; 0 otherwise**
***conditional*$_1$ `||` *conditional*$_2$**	**1 if either *conditional* is nonzero; 0 otherwise**

conditionals are evaluated left-to-right *only as far as is necessary* :

`&&`	**stops when the outcome is known to be zero**
`||`	**stops when the outcome is known to be nonzero**

- **Associativity: left to right; precedence: below the arithmetic operators**

highest	**arithmetic operators**	
	`< <= >= >`	`a + b < max || max == 0 && a == b`
	`== !=`	**is interpreted as if written**
	`&&`	`((a + b) < max) || (max == 0 && (a == b))`
lowest	`||`	

Lecture 4. Functions and Modules

- ***Functions*** are the basic building blocks of C programs
- Programmer-defined functions

  application-specific: good for only the application in which they appear

  general-purpose: good for a wide range of applications
- Libraries hold collections of ‘standard’ general-purpose functions

I/O	*Math*	*Strings*	*Other*	*...*
`printf`	`sqrt`	`strcmp`	`rand`	
`fprintf`	`sin`	`strcpy`	`malloc`	
`scanf`	`cos`	`strlen`	`atoi`	
...	...	...	...	

  Use standard functions whenever possible; reuse, don’t reinvent
- A function ***declaration*** gives the types of the arguments and the return type
- A function ***definition*** is also a declaration plus a function ***body***
- A function ***body*** is a compound statement that implements the function
- A function ***call*** invokes the named function, which executes, then returns

  the ***caller***, or calling function, is the function in which the function call appears
  the ***callee*** , or called function, is the function that is invoked

Computing e^x

- **Goal: write a program to approximate e^x, where $e = 2.718282\ldots$**

$$e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \ldots$$

where $n! = n \cdot (n-1) \cdot (n-2) \cdot \ldots \cdot 3 \cdot 2 \cdot 1$

- **Compute e^x to a given precision: iterate until e^x changes by less than the precision**

For x = 1.0, precision = 0.0001

i	$x^i / i!$	e^x
1	1.000000	1.000000
2	1.000000	1.000000
3	0.500000	2.000000
4	0.166667	2.500000
5	0.041667	2.666667
6	0.008333	2.708333
7	0.001389	2.716667
8	0.000198	2.718056
9	0.000025	2.718254

```
% lcc ex.c
% a.out
Enter x and the precision:
1 .00001
e^1.000000 = 2.718282; should be 2.718282
% a.out
Enter x and the precision:
2 .0001
e^2.000000 = 7.389047; should be 7.389056
```

Computing e^x, cont'd

```
#include <stdio.h>
#include <math.h>

float epowx(float, float);

int main(void) {
    float precision, x, ex;

    printf("Enter x and the precision:\n");
    scanf("%f%f", &x, &precision);
    ex = epowx(x, precision);
    printf("e^%f = %f; should be %f\n", x, ex, exp(x));
    return 0;
}

float epowx(float x, float epsilon) {
    int i;
    float ex = 1.0, prevex = 0.0, num = 1.0, denom = 1.0;

    i = 1;
    while (fabs(ex - prevex) > epsilon) {
        prevex = ex;
        num *= x;
        denom *= i++;
        ex += num/denom;
    }
    return ex;
}
```

Dissecting ex.c

```
#include <math.h>
```

Includes the standard header `math.h`, which contains *declarations* for the standard library functions exp and `fabs`

```
float epowx(float, float);
```

This *function declaration*, or *prototype*, says that epowx is a function that takes 2 `float` arguments and returns a `float` value

Functions must be declared (or defined) before they are used

```
scanf("%f%f", &x, &precision);
```

***Calls* `scanf` to read two floating-point values (`%f`) and store them in x and `precision`**

```
ex = epowx(x, precision);
```

***Calls* epowx with the values of x and `precision` just read; epowx returns a `float`, which is stored in ex**

`main` is the *caller*, epowx is the *callee*

```
printf("e^%f = %f; should be %f\n", x, ex, exp(x));
```

***Calls* exp`(x)` to compute the 'real' value of e^x, then *calls* `printf` with 4 arguments: a format string, the value of x, the value of ex, and the value returned by exp; *conversion specifier* `%f` prints the corresponding argument as a float**

Dissecting ex.c, cont'd

```
float epowx(float x, float epsilon) {
    ...
}
```

The *function definition* for epowx; x and `epsilon` are the function *parameters*, both `floats`, and epowx returns a value of type `float`; { ... } contains the *body*

```
int i;
float ex = 1.0, prevex = 0.0, num = 1.0, denom = 1.0;
```

These *declarations* specify the *local variables* in epowx and initialize all but `i`

```
i = 1;
while (fabs(ex - prevex) > epsilon) {
    prevex = ex;
    num *= x;
    denom *= i++;
    ex += num/denom;
}
```

This loop adds terms in the series until the difference between successive values of ex is less than or equal to `epsilon`; `fabs` is a standard library function

```
return ex;
```

This *return statement* returns the value of ex to the caller

Scope (a.k.a. Visibility)

- **The *scope* of an identifier is that part of the program in which the identifier can be used**
- ***Declarations* of parameters and local variables *introduce new identifiers***

  The scope of a function parameter is the body of the function

  The scope of a local variable extends from its declaration to the end of the compound statement in which the declaration appears

- **Identifiers in different scopes are *unrelated*, even if they have the same name**

```
int main(void) {
    float precision, x, ex;

    …
    return 0;
}
```

scope of x, ex

```
float epowx(float x, float epsilon) {
    int i;
    float ex = 1.0, prevex = 0.0, …;

    …
    return ex;
}
```

scope of x

scope of ex

Scope, cont'd

- **Cannot declare the same identifier *twice* in the same scope**

```
float epowx(float x, float epsilon) {
    int x;
    ...
}
```

error!

- **Local declarations 'hide' parameter declarations and outer-level local declarations**

```
f(int x, int a) {
    int y, b;

    y = x + a*b;
    if (...) {
        int a, b;
        ...
        y = x + a*b;
    }
}
```

a hides parameter a; b hides outer-level local b

- **Some consider it poor style to hide outer-level identifiers**

Arguments and Locals

- ***Local*** **variables are** ***temporary*** **variables**

  Created **upon entry to the function in which they are declared**

  Destroyed **upon return**

- ***Arguments*** **are transmitted** ***by value***

  the values of the actual arguments are ***copied*** **to the formal parameters**

- **Arguments are** ***initialized local variables*** **and can be used just like any locals**

```
/* Illustrate call-by-value. */
#include <stdio.h>

void f(int a, int x) {
    printf("a = %d, x = %d\n",
        a, x);
    a = 3;
    {
        int x = 4;
        printf("a = %d, x = %d\n",
            a, x);
    }
    printf("a = %d, x = %d\n", a, x);
    x = 5;
}
```

```
int main(void) {
    int a = 1, b = 2;

    f(a, b);
    printf("a = %d, b = %d\n",
        a, b);
    return 0;
}

% lcc args.c
% a.out
a = 1, x = 2
a = 3, x = 4
a = 3, x = 2
a = 1, b = 2
%
```

- **Some consider it poor style to modify arguments**

Global Variables

- A ***global variable*** is defined or declared outside of functions
- Globals are ***'permanent'*** variables

  Created when the program begins; ***destroyed*** when the program terminates

- The ***scope*** of global is from the point of declaration to the end of the file

  in file `foo.c`:

```
int main(void) {
    ...
}

int max = 0;

void compute(...) {
    ...
}
```

`max` ***cannot*** be used here (inside `main`)

`max` ***can*** be used here (inside `compute`)

- Parameters and locals 'hide' globals with the same names

```
void compute(...) {
    int max;
    ...
}
```

local `max` hides global `max`

- Global variables ***are*** initialized to 0 by default
  (some consider it poor style to rely on this feature)

Modules

- **A *module* is a set of related global variables and functions in one or more files**
- **`extern` *declarations* make globals and functions accessible from *other files***

  in file `baz.c`:

  ```
  extern int max;
  void dump(...) {
          ...
  }
  ```

  The `max` defined in `foo.c` *can* be used here

- **General-purpose *modules* are often packaged in *two* files**

  The *interface* — **a header file (a `.h` file) of *declarations* for the variables and functions**

  The *implementation* — **a `.c` file of *definitions* for those variables and functions**

- **Implementations can be *compiled separately*, and the compiled code can be stored in *libraries***

Modules, cont’d

random.h:

```
extern int random(void); /*
    returns a random number in the range 0..2147483646. */

extern int seed; /* Initial seed for random(); default 0. */
```

random.c:

```
/*
Random number generator; see Press et al.,
Numerical Recipes in C, 2/e, 278-9.
*/
#include "random.h"

int seed = 0;

int random(void) {
    int k;

    seed ^= 123459876;
    k = seed/127773;
    seed = 16807*(seed - k*127773) - 2836*k;
    if (seed < 0)
        seed += 2147483647;
    k = seed;
    seed ^= 123459876;
    return k;
}
```

Lecture 5. Arrays

- **An *array* is a named collection of variables all of the *same type***

  Each variable in the collection is an *element*

  Elements are known by their integer *positions* or *indices*

  ```
  int count[11];
  ```

  defines an array named `count` that has *11* elements with indices *0..10*

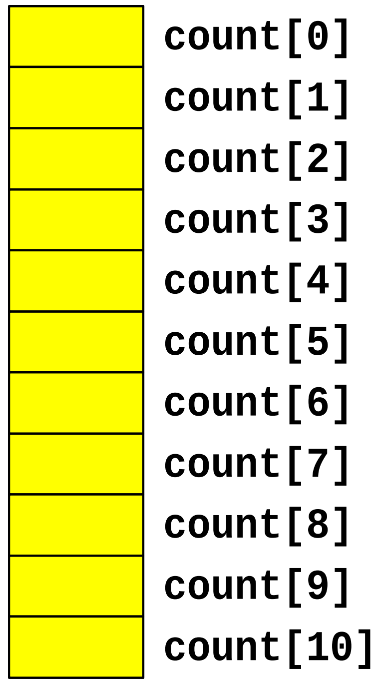
- **Array elements are accessed by *subscripting***

  `count[` *expression* `]`

  ***expression* is any expression whose value is an *integer* between 0 and 10 inclusive**

  Subscript expressions are *variables*, a.k.a. *lvalues*

  No* bounds checking — effect of out-of-bound subscripts is *undefined



- **Array elements occupy *successive locations* in memory**

- **Array elements are *uninitialized*; use loops to initialize them**

```
int i, count[11];

for (i = 0; i < 11; i++)
    count[i] = 0;
```

Printing a Histogram

- **`scores` contains 115 exam scores between 0 and 100**

```
% lcc hist.c
% a.out <scores
100 **
 90 ********
 80 ************
 70 ***************************
 60 ******************
 50 **************
 40 ************
 30 *******
 20 ******
 10 *****
  0 ****
%
```

```
/*
Print a histogram of scores from 0..100
in groups of 10.
*/
#include <stdio.h>

int main(void) {
    int i, counts[11], score;

    for (i = 0; i < 11; i++)
        counts[i] = 0;
    while (scanf("%d", &score) != EOF)
        counts[score/10]++;
    for (i = 10; i >= 0; i--) {
        int n = counts[i];
        printf("%3d ", 10*i);
        while (n-- > 0)
            printf("*");
        printf("\n");
    }
    return 0;
}
```

- **Use an array to hold the number of scores in each 10-point range**

Dissecting hist.c

```
int i, counts[11], score;
```

```
for (i = 0; i < 11; i++)
    counts[i] = 0;
```

Declares `counts` and initializes each of its 11 elements to 0

```
while (scanf("%d", &score) != EOF)
    counts[score/10]++;
```

Reads the scores and increments the appropriate element of `counts`; `scanf` returns the value EOF at the end-of-file is reached (EOF is defined in `stdio.h`)

```
for (i = 10; i >= 0; i--) {
    int n = counts[i];
    printf("%3d ", 10*i);
    while (n-- > 0)
        printf("*");
    printf("\n");
}
```

Loops from `counts[10]` down to `counts[0]` printing each line of the histogram

Multidimensional Arrays

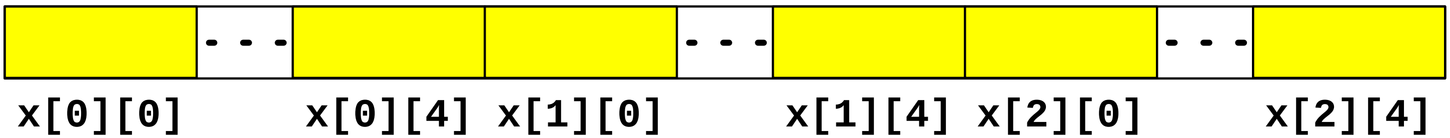
- **Multidimensional arrays have two or more indices**

```
int x[3][5];
```

defines an 2-dimensional array x that has $3 \times 5 = 15$ elements

x[0][0]	x[0][1]	x[0][2]	x[0][3]	x[0][4]
x[1][0]	x[1][1]	x[1][2]	x[1][3]	x[1][4]
x[2][0]	x[2][1]	x[2][2]	x[2][3]	x[2][4]

- **Array *rows* occupy successive locations in memory — *row-major order***



Printing a Stem-and-Leaf Plot

- **A *stem-and-leaf plot* displays the data values themselves in a histogram**

```
% lcc stem.c
% a.out <scores
10 00
 9 97765510
 8 977655533100
 7 99877766665555444333211100
 6 98877654433221000
 5 4432211111000
 4 888444444311
 3 7655211
 2 865221
 1 65311
 0 8850
%
```

- **Use a 2-dimensional array to hold the number of times each score occurs**

  `counts[i][j]` is the number of times the score 10∗`i` + `j` occurs

  Each row of `counts` is a row in the stem plot

```
/*
Print a stem-and-leaf plot of scores
from 0..100.
*/
#include <stdio.h>

int main(void) {
    int i, j, counts[11][10], score;

    for (i = 0; i < 11; i++)
        for (j = 0; j < 10; j++)
            counts[i][j] = 0;
    while (scanf("%d", &score) != EOF)
        counts[score/10][score%10]++;
    for (i = 10; i >= 0; i--) {
        printf("%2d ", i);
        for (j = 9; j >= 0; j--) {
            int n = counts[i][j];
            while (n-- > 0)
                printf("%d", j);
        }
        printf("\n");
    }
    return 0;
}
```

Dissecting stem.c

```
int i, j, counts[11][10], score;
```

```
for (i = 0; i < 11; i++)
    for (j = 0; j < 10; j++)
        counts[i][j] = 0;
```

Declares `counts` as a 11-by-10 array and initializes each of its 110 elements to 0

```
counts[score/10][score%10]++;
```

Increments the element of `counts` that holds the number of times `score` occurs

```
for (i = 10; i >= 0; i--) {
    printf("%2d ", i);
    ...
    printf("\n");
}
```

Loops down the rows of `counts`, printing each 'leaf' and a new-line character

```
    for (j = 9; j >= 0; j--) {
        int n = counts[i][j];
        while (n-- > 0)
            printf("%d", j);
    }
```

Loops down the `i`th column in `counts` printing `j = score%10` for each occurrence of `score`

Passing Arrays to Functions

- **Array parameters are declared by omitting the array size**

```
void record(int score, int counts[]) {
    counts[score/10]++;
}
```

- **Arrays are passed to functions by giving just the array name**

```
int main(void) {
    int i, counts[11], score;

    for (i = 0; i < 11; i++)
        counts[i] = 0;
    while (scanf("%d", &score) != EOF)
        record(score, counts);
    for (i = 10; i >= 0; i--) {
        printf("%3d ", 10*i);
        printhist(counts[i]);
        printf("\n");
    }
    return 0;
}
```

```
void printhist(int n) {
    while (n-- > 0)
        printf("*");
}
```

- **Arrays — and only arrays — are passed in a way that simulates *call-by-reference***

  The callee *can change* elements in the caller's array argument

  An element is passed *by value* — the callee *cannot change* the caller's element

Passing Arrays to Functions, cont'd

- **Declare multidimensional array parameters by omitting only the number of rows**

```
void printstem(int counts[][10], int nrows) {
    while (--nrows >= 0) {
        int j;
        printf("%2d ", nrows);
        for (j = 9; j >= 0; j--) {
            int n = counts[nrows][j];
            while (n-- > 0)
                printf("%d", j);
        }
        printf("\n");
    }
}

int main(void) {
    int i, j, counts[11][10], score;

    for (i = 0; i < 11; i++)
        for (j = 0; j < 10; j++)
            counts[i][j] = 0;
    while (scanf("%d", &score) != EOF)
        counts[score/10][score%10]++;
    printstem(counts, 11);
    return 0;
}
```

- **Passing the number of rows, or array size, to functions helps avoid indexing bugs**

Lecture 6. Strings

- A ***string*** is an array of characters; quotes enclose ***string constants***

```
/* Everyone’s first
    C program. */
#include <stdio.h>

int main(void) {
    char hello[13] = { 'H', 'e', 'l', 'l', 'o', ' ',
        'W', 'o', 'r', 'l', 'd', '!', '\0' };

    printf("%s\n", hello);
    return 0;
}
```

  A strings is terminated with a ***null character*** — the character with value 0

  The ***conversion specifier*** %s causes the value of the corresponding string argument to be printed instead; i.e., its characters up to the null character

- Strings can be initialized with individual characters as above, or by

```
char hello[] = "Hello World!";
char *hello = "Hello World!";
```

  let the compiler count the characters

  `char *` declares a ***character pointer***, which — for now — is the same as a string

- String variables can be used anywhere constant strings can be used

- Elements of string variables — the characters — can be changed by assignments

Printing Repeated Words

```
% lcc double.c
% echo Now is the the time | a.out
the
%
```

```
/* Print repeated words. */
#include <stdio.h>
#include <ctype.h>
#include <string.h>

int main(void) {
    char prev[100], word[100];

    prev[0] = '\0';
    while (scanf("%s", word) != EOF) {
        if (isalpha(word[0]) && strcmp(prev, word) == 0)
            printf("%s\n", word);
        strcpy(prev, word);
    }
    return 0;
}
```

Dissecting double.c

```
#include <ctype.h>
#include <string.h>
```

Includes the declarations for the character handling functions (`ctype.h`) and the string handling functions (`string.h`)

```
char prev[100], word[100];
```

```
prev[0] = '\0';
```

Declares two strings, `prev` and `word`, each capable of holding up to 100 characters, and initializes `prev` to the *empty string*

```
while (scanf("%s", word) != EOF) {
    …
}
```

Loops reading the next string of nonblank characters into `word`

```
    if (isalpha(word[0]) && strcmp(prev, word) == 0)
        printf("%s\n", word);
    strcpy(prev, word);
```

Prints `word` if it begins with a letter (`isalpha`) and holds the same word as `prev`; `strcmp` compares strings; then copies the string in `word` into `prev` (`strcpy`)

`strcmp(x, y)` returns a value <0, =0, >0 if x < y, x == y, x > y (lexicographic order)

Implementing String Handling Functions

- **`strcpy(dst, src)` copies `src` to `dst`, character-by-character up to the `'\0'`**

```
void strcpy(char dst[], char src[]) {
    int i;

    for (i = 0; src[i] != '\0'; i++)
        dst[i] = src[i];
    dst[i] = '\0';
}
```

- **`strcmp(str1, str2)` compares `str1` and `str2`, character-by-character**

```
int strcmp(char str1[], char str2[]) {
    int i;

    for (i = 0; str1[i] == str2[i] && str1[i] != '\0'; i++)
        ;
    if (str1[i] < str2[i])
        return -1;
    else if (str1[i] > str2[i])
        return +1;
    else
        return 0;
}
```

- **Other string handling functions**

`strlen(str)`	**returns the number of nonnull characters in `str`**
`strcat(dst, src)`	***appends* `src` to the *end* of `dst`**

Arrays of Strings

```
/* Shuffle a deck of cards. */
#include <stdio.h>
#include <stdlib.h>

char *suits[] = {
    "Hearts", "Diamonds", "Clubs", "Spades"
};

char *faces[] = {
    "Ace", "2", "3", "4", "5", "6", "7", "8",
    "9", "10", "Jack", "Queen", "King"
};

int main(void) {
    int i, deck[52];

    deck[0] = 0;
    deck[1] = 1;
    for (i = 2; i < 52; i++) {
        int k = rand()%i;
        deck[i] = deck[k];
        deck[k] = i;
    }
    for (i = 0; i < 52; i++)
        printf("%s of %s\n", faces[deck[i]%13], suits[deck[i]/13]);
    return 0;
}
```

```
% lcc shuffle.c
% a.out
3 of Diamonds
2 of Spades
Jack of Hearts
7 of Spades
9 of Clubs
Ace of Clubs
6 of Clubs
…
6 of Hearts
Ace of Diamonds
4 of Spades
10 of Spades
5 of Clubs
…
King of Spades
8 of Clubs
Queen of Clubs
8 of Spades
%
```

Dissecting shuffle.c

- **Integer k (0..51) represents the card with face value `k%13` (0..12) and suit `k/13` (0..3)**

```
char *suits[] = {
    "Hearts", "Diamonds", "Clubs", "Spades"
};
```

```
char *faces[] = {
    "Ace", "2", "3", "4", "5", "6", "7", "8",
    "9", "10", "Jack", "Queen", "King"
};
```

Define and initialize global arrays of strings that map integers to suits and faces

```
deck[0] = 0;
deck[1] = 1;
for (i = 2; i < 52; i++) {
    int k = rand()%i;
    deck[i] = deck[k];
    deck[k] = i;
}
```

Initializes `deck[0..51]` to a random *permutation* of the integers 0..51

```
for (i = 0; i < 52; i++)
    printf("%s of %s\n", faces[deck[i]%13], suits[deck[i]/13]);
```

Prints the permuted deck in a readable form by mapping `deck[i]%13` (0..12) to a face and `deck[i]/13` (0..3) to a suit

Command-Line Arguments

- **By convention, `main` is called with two arguments**

```
int main(int argc, char *argv[])
```

`argc` (‘***arg***ument ***c***ount’) is the number of command-line arguments, including the program name

`argv` (‘***arg***ument ***v***ector’) is an array of strings, one for each argument

```
% echo Hello World
Hello World
%
```

- **Implementing echo**

```
/* Echo my arguments. */
#include <stdio.h>

int main(int argc, char *argv[]) {
    int i;

    if (argc > 1)
        printf("%s", argv[1]);
    for (i = 2; i < argc; i++)
        printf(" %s", argv[i]);
    printf("\n");
    return 0;
}
```

```
% lcc echo.c
% a.out Hello World
Hello World
%
```

Inside `main`:

```
argc = 3
argv[0] = "a.out"
argv[1] = "Hello"
argv[2] = "World"
```

Testing random()

- **Check `argc` for optional command-line arguments**

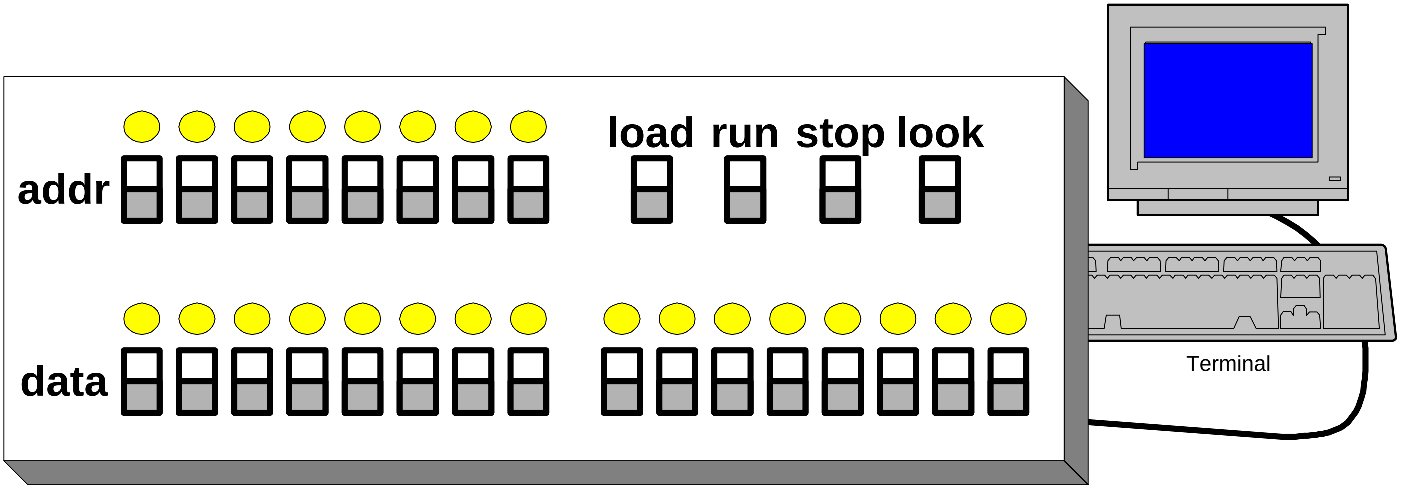
```
/*
Use random() to generate N (default 100)
random numbers, perhaps with different seeds.
*/
#include <stdio.h>
#include "random.h"

int main(int argc, char *argv[]) {
    int n = 100;

    if (argc > 1)
        sscanf(argv[1], "%d", &n);
    if (argc > 2)
        sscanf(argv[2], "%d", &seed);
    while (n-- > 0)
        printf("%d\n", random());
    return 0;
}
```

`sscanf` is like `scanf`, but reads from a string instead of from the input

```
% lcc testrandom.c random.c
% a.out | fmt
520932930 28925691 822784415 890459872 ... 100 random numbers
% a.out 1000 | fmt
520932930 28925691 822784415 890459872 ... 1000 random numbers
% a.out 4 126217318 | fmt
2088403071 1317687729 1526293439 721665858
```


Lecture 7. The TOY Machine

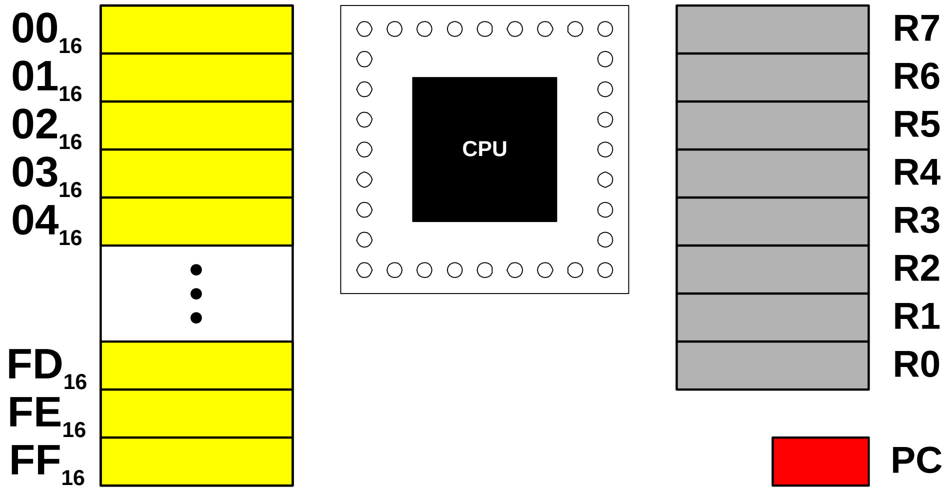
- **TOY is an imaginary machine similar to**
  - **early computers**
  - **1980s microprocessers**
- **Box with switches, lights, terminal**



- **TOY helps introduce**
  - ***machine-language*** **programming (how a C program is 'mapped' onto a machine)**
  - **computer** ***architecture*** **(how the machine works)**
- **With enough memory and time, TOY can compute** ***anything*** **a supercomputer can**

Inside the Box

- **1 central processing unit (CPU)**
- **256 16-bit *words* of memory**
- **8 16-bit *registers***
- **1 8-bit *program counter* (PC) register — the address of the 'current' instruction**
- **Machine consists of 'On/Off' switches and lights**

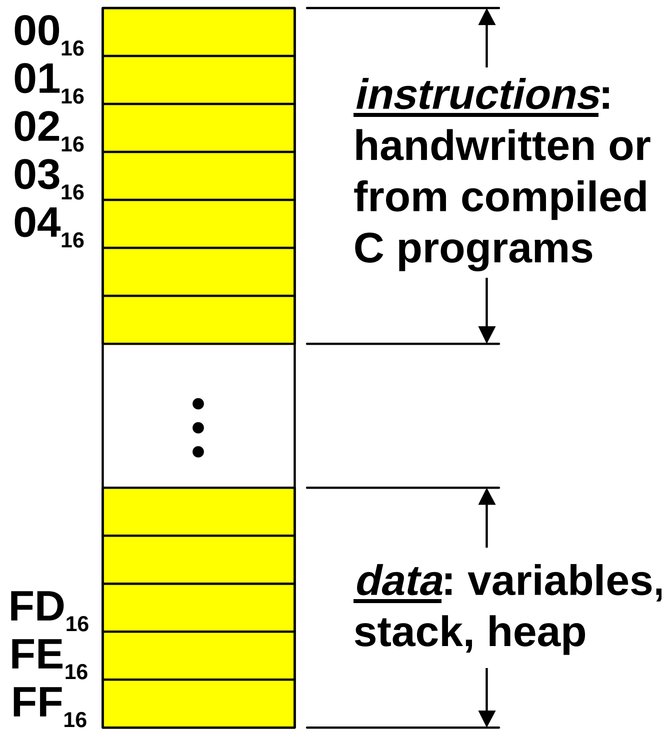


- **Numbers are encoded in base 2, e.g., 6375_{10} = $0001\ 1000\ 1110\ 0111_2$**
- **Operation**
  1. **Load the program and the data into memory using the *addr*, *data*, and *load* switches**
  2. **Set the *addr* switches to the address of the first instruction**
  3. **Press *run***
  4. **To examine memory — the 'output' — set *addr* switches to the desired address, press *look*, read the *data* lights**
- ***Everything* is encoded in binary — data, machine instructions, text, addresses, …**

Memory

- ‘Dump’ of machine state in hexadecimal includes the registers, PC, and memory

```
PC = 000C

R0 = 0000  R1 = 0037  R2 = 0001  R3 = FFFF
R4 = 0000  R5 = 0000  R6 = 0008  R7 = 00FF

00: 0000 0000 0000 0000 0000 0000 0000 0000
08: 0000 0000 0000 0000 0000 0000 0000 0000
10: 9222 9120 1121 A120 1121 A121 7211 0000
18: 0000 0000 0000 0000 0000 0000 0000 0000
20: 0000 0001 0010 0000 0000 0000 0000 0000
28: 0000 0000 0000 0000 0000 0000 0000 0000
...
E8: 0000 0000 0000 0000 0000 0000 0000 0000
F0: 0000 0000 0000 0000 0000 0000 0000 0000
F8: 0000 0000 0000 0000 0000 0000 0000 0000
```



- Programmers still look at dumps, even in the 90s
- Machine state

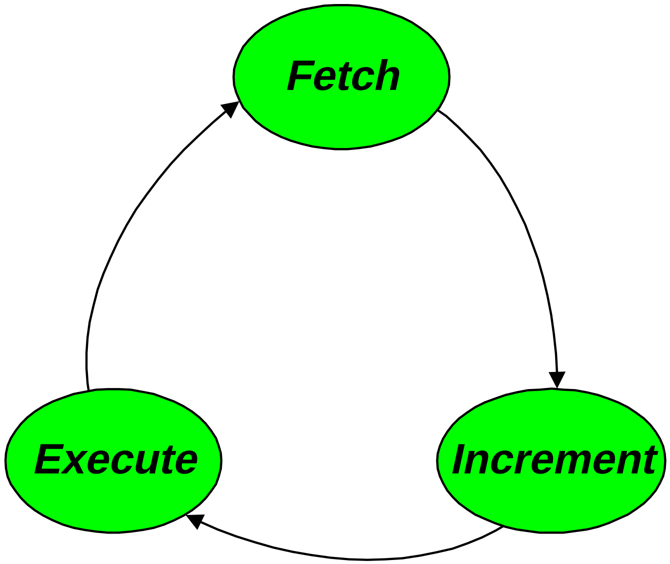
  records what a program has done

  determines what the machine will do

Basic Cycle

- **When you press *Run***

  1. ***Fetch*: load the instruction at the address given by the PC into the CPU**
  2. ***Increment* the PC by 1**
  3. ***Execute* the instruction, which may load/store data from/to memory**
  4. **Continue this *fetch-increment-execute cycle* until a halt is executed**



- **Instructions make well-defined changes to the registers, memory, and the PC**

Digression: Number Systems

- **The general form of an integer in *base* *b* is**

$$x = x_n b^n + x_{n-1} b^{n-1} + \ldots + x_1 b^1 + x_0 b^0$$

The x_i are the *positional coefficients*

- **Modern computers use binary arithmetic — base 2**

$$140_{10} = 1 \times 10^2 + 4 \times 10^1 + 0 \times 10^0$$

$$= 1 \times 2^7 + 0 \times 2^6 + 0 \times 2^5 + 0 \times 2^4 + 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0$$

$$= 10001100_2$$

- **Base 2 is easily converted to base 8 (octal) and base 16 (hexadecimal)**

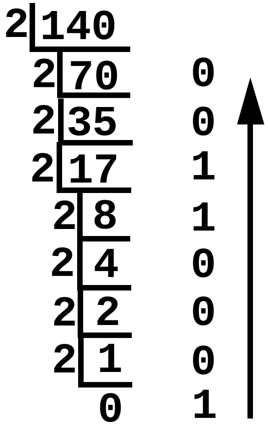
$$140_{10} = 2 \times 8^2 + 1 \times 8^1 + 4 \times 8^0 = 214_8$$

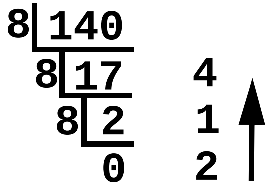
$$= 8 \times 16^1 + \mathrm{C} \times 16^0 = 8\mathrm{C}_{16}$$

Digits in base	***2***	**0 1**
	8	**0 1 2 3 4 5 6 7**
	10	**0 1 2 3 4 5 6 7 8 9**
	16	**0 1 2 3 4 5 6 7 8 9 A=10 B=11 C=12 D=13 E=14 F=15**

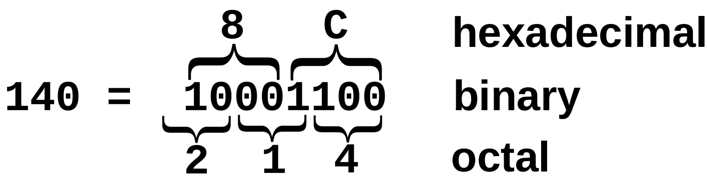
Conversions

- **To convert from decimal to binary, divide by 2 repeatedly, read remainders up**





- **Easier to convert to octal, then to binary, then to hexadecimal**



Boolean Functions

- **16 possible Boolean functions of two binary variables; *some* have names, and C operators**

Truth table			
0 0 1 1	x		
0 1 0 1	y		
		Name	***C expression***
0 0 0 0			
0 0 0 1	AND		`x & y`
0 0 1 0			
0 0 1 1			
0 1 0 0			
0 1 0 1			
0 1 1 0	XOR	‘exclusive or’	`x ^ y`
0 1 1 1	OR	‘inclusive or’	`x | y`
1 0 0 0	NOR	‘not or’	`~(x | y)`
1 0 0 1	EQV	‘not xor’	`~(x ^ y)`
1 0 1 0	NOT y	one’s complement	`~y`
1 0 1 1			
1 1 0 0	NOT x	one’s complement	`~x`
1 1 0 1			
1 1 1 0	NAND	‘not and’	`~(x & y)`
1 1 1 1			

- **Don’t confuse `&& || !` for `& | ~`**

Machine Arithmetic

- On a machine with 16-bit words, there are $2^{16} = 65{,}536$ ***unsigned*** integers 0..65,535

$0000\ 0000\ 0000\ 0000_2$	0
0000 0000 0000 0001	1
0000 0000 0000 0010	2
0000 0000 0000 0011	3
0000 0000 0000 0100	4
...	
1111 1111 1111 1100	$65{,}532_{10}$
1111 1111 1111 1101	65,533
1111 1111 1111 1110	65,534
1111 1111 1111 1111	65,535

- There are 65,536 ***two's-complement signed integers*** –32,768..+32,767

$\underline{1}000\ 0000\ 0000\ 0000_2$	$-32{,}768_{10}$
1000 0000 0000 0001	–32,767
...	
1111 1111 1111 1110	–2
1111 1111 1111 1111	–1
0000 0000 0000 0000	0
$\underline{0}000\ 0000\ 0000\ 0001$	+1
0000 0000 0000 0010	+2
...	
0111 1111 1111 1110	+32,766
0111 1111 1111 1111	+32,767

Two's-Complement Arithmetic

- Adding two's-complement numbers is easy: Ignore signs, add unsigned numbers

```
    +20      010100          -20      101100
  + - 7    + 111001        + + 7    + 000111
    ---      ------          ---      ------
    +13      001101          -13      110011

    +20      010100          -20      101100
  + + 7    + 000111        + - 7    + 111001
    ---      ------          ---      ------
    +27      011011          -27      100101
```

- To ***negate*** a two's complement number: Complement all the bits, then add 1

	Start with	Complement	Increment	
+6	000110	111001	111010	-6
-6	111010	000101	000110	+6
0	000000	111111	000000	0
+1	000001	111110	111111	-1
+31	011111	100000	100001	-31
-31	100001	011110	011111	+31
-32	100000	011111	100000	-32

Lecture 8. TOY Instructions

- A program is a sequence of instructions
- An instruction is a 16-bit word, interpreted in one of many possible ways
- 3 instruction ‘formats,’ 16 different instructions

	15–12	11–8	7–4	3–0
Format 1	*op*	*dst*	*reg_1*	*reg_2*
Format 2	*op*	*dst*	*reg*	*con4*
Format 3	*op*	*dst*	*con8*	

Format 1

0	halt	C	xor
1	add	D	and
2	subtract	E	shift right
3	multiply	F	shift left

Format 2

9	load
A	store

Format 3

4	system call
5	jump
6	jump if less
7	jump indirect
8	jump and link
B	load immediate

Format 1 Instructions

15 … 12	11 … 8	7 … 4	3 … 0
op	*dst*	reg_1	reg_2

- **Format 1 instructions are *register-to-register* instructions**

  Interpret *dst*, reg_1, and reg_2 as register numbers

  Take operands from reg_1 and reg_2, and put the result in *dst*

  Example: 1234_{16} means $R_2 \leftarrow R_3 + R_4$

15 … 12	11 … 8	7 … 4	3 … 0
1	*2*	*3*	*4*

Stores the sum of the contents of registers R_3 and R_4 into register R_2

2116_{16}	$R_1 \leftarrow R_1 - R_6$	
3267	$R_2 \leftarrow R_6 \times R_7$	
C512	$R_5 \leftarrow R_1$ ^ R_2	exclusive OR
D645	$R_6 \leftarrow R_4$ & R_5	logical AND
E056	$R_0 \leftarrow R_5 >> R_6$	shift right
F764	$R_7 \leftarrow R_6 << R_4$	shift left
0000		halt

Format 2 Instructions

15–12	11–8	7–4	3–0
op	*dst*	*reg*	*con4*

- **Format 2 instructions are *memory operation* instructions**

  Interpret *dst* and *reg* as register numbers, *con4* as a 4-bit *unsigned* constant

  Compute the *effective address* *reg* + *con4*

- ***Load* copies a word *from memory* at the effective address *to register* *dst***

  9123_{16} means $R_1 \leftarrow M[R_2 + 3]$

  Copy the contents of the memory location specifed by adding 3 to the contents of register R_2 to register R_1

- ***Store* copies a word *from register* *dst* *to memory* at the effective address**

  $A765_{16}$ means $M[R_6 + 5] \leftarrow R_7$

  Copy the contents of register R_7 to the memory location specifed by adding 5 to the contents of register R_6

- **When *con4* is 0, load/store are sometimes called *indirect* load/store**

Format 3 Instructions

15–12	11–8	7–4	3–0
op	*dst*	*con8*	

- **Most of the format 3 instructions are *control* instructions**

  Interpret *dst* as a register number, *con8* as an 8-bit *unsigned* constant or address

  Compute a *jump address* as either *con8* or *dst*

  Set PC to that address

  Oddballs: system call (4) and load immediate (B)

- ***Load immediate* copies *con8* to register *dst***

  $\underline{B}234_{16}$ **means** $R_2 \leftarrow 34_{16}$ **set register R2 to** 34_{16}

  Use load immediate to copy the contents of a register to another register:

$\underline{B}000_{16}$	$R_0 \leftarrow 0$	set R_0 to 0
$\underline{1}320$	$R_3 \leftarrow R_2 + R_0$	set R_3 to $R_2 + R_0 = R_2 + 0 = R_2$

- ***System call* invokes actions that need special permission, like I/O**

  ***con8* specifies the system call 'action code', *dst* may specify an operand**

  $\underline{4}402_{16}$ **writes the contents of** R_4 **to the standard output**

Jump Instructions

- ***Jump*** **instructions change the PC to *con8*, or to the contents of *dst***

jump

`5062`$_{16}$ PC $\leftarrow 62_{16}$

The next instruction will be taken from M[62_{16}]

jump if less

`6362` PC $\leftarrow 62_{16}$ ***if*** the contents of $R_3 < 0$

jump indirect

`7500` PC $\leftarrow R_5$

The next instruction will be taken from the address in R_5

jump and link

`3A`$_{16}$ `8462` $R_4 \leftarrow$ PC, PC $\leftarrow 62_{16}$
`3B`

The contents of the PC ($3B_{16}$) are saved in R_4, then the PC is set to 62_{16}
The next instruction will be taken from M[62_{16}]

Used for *function linkage* — calls and returns

- **All instructions of format 3 use a constant as one operand and a register or the program counter as the other operand.**

Example: Bit Twiddling

- Set b_0 of R_4 to b_{10} ^ b_3 from R_1, clear b_1–b_{15} in R_4

```
R4 = ((R1>>10) ^ (R1>>3)) & 1;
```

```
1010 0111 0111 0010    R1
0000 0000 0010 1001    R1>>10
0001 0100 1110 1110    R1>>3
0001 0100 1100 0111    (R1>>10) ^ (R1>>3)
0000 0000 0000 0001    ((R1>>10) ^ (R1>>3)) & 1
```

Assuming R_1 is initialized to $A772_{16}$

```
00:  B000     R0 <- 00
01:  1210     R2 <- R1 + R0 = A772
02:  1310     R3 <- R1 + R0 = A772
03:  B50A     R5 <- 0A
04:  B603     R6 <- 03
05:  E225     R2 <- R2 >> R5 = 0029
06:  E336     R3 <- R3 >> R6 = 14EE
07:  C323     R3 <- R2 ^ R3 = 14C7
08:  B401     R4 <- 01
09:  D443     R4 <- R4 & R3 = 0001
```

Example: Polynomial Evaluation

- **Evaluate $ax^2 + bx + c = 2x^2 + 3x + 9$ at $x = 10$ ($239_{10} = EF_{16}$)**

  Store the ‘data’ in locations $30–33_{16}$

```
30: 000A    x
31: 0002    a
32: 0003    b
33: 0009    c
```

- **Use Horner’s method: rewrite $ax^2 + bx + c$ as $(ax + b)x + c$**

```
10:  B330     R3 <- 30
11:  9430     R4 <- M[R3+00] = M[30] = 000A          x
12:  9531     R5 <- M[R3+01] = M[31] = 0002          a
13:  3554     R5 <- R5 * R4 = 0014                   a×x
14:  9632     R6 <- M[R3+02] = M[32] = 0003          b
15:  1556     R5 <- R5 + R6 = 0017                   a×x + b
16:  3554     R5 <- R5 * R4 = 00E6                   (a×x + b)×x
17:  9633     R6 <- M[R3+03] = M[33] = 0009          c
18:  1556     R5 <- R5 + R6 = 00EF                   (a×x + b)×x + c
19:  4502     system call 2: print R5 = 00EF
1A:  0000     HALT
```

- **Polynomial evaluation for arbitrary x**

  many applications, one *raison d’etre* for early computers

Lecture 9. Branches and Loops

- **Rewrite `sum.c` using labels and gotos**

```
#include <stdio.h>

int main(void) {
    int i = 1, n, sum = 0;

    printf("Enter n:\n");
    scanf("%d", &n);
    n--;
Top:if (n < 0) goto End;
        sum += i;
        i++;
        n--;
        goto Top;
End:printf("Sum from 1 to %d = %d\n", i - 1, sum);
    return 0;
}
```

- **Compilers implement C loop statements with branches and labels**

`while` (*conditional*)
**   *statement***

L_1: if (!*conditional*) goto L_2
**   *statement***
**   goto L_1**
L_2:

Ditto for do-while and for loops

Implementing Loops, cont'd

```
0E                                           starting address
0E:  B001     R0 <- 01                       R0 holds 1
0F:  B10A     R1 <- 0A                       R1 is n
10:  B201     R2 <- 01                       R2 is i
11:  B300     R3 <- 00                       R3 is sum
12:  2110     R1 <- R1 - R0                  n--
13:  6118     jump to 18 if R1 < 0           if (n < 0) goto End
14:  1332     R3 <- R3 + R2                  sum += i
15:  1220     R2 <- R2 + R0                  i++
16:  2110     R1 <- R1 - R0                  n--
17:  5013     jump to 13                     goto Top
18:  4302     print R3                       print sum
19:  0000     halt
```

```
% /u/cs126/bin/toy /u/cs126/toy/sum.toy
Toy simulator $Revision: 1.8 $
0037
PC = 001A
R0 = 0001  R1 = FFFF  R2 = 000B  R3 = 0037
R4 = 0000  R5 = 0000  R6 = 0000  R7 = 0000
0008: 0000 0000 0000 0000 0000 0000 B001 B10A
0010: B201 B300 2110 6118 1332 1220 2110 5013
0018: 4302 0000 0000 0000 0000 0000 0000 0000
%
```


Example: Computing Fibonacci Numbers

```
0F
0F:  B601     R6 <- 01
10:  B720     R7 <- 20
11:  9272     R2 <- M[R7+2] = M[22]
12:  9170     R1 <- M[R7+0] = M[20]
13:  9371     R3 <- M[R7+1] = M[21]
14:  4302     print R3
15:  1113     R1 <- R1 + R3
16:  4102     print R1
17:  1313     R3 <- R1 + R3
18:  4302     print R3
19:  2226     R2 <- R2 - R6 = R2 - 1
1A:  B000     R0 <- 0
1B:  2702     R7 <- R0 - R2 = -R2
1C:  6715     if R7 < 0 (i.e., R2 > 0) goto 15
1D:  0000     halt
20:  0000
21:  0001
22:  000B
```

```
% /u/cs126/bin/toy /u/cs126/toy/fib.toy
Toy simulator $Revision: 1.8 $
0001 0001 0002 0003 0005 0008 000D 0015 0022 0037 0059 ... 2AC2 452F 6FF1
PC = 001E ...
```

- **Each number is sum of the previous two numbers; two numbers per loop iteration**
- **Computes Fibonacci numbers 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, … limit given by R_2**

Manipulating Addresses, a.k.a. Pointers

- **Find the maximum value in an array of positive integers**

```
/*
Find the largest positive integer
in an array.
*/
#include <stdio.h>


short int a[15] = {
    0x0001, 0x0002, 0x0010, 0x1000, 0x7EFE,
    0x6030, 0x0040, 0x0000, 0x0000, 0x0000,
    0x0000, 0x0010, 0x0000, 0x1000, 0x0000 };

int main(void) {
    int i = 14, max = 0;

    while (i >= 0) {
        if (a[i] > max)
            max = a[i];
        i--;
    }
    printf("%d\n", max);
    return 0;
}
```

```
% lcc max.c
% a.out
32510
```

Manipulating Addresses, cont'd

```
0E                                              starting address
0E:  B000     R0 <- 0                           constant 0
0F:  B101     R1 <- 1                           constant 1
10:  B20E     R2 <- 0x0E                        i = 14
11:  B322     R3 <- 0x22                        address of a
12:  B600     R6 <- 0                           max = 0
13:  621B     if R2 < 0 goto 1B                 while (i >= 0) {
14:  1723     R7 <- R2 + R3                         R4 <- a[i]
15:  9470     R4 <- M[R7+0] = M[R2+R3]
16:  2546     R5 <- R4 - R6                         compute a[i] - max
17:  6519     if R4-R6 < 0 jump to 19               if (a[i] > max)
18:  1640     R6 <- R4 + R0 = R4                    max = a[i]
19:  2221     R2 <- R2 - R1 = R2 - 1                i--
1A:  5013     jump to 13                        }
1B:  4602     print R6                          print max
1C:  0000     halt

22:  0001     a[0]        28:  0040                2E:  0000
23:  0002                 29:  0000                2F:  1000
24:  0010                 2A:  0000                30:  0000     a[14]
25:  1000                 2B:  0000
26:  7EFE                 2C:  0000
27:  6030                 2D:  0010
```

- **$R_2 + R_3$ is the address of `a[i]`; R_2 is decremented, so $R_2 + R_3$ walks backwards in a**
- **What happens if location 11 is loaded with `B318`?**

Function Linkages

- **Use jump and link/jump indirect to call/return to/from functions**

jump and link	**8562**	$R_5 \leftarrow PC, PC \leftarrow 62_{16}$
jump indirect	**7500**	$PC \leftarrow R_5$

- **power computes R3** $\leftarrow x^n$ **where** x **is *passed* in** R_1, n **is *passed* in** R_2

```
int power(int x, int n) {
    int z = 1;

    while (--n >= 0)
        z *= x;
    return z;
}
```

```
14:  B401          R4 <- 1                      constant 1
15:  B301          R3 <- 1                      z = 1
16:  2224          R2 <- R2 - R4 = R2 - 1       while (--n >= 0)
17:  621A          if R2 < 0 jump to 1A
18:  3331          R3 <- R3 * R1                    z *= x;
19:  5016          jump to 16
1A:  7500          jump to address in R5        return z
```

- ***Calling conventions*** **specify the locations of the actual arguments, the return value, and the return address; can vary among operating systems and languages on the *same machine***

Function Linkages, cont'd

- **To compute $3^4 + 2^5$**

```
04:  B100     R0 <- 0
05:  B11C     R1 <- 1C
06:  9110     R1 <- M[R1+0] = M[1C] = 0003
07:  B204     R2 <- 4
08:  8514     call power, R5 <- 09
09:  1630     R6 <- R3 + R0 = R3 = 0051
0A:  B11D     R1 <- 1D
0B:  9110     R1 <- M[R1+0] = M[1D] = 0002
0C:  B205     R2 <- 5
0D:  8514     call power, R5 <- 0E
0E:  1663     R6 <- R6 + R3 = 0051 + 0020 = 0071
0F:  4602     print R6
10:  0000     halt
04

1C:  0003
1D:  0002

% /u/cs126/bin/toy /u/cs126/toy/power.toy
0071
PC = 0011
R0 = 0000  R1 = 0002  R2 = FFFF  R3 = 0020
R4 = 0001  R5 = 000E  R6 = 0071  R7 = 0000
```

- **Function linkages on 'real' machines usually involve a *stack* to hold some of the arguments**

Simulating TOY

- **Any modern computer can *simulate* TOY: Write a C program that executes TOY instructions exactly as a TOY machine would**
- **Simulate memory and registers with 16-bit integer arrays**

```
short int mem[256], regs[8];
```

- **Simulate the PC and the *fetch-increment-execute* cycle**

```
unsigned char pc;
do {
    int inst = mem[pc++];
    execute(inst);
} while (inst != HALT);
```

- **Switch statement — a multiway branch — decodes and ‘executes’ instructions**

```
void execute(int inst) {
    switch ((inst>>12)&0xF) {
    case ADD:
        regs[(inst>>8)&0F] = regs[(inst>>4)&0F] + regs[inst&0F];
        break;
    ...
    case JUMP:   pc = inst&0xFF; break;
    }
}
```

- **This is simplified slightly; see `/u/cs126/toy/toy.c` for the full story**

Lecture 10. Recursion

- A ***recursive function*** **is a function that calls itself**

```
int sum(int n) {
    if (n == 0)
        return 0;
    else
        return sum(n - 1) + n;
}
```

- **To compute f(n) using recursion**

compute f(0)		**'basis' case**
compute f(n)	**using f(k) for k $<$ n**	**'recursive' cases**

- **Recursion is like** ***mathematical induction***

To prove S(n) : prove S(0) , then prove S(n) assuming S(k) for all $k < n$

$0 + 1 + 2 + 3 + \ldots + n = n(n + 1)/2$

Trivially true for $n = 0$

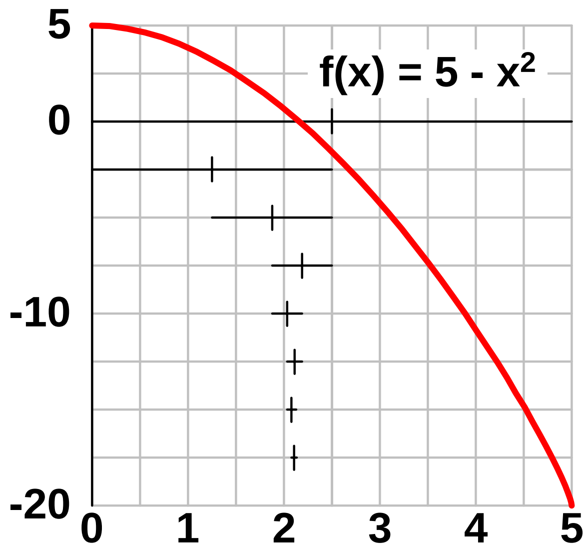
Assume it is true for $0 + \ldots + n - 1$

Is it true for $0 + \ldots + (n - 1) + n$**?**

$0 + 1 + 2 + \ldots + n = \underline{0 + \ldots + (n - 1)} + n = \underline{(n - 1)(n - 1 + 1)/2} + n = n(n + 1)/2$

Divide and Conquer

- **Solve a problem by *dividing it* into smaller ones:**
  To compute $\sqrt{n}$, find x such that $n - x^2 = 0$

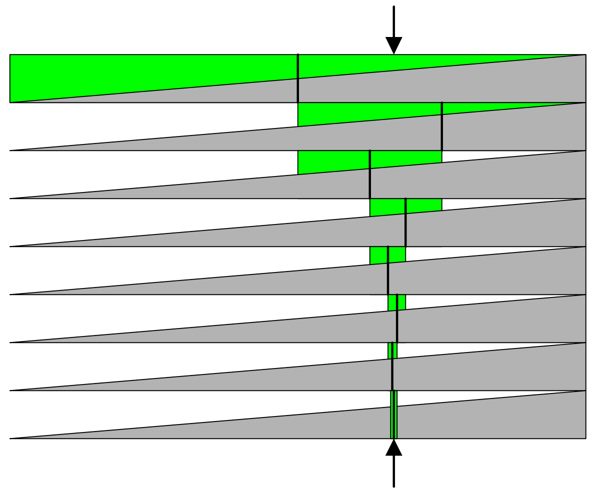



```
float sqroot(float n, float l, float r) {
    float x = (l + r)/2.0;
    if (r - l < 0.000001)
        return x;
    else if (n - x*x < 0.0)
        return sqroot(n, l, x);
    else
        return sqroot(n, x, r);
}

int main(int argc, char *argv[]) {
    int i;
    for (i = 1; i < argc; i++) {
        int n;
        sscanf(argv[i], "%d", &n);
        printf("sqrt(%d) = %f (should be %f)\n", n,
               sqroot(n, 0.0, n), sqrt(n));
    }
    return 0;
}

% lcc sqroot.c
% a.out 5
sqrt(5) = 2.236068 (should be 2.236068)
```

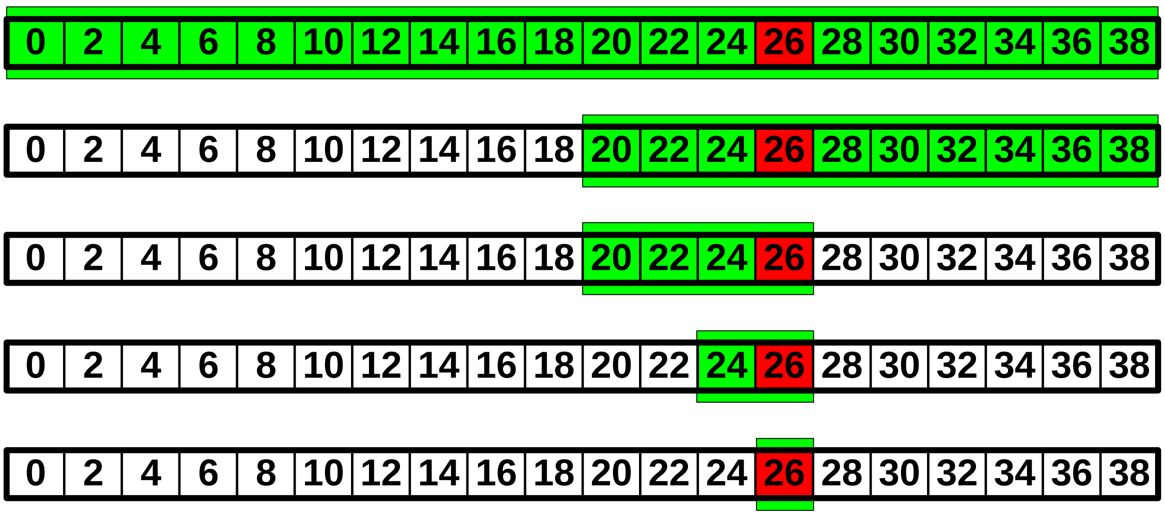
Binary Search

- **Suppose an array x contains n integers in increasing order; is q in `x[0..n-1]`?**

```
int bsearch(int x[], int lb, int ub, int q) {
    if (lb <= ub) {
        int m = (lb + ub)/2;
        if (x[m] < q)
            return bsearch(x, m + 1, ub, q);
        else if (x[m] > q)
            return bsearch(x, lb, m - 1, q);
        else
            return m;
    } else
        return -1;
}
```



`k = bsearch(x, 0, 20 - 1, 26);`



Number Conversion

- **Print an integer in base *b* (between 2 and 16)**

```
void convert(int n, int b) {
    if (n/b > 0)
        convert(n/b, b);
    printf("%c", "0123456789ABCDEF"[n%b]);
}
```

Printing 876 in base 5

$175 \times 5 + \underline{1}$
$(35 \times 5 + \underline{0}) \times 5 + 1$
$((7 \times 5 + \underline{0}) \times 5 + 0) \times 5 + 1$
$(((1 \times 5 + \underline{2}) \times 5 + 0) \times 5 + 0) \times 5 + 1$
$((((0 \times 5 + \underline{1}) \times 5 + 2) \times 5 + 0) \times 5 + 0) \times 5 + 1$
$1 \times 5^4 + 2 \times 5^3 + 0 \times 5^2 + 0 \times 5^1 + 1 \times 5^0$
12001_5

```
convert(876, 5)
    convert(175, 5)
        convert(35, 5)
            convert(7, 5)
                convert(1, 5)
                    printf("%c", '1')
                printf("%c", '2')
            printf("%c", '0')
        printf("%c", '0')
    printf("%c", '1')
```

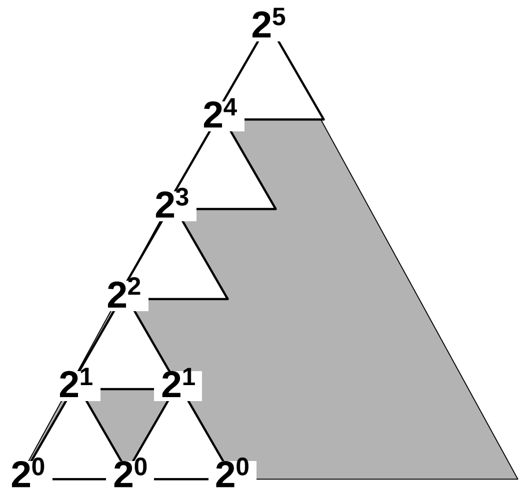
In base 16

$54 \times 16 + \underline{12}$
$(3 \times 16 + \underline{6}) \times 16 + 12$
$((0 \times 16 + \underline{3}) \times 16 + 6) \times 16 + 12$
$3 \times 16^2 + 6 \times 16^1 + 12 \times 16^0$
$36C_{16}$

Pitfalls

- **Many computations are expressed naturally as recursive functions**
- ***But*, some simple recursive functions consume excessive resources: compute 2^n**

```
int f(int n) {
    if (n == 0)
        return 1;
    else
        return f(n-1) + f(n-1);
}
```



Hard way to compute 2^n because `f` *recomputes intermediate results*

- **Even 'natural' recursive function may consume excessive resources**

```
int fib(int n) {
    if (n == 0 || n == 1)
        return 1;
    else
        return fib(n-2) + fib(n-1);
}
```

- **Despite pitfalls, thinking and writing recursively yields correct implementations**
- ***Make it right before you make it fast***

Memo Functions

- **Recursive functions can avoid recomputing intermediate results by *saving* them**

```
int fibs[51] = { 1, 1, 0 };

int fib(int n) {
    if (n <= 50 && fibs[n] != 0)
        return fibs[n];
    else {
        int f;
        if (n == 0 || n == 1)
            f = 1;
        else
            f = fib(n-2) + fib(n-1);
        if (n <= 50)
            fibs[n] = f;
        return f;
    }
}
```

```
% lcc fib2.c
% a.out 30
fib(30) = 1346269
30: 1
29: 1
28: 2
27: 3
26: 5
25: 8
24: 13
23: 21
22: 34
21: 55
20: 89
19: 144
18: 233
17: 377
16: 610
15: 987
14: 1597
13: 2584
12: 4181
11: 6765
10: 10946
 9: 17711
 8: 28657
 7: 46368
 6: 75025
 5: 121393
 4: 196418
 3: 317811
 2: 514229
 1: 832040
 0: 514229
```

Changing Recursion to Iteration

- **If the *last action* of a function is to call itself — 'tail recursion' — the call can be replaced with assignments and a loop; use labels and gotos, then a loop statement**

```
float sqroot(float n, float l, float r) {
        float x;

        x = (l + r)/2.0;                    Loop:   x = (l + r)/2.0;
        if (r - l < 0.000001)                       if (r - l < 0.000001)
                return x;                                   return x;
        else if (n - x*x < 0.0)                     else if (n - x*x < 0.0)
                return sqroot(n, l, x);                     { r = x; goto Loop; }
        else                                        else
                return sqroot(n, x, r);                     { l = x; goto Loop; }
}
```

```
float sqroot(float n, float l, float r) {
        float x;

        x = (l + r)/2.0;
        while (r - l > 0.000001) {
                if (n - x*x < 0.0)
                        r = x;
                else
                        l = x;
                x = (l + r)/2.0;
        }
        return x;
}
```

Lecture 11. Quicksort

- **Sort `x[0..n-1]` into increasing (or decreasing) order**
- **Quicksort is a well-known sorting algorithm: Recursion is natural and fast**

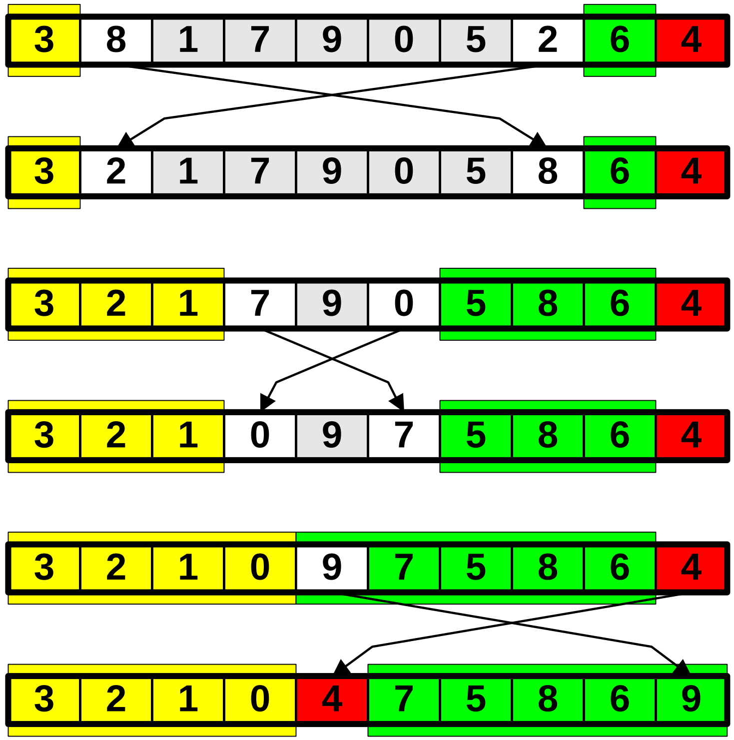
To sort `x[0..n-1]`:

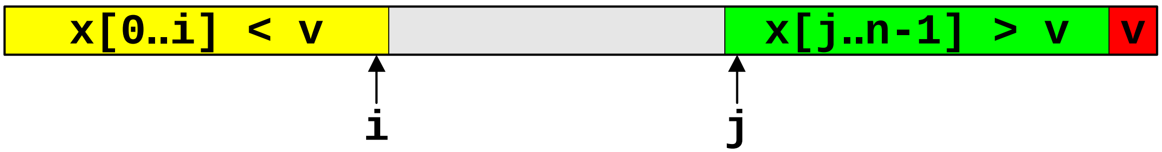
1. **Pick a 'pivot' element**
2. **Rearrange x so that:**
   `x[k]` holds this element, `x[0..k-1]` < `x[k]`, and `x[k+1..n-1]` > `x[k]`
3. **Sort `x[0..k-1]` and `x[k+1..n-1]` recursively**

```
void quicksort(int x[], int l, int r) {
    if (r > l) {
        int k = partition(x, l, r);
        quicksort(x, l, k - 1);
        quicksort(x, k + 1, r);
    }
}

int main(void) {
    int n, array[1000];

    ...
    quicksort(array, 0, n - 1);
    ...
}
```

Partitioning

```
int partition(int x[], int i, int j) {
    int k = j, v = x[k];

    i--;
    while (i < j) {
        while (            x[++i] < v)
            ;
        while (--j > i && x[  j] > v)
            ;
        if (i < j) {
            int t = x[i];
            x[i] = x[j];
            x[j] = t;
        }
    }
    x[k] = x[i];
    x[i] = v;
    return i;
}
```



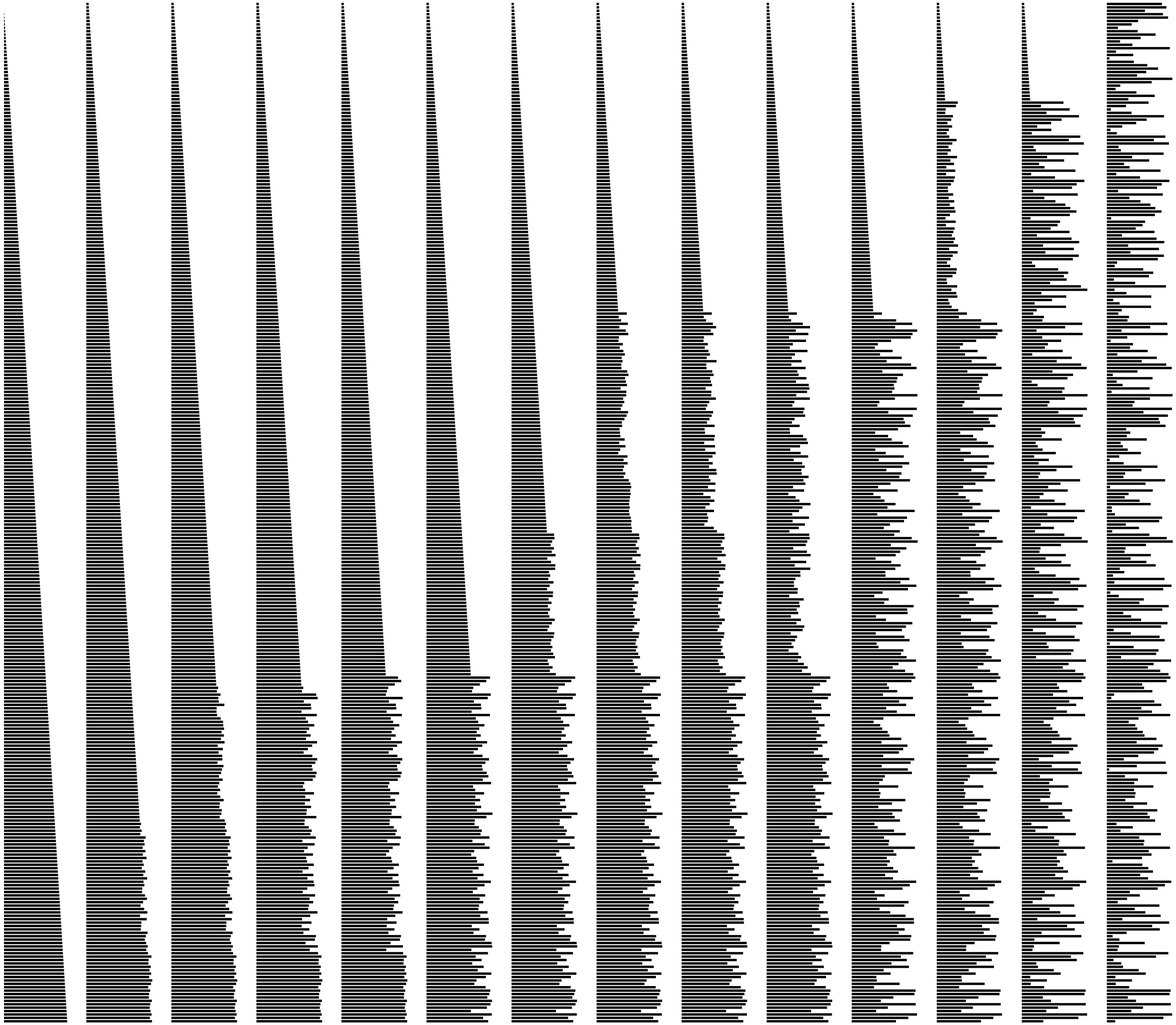


- **For more, read R. Sedgewick, *Algorithms in C*, Addison-Wesley, 1990**

Quicksort in Action

quicksort(x, 0, 9)	3	8	1	7	9	0	5	2	6	4
	3	*2*	1	7	9	0	5	*8*	6	4
	3	2	1	*0*	9	*7*	5	8	6	4
	3	2	1	0	*4*	7	5	8	6	*9*
quicksort(x, 0, 3)	3	2	1	0	4	7	5	8	6	9
	0	2	1	*3*	4	7	5	8	6	9
quicksort(x, 0, -1)										
quicksort(x, 1, 3)	0	2	1	3	4	7	5	8	6	9
	0	2	1	3	4	7	5	8	6	9
quicksort(x, 1, 2)	0	2	1	3	4	7	5	8	6	9
	0	*1*	*2*	3	4	7	5	8	6	9
quicksort(x, 1, 0)										
quicksort(x, 2, 2)										
quicksort(x, 4, 3)										
quicksort(x, 5, 9)	0	1	2	3	4	7	5	8	6	9
	0	1	2	3	4	7	5	8	6	9
quicksort(x, 5, 8)	0	1	2	3	4	7	5	8	6	9
	0	1	2	3	4	*5*	*7*	8	6	9
	0	1	2	3	4	5	*6*	8	*7*	9
quicksort(x, 5, 5)										
quicksort(x, 7, 8)	0	1	2	3	4	5	6	8	7	9
	0	1	2	3	4	5	6	*7*	*8*	9
quicksort(x, 7, 6)										
quicksort(x, 8, 8)										
quicksort(x, 10, 9)										

Quicksort in Action, cont'd



Implementing Recursive Functions

- **Consider `sum(10)`: *each call* must have *its own argument* n and its return address**
- **Use a *stack* to hold arguments, local variables, and the return address**

```
sum(n=10) calls
    sum(9)
        sum(8)
            sum(7)
                sum(6)
                    sum(5)
                        sum(4)
                            sum(3)
                                sum(2)
                                    sum(1)
                                        sum(0)
                                        returns 0
                                    returns 1
                                returns 3
                            returns 6
                        returns 10
                    returns 15
                returns 21
            returns 28
        returns 36
    returns 45
returns 55
```

ret. addr.
n=0
ret. addr.
n=1
ret. addr.
n=2
ret. addr.
n=3
ret. addr.
n=4
ret. addr.
n=5
ret. addr.
n=6
ret. addr.
n=7
ret. addr.
n=8
ret. addr.
n=9
ret. addr.
n=10

Implementing Recursive Functions, cont'd

- **Use *conventions* for the stack and for how arguments, etc. are 'pushed'**

  Use R_7 as the 'stack pointer:' it holds the address of the top element

  Stack starts at FF_{16} and grows 'down' — toward *lower* addresses

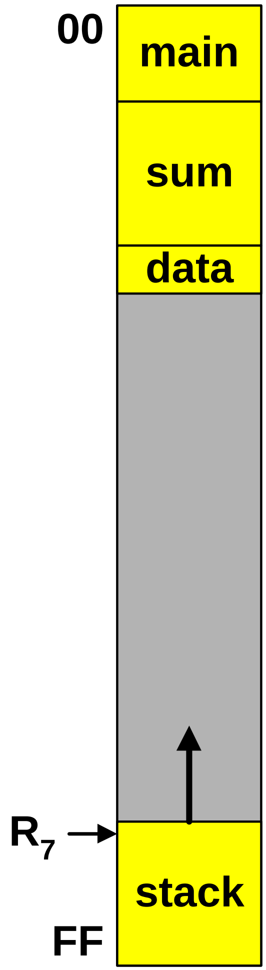
  Push the arguments onto the stack before calling a function; push the return address upon entering a function

```
30: B201    R2 <- 1                     push the return address
31: 2772    R7 <- R7 - R2 = R7 - 1
32: A670    M[R7+0] <- R6
33: 9171    R1 <- M[R7+1]               R1 <- n
34: 2312    R3 <- R1 - R2 = R1 - 1      R3 <- n - 1
35: 633D    jump to 3D if R3 < 0        if (n == 0) return 0
36: 2772    R7 <- R7 - R2 = R7 - 1      push n - 1
37: A370    M[R7+0] <- R3
38: 8630    R6 <- PC, PC <- 30          call sum
39: B201    R2 <- 1                     pop n - 1
3A: 1772    R7 <- R7 + R2 = R7 + 1
3B: 9271    R2 <- M[R7+1]               R2 <- n
3C: 1112    R1 <- R1 + R2               R1 <- sum(n-1) + n
3D: 9670    R6 <- M[R7+0]               pop return address
3E: B201    R2 <- 1
3F: 1772    R7 <- R7 + R2 = R7 + 1
40: 7600    PC <- R6                    return
```

Implementing Recursive Functions, cont'd

- **Main program makes the first call**

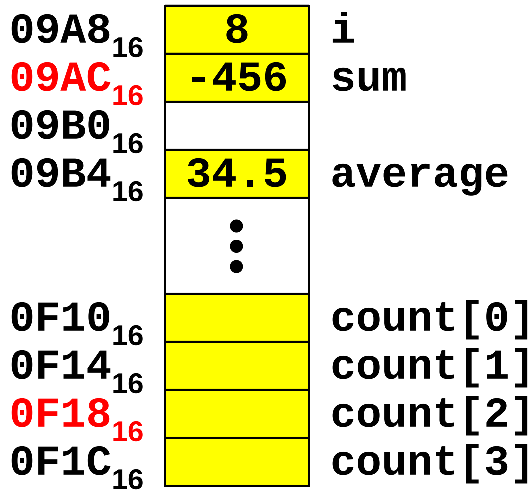
```
00:  B000     R0 <- 0                    R0 holds 0
01:  B7FF     R7 <- FF                   initialize stack pointer
02:  B210     R2 <- 50                       R2 <- address of n
03:  9220     R2 <- M[R2+0]                  R2 <- n
04:  B101     R1 <- 1                        push n
05:  2771     R7 <- R7 - R1 = R7 - 1
06:  A270     M[R7+0] <- R2
07:  8630     R6 <- PC, PC <- 30             call sum
08:  B201     R2 <- 1                        pop n
09:  1772     R7 <- R7 + R2 = R7 + 1
0A:  4102     print R1                       print sum(n)
0B:  0000     halt

50:  0000                                    n
```



Lecture 12. Pointers

- Variables denote ***locations in memory*** that can hold values; arrays denote ***contiguous locations***

```
int i = 8, sum = -456;
float average = 34.5;
unsigned count[4];
```



- The ***location*** of a variable is its ***lvalue*** or ***address***; the contents stored in that location is its ***rvalue***
- A ***pointer*** is a variable whose ***rvalue*** is the ***lvalue*** of another variable — the address of that variable
- Pointers are typed: a 'pointer to an `int`' may hold only the lvalue of an `int` variable

  If p points to `sum`, q points to `count[2]`:

```
int *p; unsigned *q;

p = &sum;
q = &count[2];
```

  p and q ***cannot*** point to `average`

- The ***null pointer*** — denoted `NULL` — points to ***nothing***

```
p = NULL;
```

Pointer Operations

- **Two fundamental operations: *__creating__* pointers, *__accessing__* the values they point to**

  unary & ‘address of’ returns the address of its *__lvalue__* operand as an *__rvalue__*

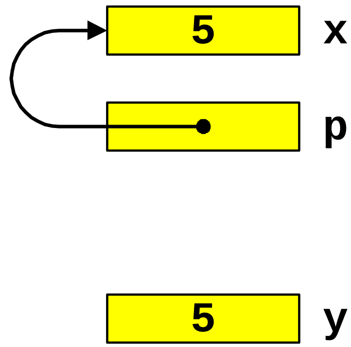
  unary * ‘indirection’ returns the *__lvalue__* given by its *__pointer__* operand’s *__rvalue__*

  Suppose `x` and `y` are `int`s, `p` is a pointer to an `int`

  `p = &x;` **`p` is assigned the address of `x`**

  `y = *p;` **`y` is the value pointed to by `p`**

  `y = *(&x);` **same as `y = x`**



- **Declaration syntax for pointer types *__mimics the use__* of pointer variables in expressions**

  `int x, y;`

  `int *p;` **`*p` is an `int`, so `p` must be a pointer to an `int`**

- **Unary `*` and & have higher precedence than most other operators**

```
y = *p + 1;      y = (*p) + 1;
y = *p++;        y = *(p++);
```

Indirection

- **Pointer indirection (e.g., `*p`) yields an *lvalue* — a *variable* — and pointer values can be manipulated like other values**

```
int x, y, *px, *py;
```

`px = &x;`	px is the address of x	no effect on x
`*px = 0;`	sets x to 0	no effect on px
`py = px;`	py also points to x	no effect on px or x
`*py += 1;`	increments x to 1	no effect on px or py
`y = (*px)++;`	sets y to 1, x to *2*	no effect on px or py

- **Passing pointer arguments *simulates* passing arguments 'by reference'**

```
void swap(int x, int y) {
    int t;

    t = x;
    x = y;
    y = t;
}

int a = 1, b = 2;
swap(a, b);
printf("%d %d\n", a, b);

1 2
```

```
void swap(int *x, int *y) {
    int t;

    t = *x;
    *x = *y;
    *y = t;
}

int a = 1, b = 2;
swap(&a, &b);
printf("%d %d\n", a, b);

2 1
```

Pointers and Arrays

- **Pointers can 'walk along' arrays by pointing to each element in turn**

```
int a[10], i, *p, x;
```

`p = &a[0];`	**p is assigned the address of the 1st element of a**
`x = *p;`	**x is assigned `a[0]`**
`x = *(p + 1);`	**x is assigned `a[1]`**
`p = p + 1;`	**p is assigned the address of `a[1]`, *by definition***
`p++;`	**p points to `a[2]`**

- **Pointer arithmetic: If p points to `a[i]`, `p + k` points to `a[i+k]`**

- **An array name is a *constant* pointer to the first element of the array**

`p = a;`	**p is assigned the address of `a[0]`**
`a++;`	***illegal*: can't change a constant**
`p++;`	**legal: p is a variable**

- **The idiom `*p++` walks along the array pointed to by p**

```
p = a;
for (i = 0; i < 10; i++)
    printf("%d\n", *p++);
```

```
for (i = 0; i < 10; i++)
    printf("%d\n", a[i]);
```

Both loops print the same output, both are efficient, both are acceptable

Pointers and Array Parameters

- **An array parameter type is identical to a pointer to the element type**

  Array parameters are *not* constants, they are *variables*

  Passing an array as an actual argument passes a *pointer* to the *first element*

  In effect, arrays — and *only* arrays — are passed *by-reference*

```
void print(int x[], int size) {
    int i;

    for (i = 0; i < size; i++)
        printf("%d\n", x[i]);
}
```

```
void print(int *x, int size) {

    while (size-- > 0)
        printf("%d\n", *x++);
}
```

- **A *string* is an *array of characters*; the name of a character array is thus a `char *`**
- **String functions can be written using arrays or pointers, but often *return pointers***

  `char *strcpy(char *dst, char *src)` copies `src` to `dst`, then returns `dst`

```
char *strcpy(char dst[], char src[]) {
    int i;

    for (i = 0; src[i] != '\0'; i++)
        dst[i] = src[i];
    dst[i] = '\0';
    return dst;
}
```

Pointers and Array Parameters, cont'd

- **Pointer version**

```
char *strcpy(char *dst, char *src) {
    char *d = dst, *s = src;

    while (*d = *s) {                  while ((*d = *s) != '\0')
        d++;
        s++;
    }
    return dst;
}
```

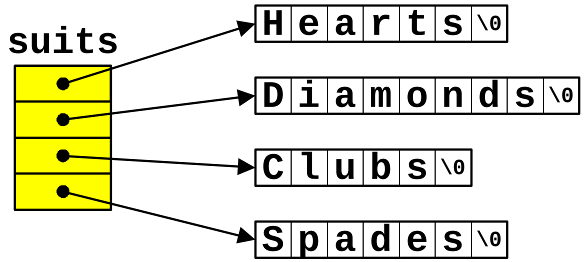
- ***Idiomatic* version**

```
char *strcpy(char *dst, char *src) {
    char *d = dst;

    while (*dst++ = *src++)            while ((*dst++ = *src++) != '\0')
        ;
    return d;
}
```

- **Pointer versions *might* be faster, but strive for *clarity*, not microefficiency**

Arrays of Pointers

- **Arrays of pointers help build tabular structures**




```
char *suits[] = {
    "Hearts", "Diamonds", "Clubs", "Spades"
};

char *faces[] = {
    "Ace", "2", "3", "4", "5", "6", "7", "8",
    "9", "10", "Jack", "Queen", "King"
};
```

Declare `suits` and `faces` each to be an 'array of pointers to characters,' *not* 'a pointer to an array of characters', and initialize them as shown

- **Indirection (*) has *lower* precedence than `[]`**

`char *suits[];`   is the same as   `char *(suits[]);`

Declaration mimics use: `*suits[i]` refers to the 0th character in the `i`th string

```
printsuit(int card) {
    printf("%c", *suits[card%13]);
}
```

- **A string constant is shorthand for the name of an array of characters**

```
print("0123456789ABCDEF"[n%b]);    char digits[] = "0123456789ABCDEF";
                                   print(digits[n%b]);
```

Common Errors

- **Only *addresses* can be assigned to pointers**

```
int *p, i;
p = i;                    p = &i;
```

- **Only addresses of variables of the *correct types* can be assigned to pointers**

```
int *p;                   float *p;
float x;
p = &x;
```

- **Only pointers can be used with *indirection***

```
p = *i;                   i = *p; ?
```

- **Pointers must be *initialized* to valid addresses *before* using indirection**

```
                          p = &i;
*p = 5;
printf("%d\n", *p);
```

- **The null pointer must *not* be dereferenced, because it points to ‘nothing’**

```
p = NULL;                 p = &i;
*p = 6;
```

Common Errors, cont'd

- **Pointers must point to variables that *exist*! See page 4-8**

```
int *SumPtr(int a, int b) {
    int sum = a + b;

    return &sum;
}

p = SumPtr(2, 5);                    sum does not exist!
printf("%d\n", *p);


char *itoa(int n) {
    char buf[100];

    sprintf(buf, "%d", n);
    return buf;
}

char *s;
s = itoa(56);                        buf does not exist!
printf("%s\n", s);
```

`sprintf` is like `printf`, but stores the 'output' in a string

- **When faced with bugs involving a pointer, ask: Is this pointer initialized? Does the memory it points to exist?**

Lecture 13. Structures

- **An array is a *homogeneous* collection: all of its elements have the *same type***

- **A structure is a *heterogeneous collection*: its elements can have *different* types**

```
struct date {
    int day;
    int month;
    int year;
    char monthname[4];   /* "Jan", "Feb", etc. */
};
```

Declares a *new type*, `struct date`, with four named elements, called *fields*

- **Structures can be *nested***

```
struct student {
    char name[30];
    float gpa;
    struct date birthday;
};
```

- **Structure types can be used like `int`, `float`, etc. to declare variables and arrays, which can optionally be initialized — and they must be initialized before use**

```
struct date today;
struct student cs126[140];

struct date bday = { 2, 11, 1977, "Nov" };
```

Fields

- **Structure fields are accessed by *variable*`.`*field***

`bday.day`	**the day field in bday, the `int 2`**
`bday.name[i]`	**the `i`th character in the `monthname` field of bday, a `char`**

- ***Field selection*** **operator associates to the *left* and has high precedence**

```
struct student cs126[140];
```

`cs126[i].gpa`	**the GPA of the `i`th `student` in `cs126`**
`cs126[i].name[j]`	**the `j`th character in the name of the `i`th `student`**
`cs126[i].birthday.year`	**the `year` of the `i`th `student`'s `birthday`**
`cs126[i].birthday.monthname[0]`	**the first letter in the `monthname` of the `i`th `student`'s `birthday`**

- **Field selection denotes an *lvalue*; use assignments to initialize/change field values**

```
today.day = 24;
today.month = 10;
today.year = 1996;
strcpy(today.monthname, "Oct");

swap(&today.day, &bday.day);
```

Arrays of Structures

- **A structure type provides a way to package related data in one variable**

```
struct card {
    char *face;
    char *suit;
};

char *suits[] = { "Hearts", "Diamonds", "Clubs", "Spades" };

char *faces[] = { Ace", "2", "3", "4", "5", "6", "7", "8",
    "9", "10", "Jack", "Queen", "King" };

int main(void) {
    int i;
    struct card deck[52];

    deck[0].face = faces[0]; deck[0].suit = suits[0];
    deck[1].face = faces[1]; deck[1].suit = suits[0];
    for (i = 2; i < 52; i++) {
        int k = rand()%i;
        deck[i] = deck[k];
        deck[k].face = faces[i%13]; deck[k].suit = suits[i/13];
    }
    for (i = 0; i < 52; i++)
        printf("%s of %s\n", deck[i].face, deck[i].suit);
    return 0;
}
```

Once shuffled, cards are represented by `struct card` values, not integers 0..51

Pointers to Structures

- A ***structure pointer*** holds the address of a structure variable

```
struct date today, bday, *pdate;
```

```
pdate = &today;              assigns the address of today to pdate
(*pdate).day = 2;            sets the day field of today to 2
(*pdate).year++;             increments the year field of today
printf("%s %d, %d\n", (*pdate).monthname, (*pdate).day,
    (*pdate).year);          prints the date given by today
bday = *pdate;               assigns today to bday, field-by-field
```

- Structure pointers can 'walk along' arrays of structures

```
struct card *dptr;
```

```
dptr = deck;
for (i = 0; i < 52; i++) {
    printf("%s of %s\n", (*dptr).face, (*dptr).suit);
    dptr++;
}
```

```
dptr = dptr + 1;    increment dptr means
dptr +=1;               'advance dptr to the next struct card element'
dptr++;                 not 'add 1 to dptr'
```


Pointers to Structures, cont'd

- `(*`*ptr*`).`*field* is so common that there's an abbreviation: *ptr*`->`*field*

  use *var*`.`*field* when *var* is a ***structure***

  use *var*`->`*field* when var is a ***pointer to a structure***
  or `(*`*var*`).`*field*

  `->` has high precedence, but less than `.`

  `pdate->day = 2;` sets the day field of `*pdate` to 2
  `pdate->year++;` increments the year field of `*pdate`
  `printf("%s %d, %d\n", pdate->monthname, pdate->day, pdate->year);` prints the date given by `*pdate`

```
for (i = 0; i < 52; i++) {
    printf("%s of %s\n", dptr->face, dptr->suit);
    dptr++;
}
```

- Pointer madness! Structures can contain other pointers, but watch precedence

```
struct foo { int x, *y; } *p;
```

  `++p->x` increments field x in `*p`
  `(++p)->x` increments p, ***then*** acesses field x
  `*p->y++` returns the `int` pointed to by field y in `*p`, increments y
  `*p++->y` returns the `int` pointed to by field y in `*p`, increments p

Typedefs

- **‘`struct card`’ is a bit wordy and can make code hard to read**
- **A `typedef` *associates* an *identifier* with a *type*, which makes code more readable**

```
typedef struct card Card;
```

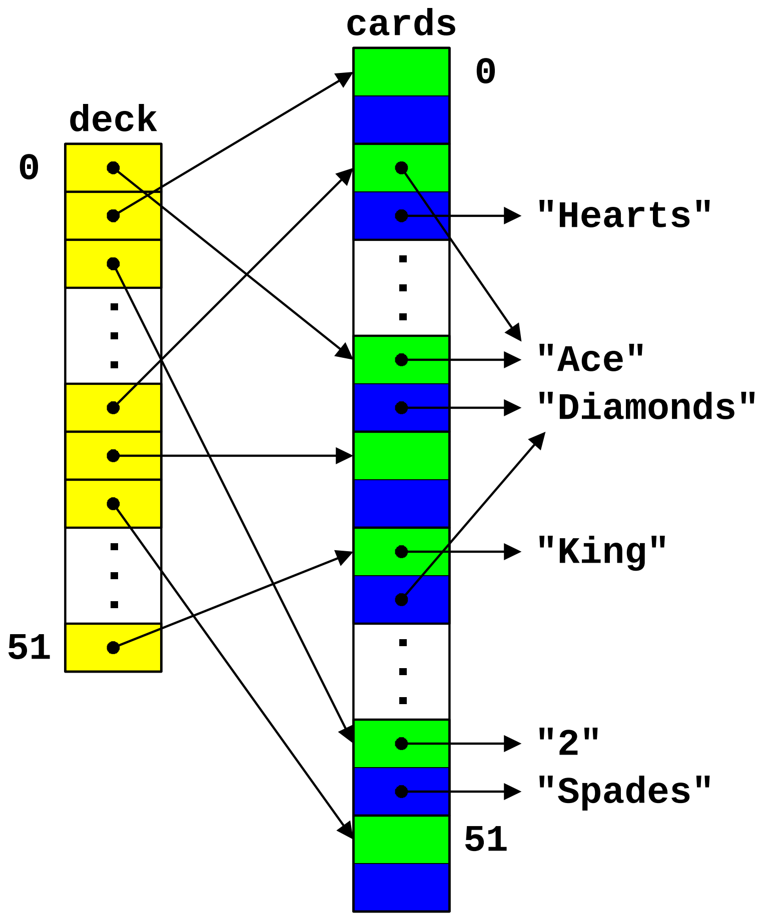
Declares `Card` to be a type name for ‘`struct card`’
`Card` may be used anywhere `struct card` can be used

Case matters!

Putting it all Together: Card Shuffling Revisited

- **Represent a deck by an *array of pointers to cards*; shuffle by rearranging the pointers, not the cards themselves**

```
typedef struct card Card;

struct card {
    char *face;
    char *suit;
};

Card cards[52];

void shuffle(Card *deck[52]) {
    int i;

    deck[0] = &cards[0];
    deck[1] = &cards[1];
    for (i = 2; i < 52; i++) {
        int k = rand()%i;
        deck[i] = deck[k];
        deck[k] = &cards[i];
    }
}
```



Card Shuffling Revisited, cont'd

- **Mapping of 0..51 onto faces and suits is confined to initialization**

```
char *suits[] = { "Hearts", "Diamonds", "Clubs", "Spades" };

char *faces[] = { "Ace", "2", "3", "4", "5", "6", "7", "8",
    "9", "10", "Jack", "Queen", "King" };

void initialize(void) {
    int i;

    for (i = 0; i < 52; i++) {
        cards[i].face = faces[i%13];
        cards[i].suit = suits[i/13];
    }
}

int main(void) {
    int i;
    Card *deck[52];

    initialize();
    shuffle(deck);
    for (i = 0; i < 52; i++)
        printf("%s of %s\n", deck[i]->face, deck[i]->suit);
    return 0;
}
```

- **Can handle *many* decks (arrays of pointers) with only *one* array of card structures**

Lecture 14. Dynamic Memory Allocation

- **The number of variables and their sizes are determined at *compile-time* — *before* a program runs**

```
/*
Read up to 1000 integers from
standard input and sort them using Quicksort.
*/
#include <stdio.h>
#include "quicksort.h"

int main(void) {
    int i, n = 0, array[1000];

    while (n < 1000 && scanf("%d", &array[n]) == 1)
        n++;
    quicksort(array, 0, n - 1);
    for (i = 0; i < n; i++)
        printf("%d\n", array[i]);
    return 0;
}
```

Suppose you want to sort 1001 integers? An unknown number of integers?

Size of the input is unknown at compile-time; it's known only at runtime

Need a way for the program to *adapt* to the size of the input

Solution: *allocate* the array at runtime, not at compile time

Allocating Memory at Runtime

- **To allocate 100 bytes of memory**

```
char *ptr;

ptr = malloc(100);
if (ptr == NULL) {
    printf("Cannot allocate memory\n");
    exit(1);
}
```

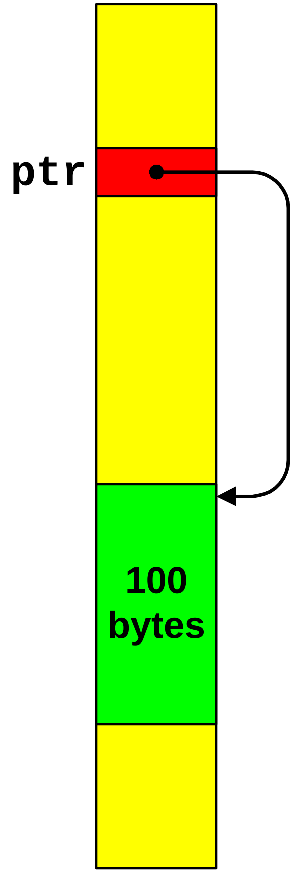
`malloc` allocates a contiguous block of memory at least `100` bytes long and returns the address of the first byte

If `malloc` cannot allocate the memory requested, it returns `NULL` — *always* check! Better yet, use `emalloc` in `libmisc.a`

`malloc` returns a *generic pointer*, which can be assigned to any pointer type

```
strcpy(ptr, "Hello World!\n");
printf("%s", ptr);
```

```
Hello World!
```



- **The memory block returned by `malloc` can be accessed *only* through a pointer; no variable labels that block**

Deallocating Memory

- **To deallocate the memory pointed to by `ptr`**

  `free(ptr);`

  `free` deallocates the block of memory pointed to by `ptr`

  After* calling `free`, `ptr` is *uninitialized*; using this uninitialized value is an *error

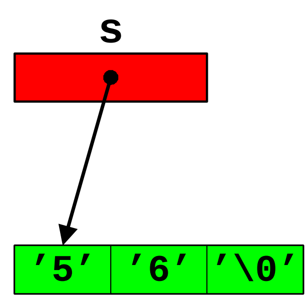
- **Memory blocks are allocated/deallocated by *explicit calls* to `malloc`/`free`**

  A block allocated by `malloc` exists until a call to `free` deallocates it

  `malloc` 'creates' a block of memory, `free` 'destroys' it

- **The *lifetime* of an allocated block is determined only by `malloc`/`free`; other function calls have *no* effect on its existence**

```
char *itoa(int n) {
    char buf[100], *ptr;

    sprintf(buf, "%d", n);
    ptr = emalloc(strlen(buf) + 1);
    strcpy(ptr, buf);
    return ptr;
}
```




```
char *s;
s = itoa(56);
printf("%s\n", s);
```

`ptr` no longer exists,
but the memory pointed to by `s` *does* exist!

Sizeof

```
int *SumPtr(int a, int b) {
    int *ptr, sum = a + b;

    ptr = emalloc(          );
    *ptr = sum;
    return ptr;
}

int *p = SumPtr(2, 5);
printf("%d\n", *p);
free(p);
```

how big is an `int`?

- `sizeof` (*type*) is a ***constant*** that gives the size of values of *type* in bytes

```
    ptr = emalloc(sizeof (int));
```

allocate space for an `int`

- Values given by `sizeof` are machine-dependent

	Sparc	Alpha	PCs
`sizeof (int)`	4 bytes	4 or 8	2 or 4
`sizeof (int *)`	4	8	2, 4, or 8
`sizeof (float)`	4	4	4
`sizeof (int *)`	4	8	2, 4, or 8
`sizeof (void *)`	4	8	8

These values are only typical, not exhaustive

Sizeof, cont’d

- **The size of a structure type may *not* be the sum of the sizes of its fields**

```
struct date {
    int day, month, year;
    char monthname[4];
};
```

```
struct student {
    char name[30];
    float gpa;
    struct date birthday;
};
```

`sizeof (struct date)`	**10–32 bytes**
`sizeof (struct student)`	**54–72**

- **Use `sizeof` and `malloc/emalloc` to allocate *instances* of structure types**

```
char *months[] = { "Jan", "Feb", "Mar", "Apr", "May", Jun",
    "Jul", "Aug", "Sep", "Oct", "Nov", "Dec" };

struct date *mkdate(int day, int month, int year) {
    struct date *ptr = emalloc(sizeof (struct date));

    ptr->day = day; ptr->month = month; ptr->year = year;
    strcpy(ptr->monthname, months[month-1]);
    return ptr;
}
```

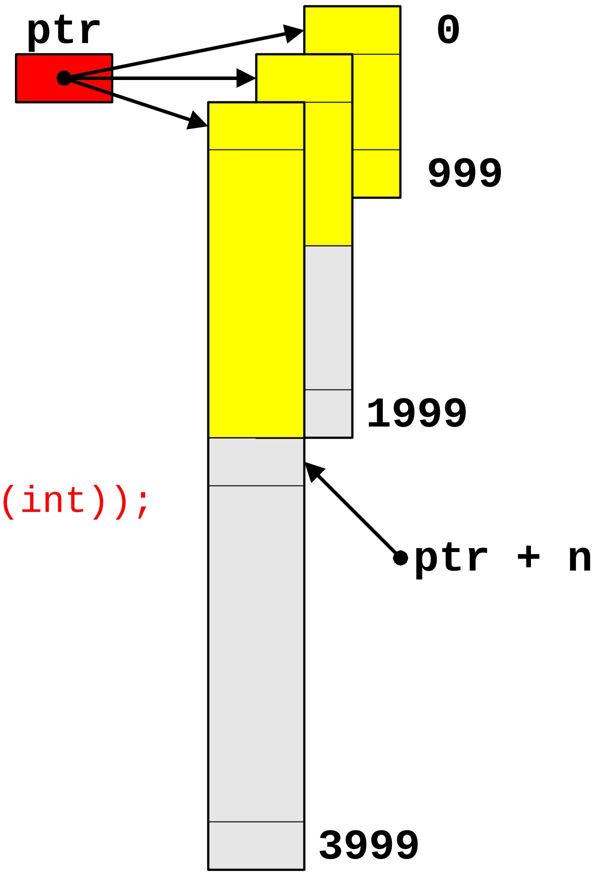
Dynamic Arrays

- **To sort an arbitrary number of integers**

  Start with an array than can hold 1000 integers

  ***Double the size* of this array when more space is needed; 1000, 2000, 4000, …**

```
#include <stdio.h>
#include "quicksort.h"
#include "misc.h"

int main(void) {
    int i, n = 0, *ptr, x, size = 1000;

    ptr = emalloc(size*sizeof (int));
    while (scanf("%d", &x) == 1) {
        if (n >= size) {
            size *= 2;
            ptr = erealloc(ptr, size*sizeof (int));
        }
        ptr[n++] = x;
    }
    quicksort(ptr, 0, n - 1);
    for (i = 0; i < n; i++)
        printf("%d\n", ptr[i]);
    return 0;
}
```



Dissecting sort2.c

```
#include "misc.h"
```

Includes the header file `misc.h`, which declares `emalloc` and `erealloc`

```
lcc -I/u/cs126/include sort2.c quicksort.c /u/cs126/lib/libmisc.a
```

Compiles `sort2.c` and `quicksort.c`, and searches `libmisc.a` to build `a.out`

```
int i, n = 0, *ptr, x, size = 1000;
```

Declares `ptr` and `size` (and `i`, n, and x), and initializes `size` to 1000

```
ptr = emalloc(size*sizeof (int));
```

Allocates space for `size` integers, and assigns the addess of this *array* to `ptr`

```
while (scanf("%d", &x) == 1) {
    ...
    ptr[n++] = x;
}
```

Reads each integer and assigns it to the next element in the array `ptr`

For any pointer `ptr`: `ptr[i]` is equivalent to `*(ptr + i)`

If `ptr` points to the first element of a dynamically allocated array:

> **`ptr + i` points to the `i`th element,**
> **so `ptr[i]` refers to the `i`th element, too**

Dissecting sort2.c, cont'd

```
if (n >= size) {
    size *= 2;
    ptr = erealloc(ptr, size*sizeof (int));
}
```

Doubles the size of the array pointed to by `ptr`, if necessary

If n exceeds the current size of the array, `size` is doubled, and `erealloc` is called to expand the array accordingly

`erealloc` returns the address of the expanded array, which is assigned to `ptr`

`erealloc` is like `emalloc`: It calls the standard library function `realloc` and checks for errors

```
quicksort(ptr, 0, n - 1);
for (i = 0; i < n; i++)
    printf("%d\n", ptr[i]);
```

Sorts and prints the integers in `ptr[0..n-1]`

Common Errors

- **Failing to allocate memory**

```
int *p, i;
                                p = emalloc(sizeof (int));
*p = i;
```

- **Failing to allocate *enough* memory**

```
p = emalloc(sizeof (int *));        p = emalloc(sizeof (int));
*p = i;

char *strsave(char *str) {
    return strcpy(emalloc(strlen(str)), str);
}                                         strlen(str) + 1
```

- **Deallocating memory that was *not* allocated by `malloc`**

```
char buf[100];
free(buf);                          free(buf);
```

- **Deallocating memory that has *already been deallocated***

```
p = emalloc(sizeof (int));
free(p);
...
free(p);                            free(p);
```

Common Errors, cont'd

- Changing the value of a pointer returned by `emalloc`, then passing it to `free`

```
char *itoa(int n) {
    char buf[100];

    sprintf(buf, "%d", n);
    return strsave(buf);
}
```

```
char *s = itoa(56);                 char *s = itoa(56), *p = s;
while (*s != '\0')
    putchar(*s++);
free(s);                            free(p);
```

- Thinking that `sizeof` is a ***runtime*** operation

```
int i, n, *p;

p = emalloc(sizeof (n));            p = emalloc(n*sizeof (int));
for (i = 0; i < n; i++)
    p[i] = 0;
```

- Failing to deallocate memory

Lecture 15. Dynamic Data Structures

- Pointers and structures can be used to build data structures that ***expand*** and ***shrink*** during execution, e.g., lists, stacks, queues, trees, …
- Dynamic data structures are constructed using ***self-referential*** structure types

```
struct node {
    int value;
    struct node *link;
};
```

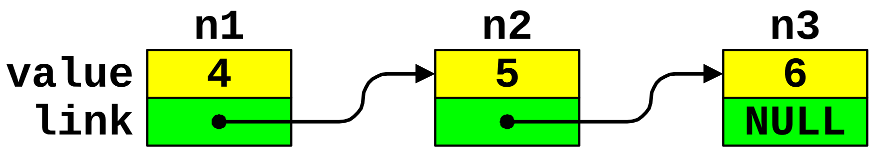
Declares a structure type with two fields

`value`	holds a integer
`link`	holds a pointer to a `struct` node

The type `struct` node is defined in terms of *itself* — self reference

```
struct node n1, n2, n3;
```

```
n1.value = 4;
n1.link = &n2;
n2.value = 5;
n2.link = &n3;
n3.value = 6;
n3.link = NULL;
```



Builds a *singly linked list* with 3 nodes holding 4, 5, and 6

Lists

- **Use a pointer to *traverse* a list — follow the `link` fields until you reach `NULL`**

```
struct node *p;

for (p = &n1; p != NULL; p = p->link)
    printf("%d\n", p->value);
```

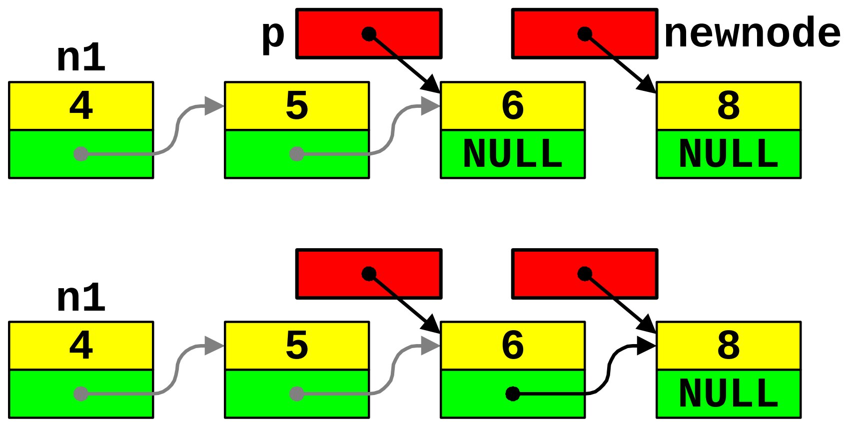
```
4
5
6
```

- **Use `emalloc`/`malloc` to allocate as many `struct` nodes as needed**

```
struct node *newnode = emalloc(sizeof (struct node));
newnode->value = 8;
newnode->link = NULL;
```

- **To add a new node at the end of the list, walk a pointer down to the *last node***

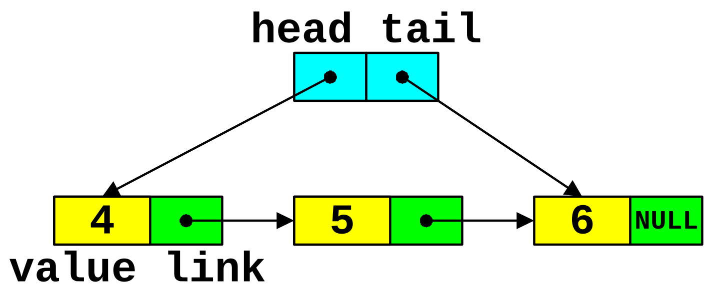
```
for (p = &n1; p->link != NULL; p = p->link)
    ;
p->link = newnode;
```



List Headers

- **Using a header node often simplifies list manipulations**

```
struct intlist {
    struct node *head;
    struct node *tail;
};
```



- **Important boundary conditions**

```
struct intlist alist;
alist.head = alist.tail = NULL;
```

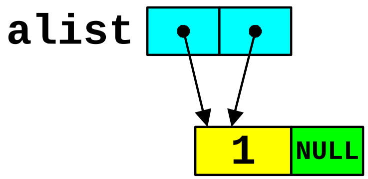
creates an *empty list*

so does `struct intlist alist = { NULL, NULL };`

```
struct node *p = emalloc(sizeof (struct node));
```

```
p->value = 1;
p->link = NULL;
alist.head = alist.tail = p;
```

creates a *one-node list*



- **List headers can be allocated, too, if you need an arbitrary number of lists (as opposed to a list of arbitrary length)**

```
struct intlist *mylist = emalloc(sizeof (struct intlist));
```

A Simple List Module

- **The *interface* defines the list types and list-manipulation functions**

```
/* Lists of ints */

struct intnode {
    int value;
    struct intnode *link;
};

struct intlist {
    struct intnode *head;
    struct intnode *tail;
};

extern void intlist_addhead(struct intlist *list, int value);
/* adds a new node holding value at the beginning of list */

extern void intlist_addtail(struct intlist *list, int value);
/* Adds a new node holding value at the end of list */

extern int  intlist_remhead(struct intlist *list);
/* Removes the node at the beginning of a non-empty list
    and returns the value from that node */
```

This interface appears in `intlist.h`

- **This kind of interface is an *abstract data type* because it defines a type and the operations on values of that type**

Implementing the List Module

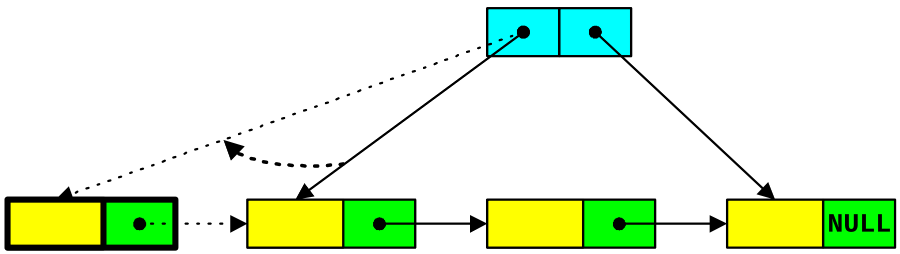
- **The *implementation* defines the functions specified in the interface**

```
/* Implementation of lists of ints */

#include <stdlib.h>
#include "intlist.h"
#include "misc.h"

void intlist_addhead(struct intlist *list, int value) { ... }
void intlist_addtail(struct intlist *list, int value) { ... }
extern int intlist_remhead(struct intlist *list) { ... }
```

This implementation appears in `intlist.c`

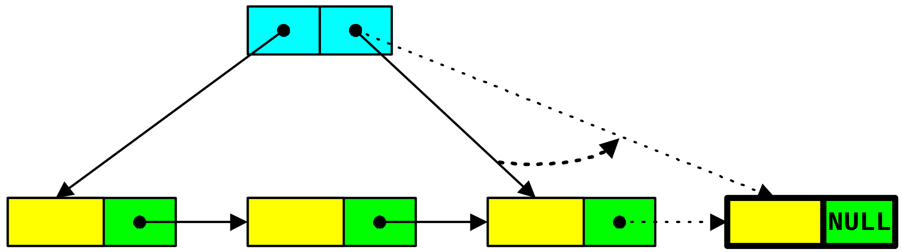
- **Adding a new node at the *head* of an `intlist` — beware *boundary conditions***

```
void intlist_addhead(struct intlist *list, int value) {
    struct intnode *p = emalloc(sizeof (struct intnode));

    p->value = value;
    if (list->head == NULL) {
        p->link = NULL;
        list->head = list->tail = p;
    } else {
        p->link = list->head;
        list->head = p;
    }
}
```



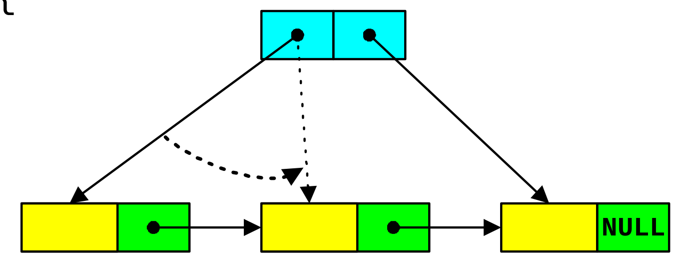
Implementing the List Module, cont’d

```
void intlist_addtail(struct intlist *list, int value) {
    struct intnode *p = emalloc(sizeof (struct intnode));

    p->value = value;
    p->link = NULL;
    if (list->tail == NULL)
        list->head = list->tail = p;
    else {
        list->tail->link = p;
        list->tail = p;
    }
}
```



- **When a node is deleted, it is also *deallocated***

```
int intlist_remhead(struct intlist *list) {
    int value;
    struct intnode *p = list->head;

    if (list->head == list->tail)
        list->head = list->tail = NULL;
    else
        list->head = p->link;
    value = p->value;
    free(p);
    return value;
}
```




```
free(p);
return p->value;
```

Wrong! **Why?**

Sorting Revisited

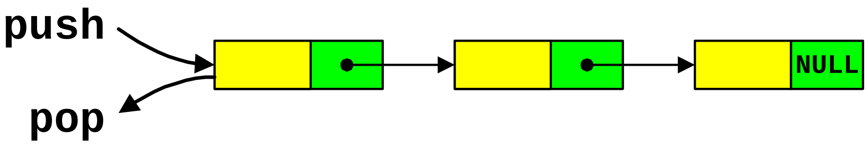
- **Another way to sort an arbitrary number of integers**

  1. **Read them into an `intlist`, thus determining the number of integers**
  2. **Allocate an array**
  3. **Pour the integers in the list into the array**
  4. **Sort it and print it**

```
#include <stdio.h>
#include "quicksort.h"
#include "intlist.h"
#include "misc.h"

int main(void) {
    int i, n, *ptr, x;
    struct intlist input = { NULL, NULL };

    for (n = 0; scanf("%d", &x) == 1; n++)
        intlist_addtail(&input, x);
    ptr = emalloc(n*sizeof (int));
    for (i = 0; i < n; i++)
        ptr[i] = intlist_remhead(&input);
    quicksort(ptr, 0, n - 1);
    for (i = 0; i < n; i++)
        printf("%d\n", ptr[i]);
    return 0;
}
```

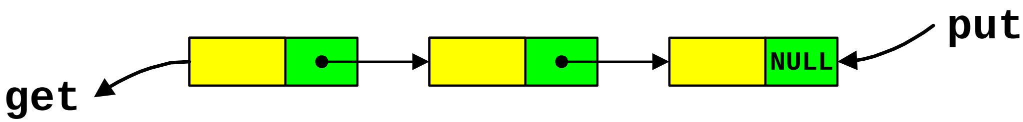
Other Kinds of Lists

- **Stacks: Add/remove nodes at only one end**




```
push    intlist_addhead
pop     intlist_remhead
```

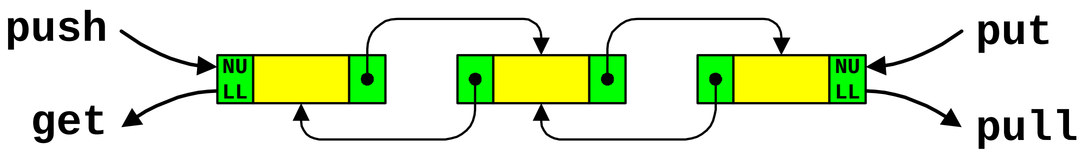
- **Queues: Add nodes at the tail, remove nodes from the head**




```
put     intlist_addtail
get     intlist_remhead
```

- **What about `intlist_remtail`? Need a *doubly* linked list for efficient removal**

- **Deques: Add/remove nodes at either end**




```
push    intlist_addhead          put     intlist_addtail
get     intlist_remhead          pull    intlist_remtail
```

Lecture 16. Writing Efficient Programs

- **Is n a prime?**

```
int isprime(int n) {
    if (n > 2) {
        int i, m = n/2;
        for (i = 2; i < m; i++)
            if (n%i == 0)
                return 0;
    }
    return 1;
}

int main(int argc, char *argv[]) {
    int i;

    for (i = 1; i < argc; i++) {
        int n;
        sscanf(argv[i], "%d", &n);
        if (isprime(n))
            printf("%d is a prime\n", n);
        else
            printf("%d is not a prime\n", n);
    }
    return 0;
}
```

```
% lcc isprime.c
% a.out 2147483647
...
```

- **2147483647 is a prime, but `isprime` takes 1073741823 iterations to check!**

Use a Better Algorithm

- **Observations:**

  Need to check only odd integers

  If n $= a \times b$, then either *a* or *b* must be $< \sqrt{n} + 1$

```
#include <math.h>

int isprime(int n) {
    if (n > 2 && n%2 != 0) {
        int i, m = sqrt(n) + 1;
        for (i = 3; i < m; i += 2)
            if (n%i == 0)
                return 0;
    }
    return 1;
}

% lcc isprime2.c
% a.out 2147483647
2147483647 is a prime
```

≈**23169 iterations**

- **Better algorithms make programs faster, not microscopic code hacks**
- **Programs must be fast enough, not necessarily as fast as possible**
- **Don’t sacrifice clarity for speed**

Searching

- **A small 'database' problem: Maintain a list of names; lookup 'queries,' adding the new names, if necessary**

```
int main(int argc, char *argv[]) {
    int i;
    char buf[128];

    ptr = emalloc(size*sizeof (char *));
    ptr[0] = NULL;
    while (scanf("%s", buf) == 1)
        lookup(buf);
    for (i = 1; i < argc; i++) {
        int k = lookup(argv[i]);
        printf("%d\t%s\n", k, argv[i]);
    }
    printf("\n");
    for (i = 0; ptr[i] != NULL; i++)
        printf("%d\t%s\n", i, ptr[i]);
    return 0;
}

% lcc -I/u/cs126/include lookup.c /u/cs126/lib/libmisc.a
% a.out drh appel <names
3525    drh
794     appel
...
14210   zzwang
```

Searching, cont'd

- **We know a good algorithm for searching — binary search (see page 10-3)**

```
int bsearch(char *x[], int lb, int ub, char *q) {
    if (lb <= ub) {
        int m = (lb + ub)/2;
        int cond = strcmp(x[m], q);
        if (cond < 0)
            return bsearch(x, m + 1, ub, q);
        else if (cond > 0)
            return bsearch(x, lb, m - 1, q);
        else
            return m;
    } else
        return -1;
}
```

see page 6-4 for `strcmp`

- **`ptr[0..count-1]` holds the names in ascending order; `ptr[count]` is `NULL`**

```
int count = 0;
char **ptr;

int lookup(char *name) {
    int k = bsearch(ptr, 0, count - 1, name);

    if (k == -1)
        k = insert(strsave(name));
    return k;
}
```


Cost of Binary Search

- **Counting *comparisons* — calls to `strcmp` in this version of `bsearch` — is a good measure of the cost of binary search**

- **Each recursive call cuts the problem in *half*, so the cost to search *N* names is**

$$C_N = C_{N/2} + 1 = C_{N/4} + 1 + 1 = \ldots$$

Suppose $N = 2^n$, then

$$C_{2^n} = C_{2^{n-1}} + 1 = C_{2^{n-2}} + 1 + 1 = \ldots = C_1 + 1 + \ldots + 1 = n$$

$$C_N = \log_2 N = \lg N$$

Even for huge *N*, lg *N* is small (conversely, even for small *n*, 2^n is huge…)

N	**lg *N***
10	**4**
100	**7**
1,000	**10**
10,000	**14**
100,000	**17**
1,000,000	**20**
10^k	$\approx 3.129 \times k$

- **Bottom line: Binary search, and other lg *N* algorithms, are *fast***

Inserting Names

- **To keep the names in ascending order, `insert(q)`**

  Expands the array, if necessary

  Slides `ptr[k..count-1]` down into `ptr[k+1..count]` where `ptr[k]` > `q`

  Stores `q` in `ptr[k]`, increments `count` and sets `ptr[count]` to `NULL`

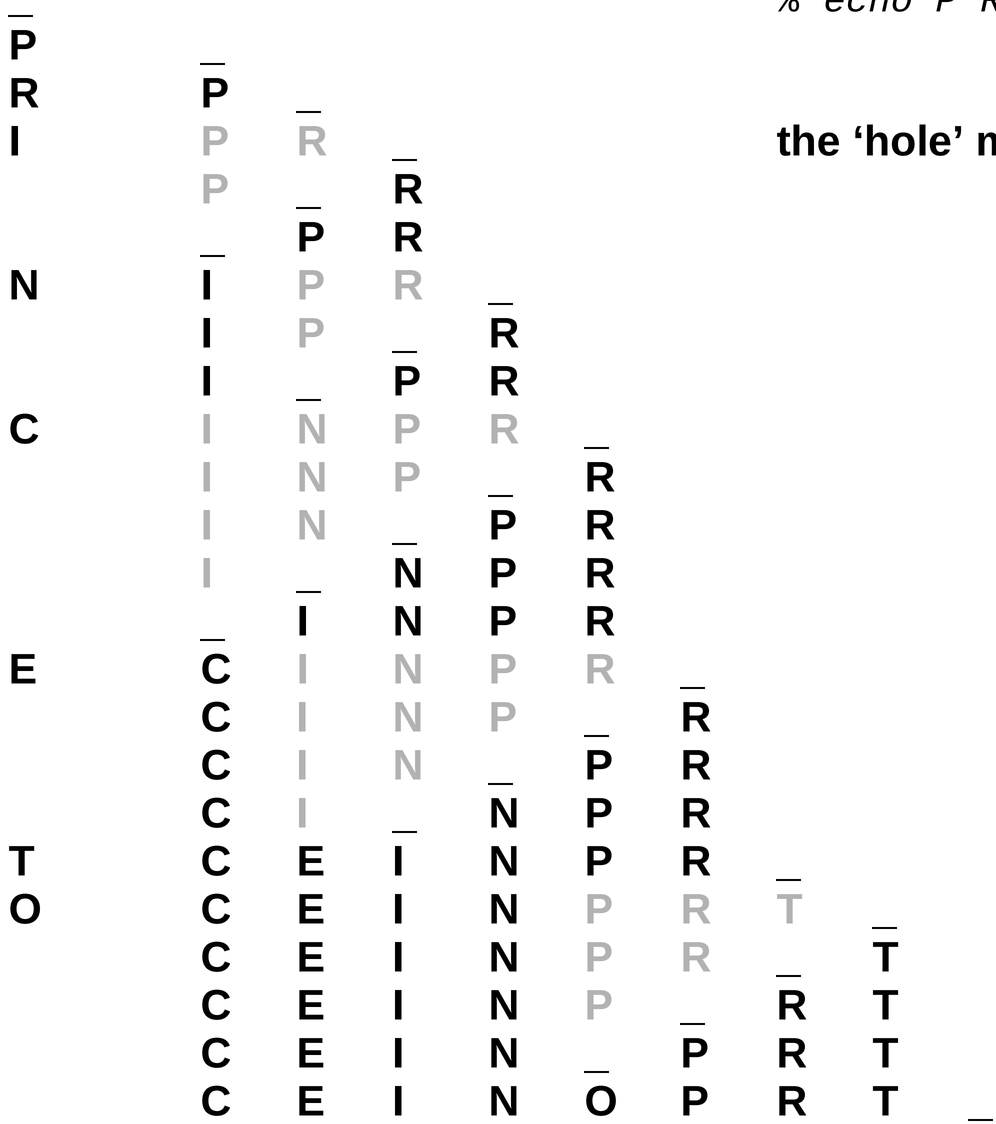
```
int size = 1;

int insert(char *q) {
    int k;

    if (count + 1 >= size) {
        size *= 2;
        ptr = erealloc(ptr, size*sizeof (char *));
    }
    for (k = count; k > 0 && strcmp(ptr[k-1], q) > 0; k--)
        ptr[k] = ptr[k-1];
    ptr[k] = q;
    ptr[++count] = NULL;
}
```

- **Oh oh… If the array holds *N* names, insert could take *N* comparisons**

insert in Action

`% echo P R I N C E T O N | a.out`

the 'hole' moves over dimmed letters



Binary Search Trees

- **Different representations have different costs**

	Search	**Insertion**	**Deletion**
Array	**fast**	**slow**	**slow**
Linked list	**slow: ≈*N***	**fast w/search** **slow w/o search**	**fast w/search** **slow w/o search**
Binary tree	***fast*: ≈*lg N***	***fast***	***fast***

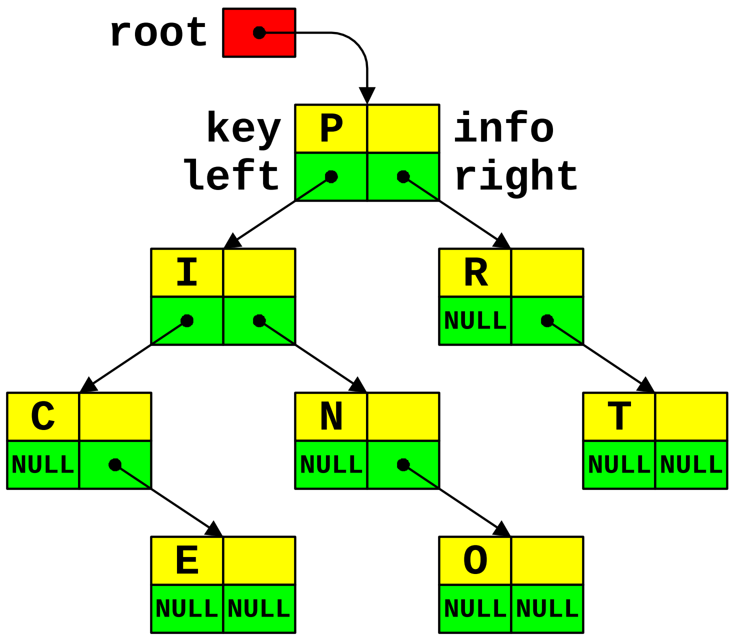
- **In a binary search tree**

```
struct node {
    char *key;
    int info;
    struct node *left, *right;
};
```

Names in the *left* subtree are $<$ than the name in the *root*

Names in *right* subtree are $\geq$ the name in the root

Holds for any node in the tree

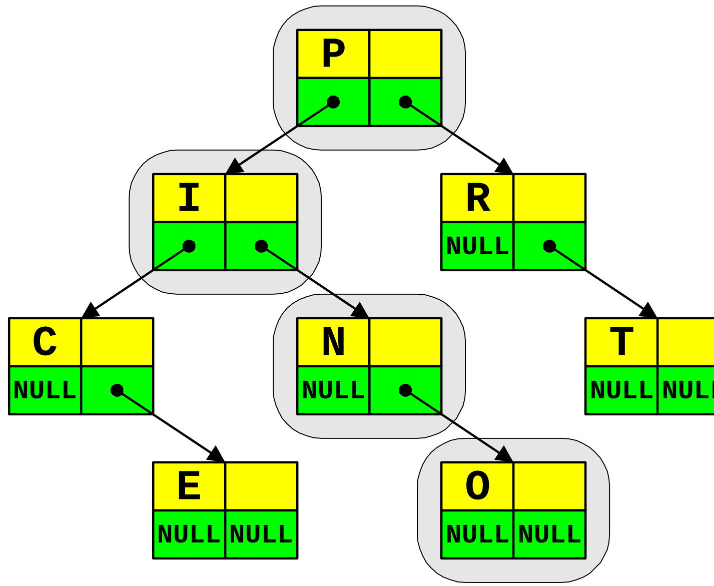


Searching in Binary Trees

- **To search for q in a binary search tree, start with `tree` = `root`**

  1. **If `tree` is `NULL`, the search fails — an important boundary condition**
  2. **If q < `tree->key`, search the *left* subtree**
  3. **If q > `tree->key`, search the *right* subtree**
  4. **q must be equal to `tree->key`**

```
struct node *search(struct node *tree, char *q) {
    if (tree != NULL) {
        int cond = strcmp(q, tree->key);
        if (cond < 0)
            return search(tree->left,  q);
        else if (cond > 0)
            return search(tree->right, q);
        else
            return tree;
    } else
        return NULL;
}
```



- **Cost of searching in *balanced* binary trees is the same as for binary search in arrays — lg *N***

- **It's possible to keep trees balanced during insertion; take COS 226, Data Structures, to find out how, and read R. Sedgewick, *Algorithms in C*, Addison-Wesley, 1990 (used in COS 226)**

Searching, cont'd

```
int count = 0;
struct node *root = NULL;

int lookup(char *name) {
    struct node *p = search(root, name);

    if (p == NULL) {
        p = insert(root, NULL, strsave(name));
        p->info = count++;
    }
    return p->info;
}

int main(int argc, char *argv[]) {
    int i;
    char buf[128];

    while (scanf("%s", buf) == 1)
        lookup(buf);
    for (i = 1; i < argc; i++) {
        int k = lookup(argv[i]);
        printf("%d\t%s\n", k, argv[i]);
    }
    print(root);
    return 0;
}
```

Printing Trees

- **Sorting is ‘free:’ Print the left subtree, print the key, print the right subtree**

```
void print(struct node *tree) {
    if (tree != NULL) {
        print(tree->left);
        printf("%d\t%s\n", tree->info, tree->key);
        print(tree->right);
    }
}
```

```
% lcc -I/u/cs126/include lookup2.c /u/cs126/lib/libmisc.a
% echo P R I N C E T O N | a.out
```

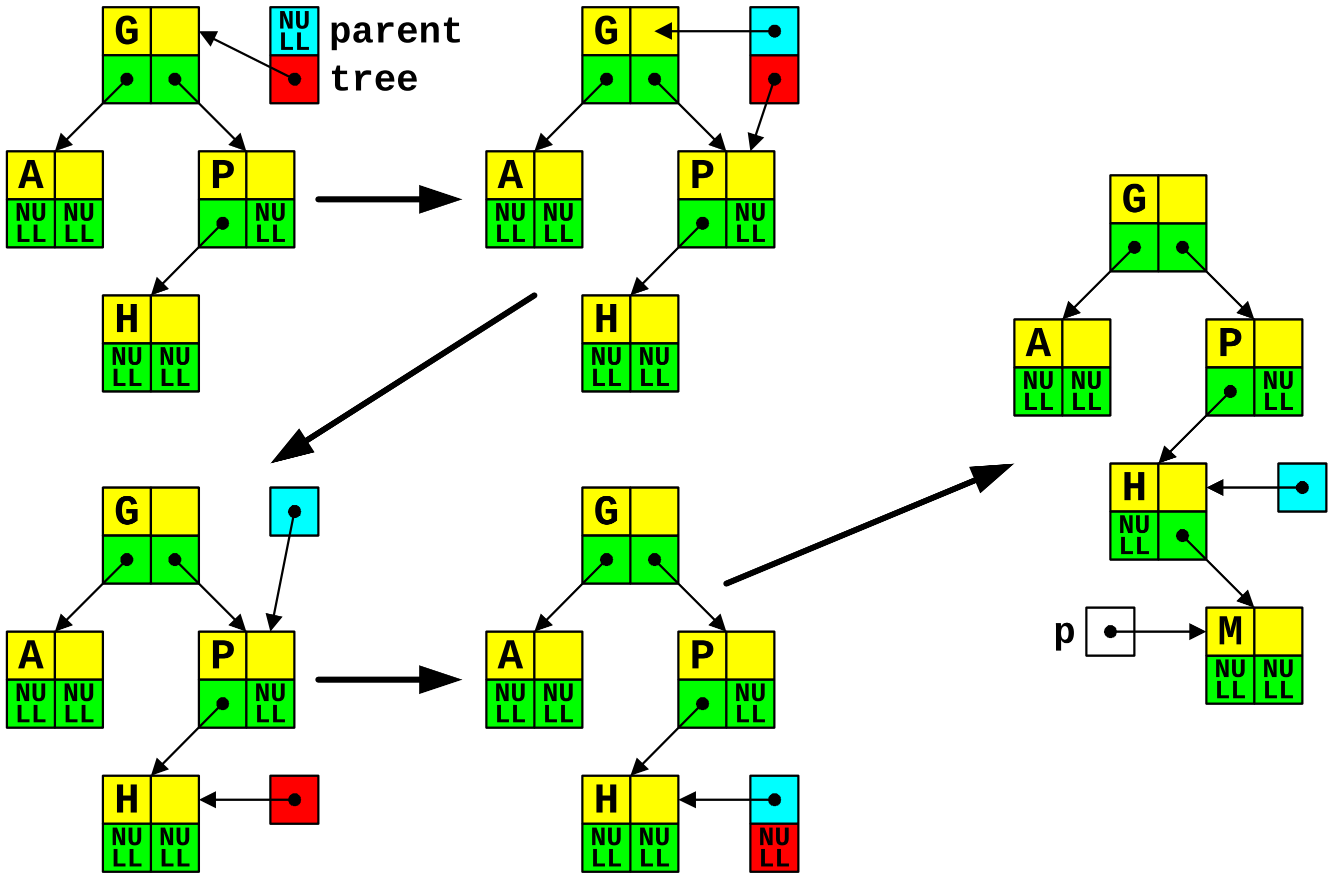
```
4   C
5   E
2   I
3   N
7   O
0   P
1   R
6   T
```

- **Ways to *traverse* trees; ‘visit’ means ‘process the node,’ e.g., print its key**

preorder:	***visit***	**traverse left**	**traverse right**
inorder:	**traverse left**	***visit***	**traverse right (alá `print`)**
postorder:	**traverse left**	**traverse right**	***visit***

Inserting in Binary Trees

- **`insert` is like `search`, but it must remember *parent nodes* in order to set the `left` or `right` field**



`insert` must also handle the *empty tree*, which occurs when `parent` is `NULL`

Inserting in Binary Trees, cont'd

```
struct node *insert(struct node *tree, struct node *parent, char *q) {
    if (tree != NULL) {
        if (strcmp(q, tree->key) < 0)
            return insert(tree->left,  tree, q);
        else
            return insert(tree->right, tree, q);
    } else {
        struct node *p = emalloc(sizeof (struct node));
        p->key = q;
        p->left = p->right = NULL;
        if (parent == NULL)
            root = p;
        else if (strcmp(q, parent->key) < 0)
            parent->left = p;
        else
            parent->right = p;
        return p;
    }
}

int lookup(char *name) {
    struct node *p = search(root, name);

    if (p == NULL) {
        p = insert(root, NULL, strsave(name));
    …
}
```

Lecture 17. Analysis of Algorithms

- **An *algorithm* is a 'method' for solving a problem that is *independent* of a specific computer or programming language**
- ***Design*: Finding a way to solve the problem**
- ***Analysis*: Determining the algorithm's cost in machine-independent terms, e.g. lg *N***
- **Need to make a program faster?**

  Get a new machine

  - **Costs $$$ or more**
  - **Makes 'everything' run faster**
  - **But, it may — or *may not* — have much impact on a specific problem**

  Get a new algorithm

  - **Costs ¢ or less**
  - **Can make or break a specific problem by allowing it to be solved at all**
  - **But, it may have *little or no* impact on 'everything'**

Sublist Sum Problem

- Given a list of numbers, find the contiguous sublist that has the largest sum

31	-41	59	26	-53	58	97	-93	-23	84	
						187				
31	*31*									
31	-41	59	*49*							
31	-41	59	26	*75*						
31	-41	59	26	-53	*22*					
31	-41	59	26	-53	58	*80*				
31	-41	59	26	-53	58	97	*177*			
31	-41	59	26	-53	58	97	-93	*84*		
31	-41	59	26	-53	58	97	-93	-23	*61*	
31	-41	59	26	-53	58	97	-93	-23	84	*145*

- Easy if all the numbers are nonnegative; tricky when some numbers are negative
- Sums must be positive; negative sublist sums are taken to be zero

A Simple Brute-Force Solution

- **Try all possible sublists of n integers: `x[lb..ub]` for all `lb`, `ub` from 0 to n**

```
void sublist(int x[], int n) {
    int lb, ub, l, r, max = 0;

    for (lb = 0; lb < n; lb++)
        for (ub = lb; ub < n; ub++) {
            int i, sum = 0;
            for (i = lb; i <= ub; i++)
                sum += x[i];
            if (sum > max) {
                max = sum;
                l = lb;
                r = ub;
            }
        }
    printf("x[%d..%d] = %d\n", l, r, max);
}
```

```
% lcc -I/u/cs126/include sublistn3.c /u/cs126/lib/libmisc.a
% echo 31 -41 59 26 -53 58 97 -93 -23 84 | a.out
x[2..6] = 187
```

Profiling

- **Program *profiles* help understand execution *frequencies*; use `lcc -b` and `bprint`**

```
% lcc -b -I/u/cs126/include sublistn3.c /u/cs126/lib/libmisc.a
% echo 31 -41 59 26 -53 58 97 -93 -23 84 | a.out
x[2..6] = 187
% bprint
...
        ❶  for (<1>lb = 0; <11>lb < n; <10>lb++)
           ❷   for (<10>ub = lb; <65>ub < n; <55>ub++) {
                   int i, sum = <55>0;
               ❸   for (<55>i = lb; <275>i <= ub; <220>i++)
                       <220>sum += x[i];
                   if (<55>sum > max) {
                       <6>max = sum;
                       <6>l = lb;
                       <6>r = ub;
                   }
           }
           <1>printf("x[%d..%d] = %d\n", l, r, max);
```

- **For $N = 10$**

Loop	❶	**is executed**	$11 \approx 10^1$	**times**
	❷		$65 \approx 10^2/2$	
	❸		$275 \approx 10^3/3$	

Execution time $\approx N^3$, can't solve $N = 10{,}000$, since 10^{12} microseconds ≈ 11 days

A Better Algorithm

- **Don’t recompute the whole sum every time**

x[lb] + x[lb+1] + … + x[ub] = (x[lb] + … + x[ub-1]) **+ x[ub]**

```
void sublist(int x[], int n) {
    int lb, ub, l, r, max = 0;

    for (lb = 0; lb < n; lb++) {
        int sum = 0;
        for (ub = lb; ub < n; ub++) {
            sum += x[ub];
            if (sum > max) {
                max = sum;
                l = lb;
                r = ub;
            }
        }
    }
    printf("x[%d..%d] =
}
```

31	-41	59	26	-53	58	97	-93	-23	84
31	-10	**49**	**75**	22	**80**	**177**	84	61	145
	-41	18	44	-9	49	146	53	30	114
		59	85	32	90	**187**	94	71	155
			26	-27	31	128	35	12	96
				-53	5	102	9	-14	70
					58	155	62	39	123
						97	4	-19	65
							-93	-116	-32
								-23	61
									84

Profiling the Better Algorithm

```
❶   for (<1>lb = 0; <11>lb < n; <10>lb++) {
        int sum = <10>0;
❷       for (<10>ub = lb; <65>ub < n; <55>ub++) {
            <55>sum += x[ub];
            if (<55>sum > max) {
                <6>max = sum;
                <6>l = lb;
                <6>r = ub;
            }
        }
    }
    <1>printf("x[%d..%d] = %d\n", l, r, max);
```

- **For $N = 10$**

  Loop ❶ is executed $11 \approx 10^1$ times
  ❷ $65 \approx 10^2/2$

  Execution time $\approx N^2$, but can't solve $N = 1{,}000{,}000$, because 10^{12} microseconds $\approx$ 11 days

- **There is a divide-and-conquer algorithm that takes $\approx N \lg N$, but there's even a better way**

The Optimal Algorithm

- Keep track of the maximum sum so far ***and*** the sum of the sublist that ends at **`x[i]`**

  Suppose `max` is the maximum sum in `x[0..i-1]`; extend that solution to `x[i]`

31	-41	59	26	-53	58	97	-93	-23	84
			85	*32*					

31	-41	59	26	-53	58	97	-93	-23	84
					90				

```
void sublist(int x[], int n) {
    int i, l, r, max = 0, maxi = 0;

    for (i = 0; i < n; i++) {
        if (maxi + x[i] > 0)
            maxi += x[i];
        } else
            maxi = 0;
        if (maxi > max)
            max = maxi;
    }
    printf("x[%d..%d] = %d\n", l, r, max);
}
```

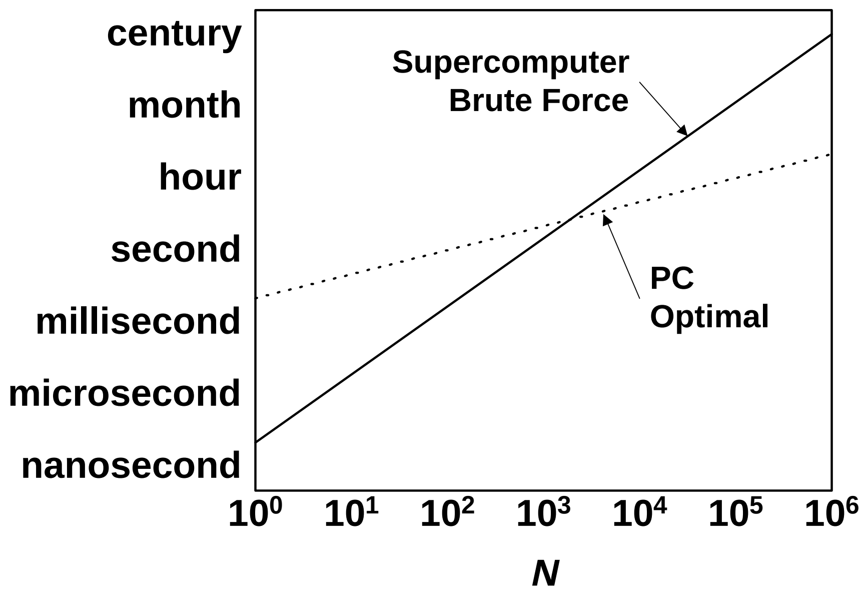
31	-41	59	26	-53	58	97	-93	-23	84
31	*0*	*59*	*85*	*32*	*90*	*187*	*94*	*71*	*155*
31	*31*	*59*	*85*	*85*	*90*	*187*	*187*	*187*	*187*

- **Execution time ≈ *N*, because there's just one loop; *N* = 1,000,000 takes ≈ 1 second**
- **See `sublistn.c` for details of computing `l` and `r`**

Summary

- **A good algorithm can be more powerful than a supercomputer**

		Thousand	Million
Brute Force	N^3	17 min	300 centuries!
Better	N^2	1 sec	11 days
Divide and Conquer	$N \lg N$	0.01 sec	20 sec
Optimal	N	0.001 sec	1 sec



- **For more, see J. Bentley, *Programming Pearls*, Addison Wesley, 1986**

Lecture 18. Elementary Systems Programming

- ***Software tools*** **are programs that** ***manipulate programs*****, each in potentially different** ***languages***

	Name	Input	Output
Macro preprocessor	`cpp`	C	C
Compiler	`rcc`	C	assembly code
Assembler	`as`	assembly code	object code
Linker	`ld -r`	object code, libraries	object code
Loader	`ld`	object code	executable code
Operating system	UNIX	executable code	

- **'Driver' programs, like `lcc`, hide many of these steps**

```
% lcc -v hello.c
/usr/local/lcc/lib/cpp ... hello.c hello.i
/usr/local/lcc/lib/rcc -target=sparc-solaris hello.i hello.s
/bin/as -o hello.o hello.s
/bin/ld -o a.out ... hello.o -lm -lc
% a.out
Hello world!
```

Compilation Pipeline

```
% cat hello.c
/* Everyone's first
    C program. */
#include <stdio.h>

int main(void) {
    printf("Hello world!\n");
    return 0;
}
```

- **The macro *preprocessor* strips comments, expands macro definitions, processes conditional compilation directives, and injects include files**

```
% lcc -E hello.c >hello.i; cat hello.i
#line 1 "hello.c"
...
#line 1 "/usr/local/lib/lcc/include/stdio.h"
...
extern int printf(const char *, ...);
...
#line 4 "hello.c"

int main(void) {
    printf("Hello world!\n");
    return 0;
}
```

See Chap. 13 in Deitel and Deitel for details

Compilation and Assembly

- **The *compiler* translates C to symbolic assembly language, alà symbolic TOY instructions**

```
% lcc -S hello.i; cat hello.s
...
_main:
save %sp,-96,%sp
set L2,%o0
call _printf; nop
mov %g0,%i0
L1:
ret; restore
L2: ...
```

- **The *assembler* translates symbolic assembly language to relocatable object code, alà TOY instruction encodings**

```
% lcc -c hello.s; dis hello.o
0:  9d e3 bf a0      save     %sp, -96, %sp
4:  11 00 00 00      sethi    %hi(printf), %o0
8:  90 12 20 00      or       %o0, printf, %o0
c:  40 00 00 00      call     0xc
10: 01 00 00 00      nop
14: b0 10 00 00      clr      %i0
18: 81 c7 e0 08      ret
1c: 81 e8 00 00      restore
```

Linking

- **The *linker* combines object code files and libraries in a new object code file**

```
% ld -r -o foo.o hello.o -lc; dis foo.o
main     0:   9d e3 bf a0       save     %sp, -96, %sp
         4:   11 00 00 00       sethi    %hi(.L350), %o0
         8:   90 12 20 00       or       %o0, .L350, %o0
         c:   40 00 00 00       call     (.L350+12)
        10:   01 00 00 00       nop
        14:   b0 10 00 00       clr      %i0
        18:   81 c7 e0 08       ret
        1c:   81 e8 00 00       restore
printf  20:   9d e3 bf a0       save     %sp, -96, %sp
        24:   15 00 00 00       sethi    %hi(0x0), %o2
        28:   f2 27 a0 48       st       %i1, [%fp + 72]
        2c:   d4 02 a0 00       ld       [%o2], %o2
        30:   11 00 00 00       sethi    %hi(0x0), %o0
        34:   f4 27 a0 4c       st       %i2, [%fp + 76]
...
```

Loading

- **The *loader* translates object code to executable code**

```
% ld foo.o; dis a.out
...
15148:   9d e3 bf a0       save     %sp, -96, %sp
1514c:   11 00 00 8a       sethi    %hi(0x22800), %o0
15150:   90 12 22 2c       or       %o0, 0x22c, %o0
15154:   40 00 00 05       call     0x15168
15158:   01 00 00 00       nop
1515c:   b0 10 00 00       clr      %i0
15160:   81 c7 e0 08       ret
15164:   81 e8 00 00       restore
15168:   9d e3 bf a0       save     %sp, -96, %sp
1516c:   13 00 00 e8       sethi    %hi(0x3a000), %o1
15170:   f2 27 a0 48       st       %i1, [%fp + 72]
15174:   d2 0a 62 b4       ldub     [%o1 + 692], %o1
15178:   f4 27 a0 4c       st       %i2, [%fp + 76]
...
```

- **The operating system loads the executable code into memory and jumps to it**

```
% a.out
Hello world!
```

Assembly Language

- An ***assembly language*** is a ***symbolic representation*** for machine language

  Mnemonic names for opcodes and registers; usually terse

  Symbolic names for addresses — data locations and jump ‘targets’

  Easy to delete, insert, and rearrange instructions

- TAL: *T*OY *A*ssembly *L*anguage

HALT		halt	
ADD	R,R_1,R_2	add	$R \leftarrow R_1 + R_2$
SUB	R,R_1,R_2	subtract	$R \leftarrow R_1 - R_2$
MUL	R,R_1,R_2	multiply	$R \leftarrow R_1 \times R_2$
XOR	R,R_1,R_2	exclusive OR	$R \leftarrow R_1 \wedge R_2$
AND	R,R_1,R_2	logical AND	$R \leftarrow R_1 \,\&\, R_2$
SHL	R,R_1,R_2	shift left	$R \leftarrow R_1 << R_2$
SHR	R,R_1,R_2	shift right	$R \leftarrow R_1 >> R_2$
LI	R,*const8*	load immediate	$R \leftarrow$ *const8* (8-bit constant)
LD	$R,(R_1 + \mathit{const8})$	load	$R \leftarrow M[R_1 + \mathit{const8}]$
ST	$R,(R_1 + \mathit{const8})$	store	$M[R_1 + \mathit{const8}] \leftarrow R$
SYS	R,*const8*	system call	system call *const8*, arg in R
J	*label*	jump	$PC \leftarrow$ *label*
JLT	R,*label*	jump if less	$PC \leftarrow$ *label* if $R < 0$
JI	(R)	jump indirect	$PC \leftarrow R$
JAL	R,*label*	jump and link	$R \leftarrow PC$, $PC \leftarrow$ *label*

Programming in TAL

`power.t`: (see page 9-6)

```
POWER    LI   R4,1          initialize R4
         LI   R3,1          initialize z
LOOP     SUB  R2,R2,R4      decrement exponent
         JLT  R2,DONE       quit when done
         MUL  R3,R3,R1      set z to z*x
         J    LOOP          do it again
DONE     JI   (R5)          return to caller
```

`main.t`: computes $A^4 + B^5$ (see page 9-7)

```
MAIN     LI   R0,0          initialize R0
         LI   R1,A          load A into R1
         LD   R1,(R1+0)
         LI   R2,4          want A^4
         JAL  R5,POWER      call POWER
         ADD  R6,R3,R0      copy A^4 to R6
         LI   R1,B          do it again for B^5
         LD   (R1+0)
         LI   R2,5
         JAL  R5,POWER
         ADD  R6,R6,R3      R6 now holds A^4 + B^5
         SYS  R6,2          print it
         HALT
A        3
B        2
```

Object Code

- The assembler reads TAL and emits ***relocatable object code***

  `power.o`:

```
00:      B401     =POWER            initialize R4
01:      B301                       initialize z
02:      2224                       decrement exponent
03:      6206     +start address    quit when done
04:      3331                       set z to z*x
05:      5002     +start address    do it again
06:      7500                       return to caller
```

- Relocation information tells the ***linker***

  The definitions of symbols

  How to adjust jump targets relative to the ultimate ***starting address*** of the module

  Which symbols are defined in other ***separately compiled modules***

- Object code is usually a compact, binary format, not text as suggested above

Object Code, cont'd

`main.o`:

```
00:     B100    =MAIN          initialize R0
01:     B100    +A             load A into R1
02:     9110
03:     B204                   want A^4
04:     8500    +POWER         call POWER
05:     1630                   copy A^4 to R6
06:     B100    +B             do it again for B^5
07:     9110
08:     B205
09:     8500    +POWER         call POWER
0A:     1663                   R6 now holds A^4 + B^5
0B:     4602                   print it
0C:     0000
0D:     0003    =A
0E:     0002    =B
```

- **Assemblers maintain symbol tables: Sets of (symbol,value) pairs used to map**

  Mnemonics to values — **LI → B_{16}, R6 → 6, …**
  Labels to offsets — **LOOP → 2_{16}, DONE → 6_{16}, POWER → 0, A → $0D_{16}$, …**

  `power.o` symbol table: **(POWER, 0)**

  `main.o` symbol table: **(MAIN, 0) (A, $0D_{16}$) (POWER, ?) (B, $0E_{16}$)**

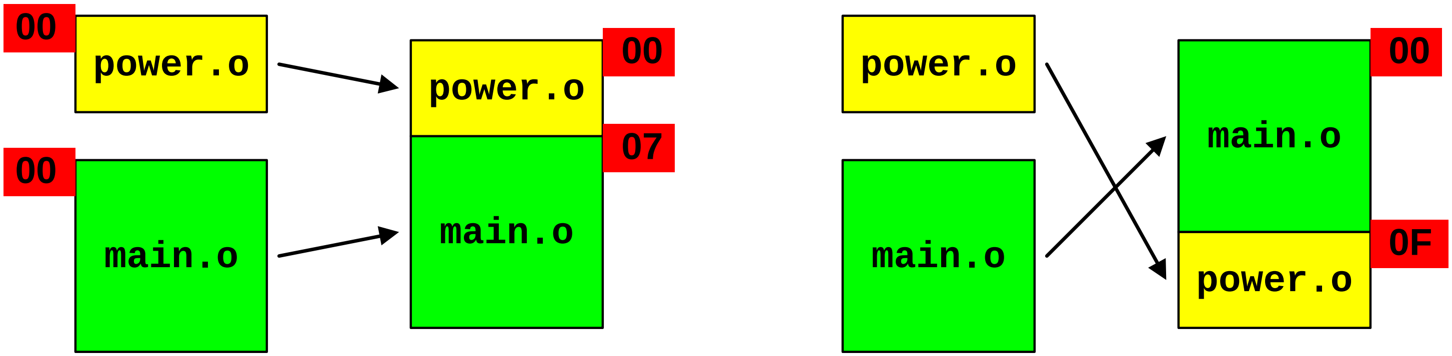
  Can implement symbol tables with binary trees

Linking

- **The linker reads several object files and emits *one relocatable object code* file**

  Concatenates **object code from input files**

  Relocates **symbol definitions and instructions based on starting addresses in output object code**



  Resolves **references to undefined symbols**

  Merges **symbol tables**

Linking, cont’d

- **Linking `main.o` and `power.o` resolves references to `POWER`, `A`, `B`, and adjusts offsets to jump targets**

```
00:   B100   =MAIN            initialize R0
01:   B10D   +start address   load A into R1
02:   9110
03:   B204                    want A^4
04:   850F   +start address   call POWER
05:   1630                    copy A^4 to R6
06:   B10E   +start address   do it again for B^5
07:   9110
08:   B205
09:   850F   +start address   call POWER
0A:   1663                    R6 now holds A^4 + B^5
0B:   4602                    print it
0C:   0000
0D:   0003   =A
0E:   0002   =B

0F:   B401   =POWER           initialize R4
10:   B301                    initialize z
11:   2224                    decrement exponent
12:   6215   +start address   quit when done
13:   3331                    set z to z*x
14:   5011   +start address   do it again
15:   7500                    return to caller
```

Output includes relocation information for additional linking

Loading

- **The loader reads a *starting address* and object code with *no undefined symbols* and emits executable code, adding in the starting address where necessary**

```
            20
20:         B100              initialize R0
21:         B12D              load A into R1
22:         9110
23:         B204              want A4
24:         852F              call POWER
25:         1630              copy A^4 to R6
26:         B12E              do it again for B^5
27:         9110
28:         B205
29:         852F              call POWER
2A:         1663              R6 now holds A^4 + B^5
2B:         4602              print it
2C:         0000
2D:         0003
2E:         0002

2F:         B401              initialize R4
30:         B301              initialize z
31:         2224              decrement exponent
32:         6235              quit when done
33:         3331              set z to z*x
34:         5031              do it again
35:         7500              return to caller
```

Separate Compilation

- A ***program*** is made up of many small ***modules***

    A 'few' application-specific modules

    'Many' general-purpose modules, e.g., standard I/O functions like `printf`

- Compile general-purpose modules ***separately***, collect their object code in ***libraries***

- Compile application-specific modules separately, keep their object code

- To build a program

    1. Link together the application-specific object code modules
    2. Search the libraries for the general-purpose modules used by (1)

- Advantages

    Avoid recompiling infrequently changed modules

    Share libraries of well-tested general-purpose modules — don't reinvent, reuse

- Designing and implementing general-purpose modules sounds easy, but it's ***not***

    Take COS 217, Introduction to Programming Systems

    Read D. R. Hanson, *C Interfaces and Implementations: Techniques for Creating Reusable Software*, Addison-Wesley, 1997 (used in COS 217)

Lecture 19. Compilers

- **The *compiler* translates a high-level language to a machine-level language**

`lcc`:	C → SPARC assembly language → … → SPARC machine code
`compile`:	arithmetic expressions → TOY instructions

- **Most compilers have the basic phases**

Lexical Analysis	source code → 'tokens'
Syntax Analysis	tokens → abstract syntax trees
Code Generation	abstract syntax trees → machine-level code

- **A compiler is a good example of**

  Application of theoretical computer science to a practical problem

  Interaction between programming language design and computer architecture

  Building a program from independent modules — 'software engineering'

- **For *much* more**

  Take COS 320, Compiler Design

  Read A. W. Appel, *Modern Compiler Implementation in Java*, Cambridge Univ. Press, 1997 (used in COS 320)

  Read C. W. Fraser and D. R. Hanson, *A Retargetable C Compiler: Design and Implementation*, Addison-Wesley, 1995

Lexical Analysis

- **The lexical analyzer reads the source program and emits *tokens* or *terminal symbols*: the 'letters' in the 'alphabet' of the programming language**

  English:

  a b c d e f g h ... A B C ... . ; ' ' ! : — - ( ) ...

  C tokens:

  ```
  if else while do for int float sizeof ...
  { } ; . -> + - * / % ++ -- < <= == != & ^ | ~ >= > ( ) ...
  ```
  "strings" constants identifiers ...

  Simple arithmetic expressions:

  ```
  ( ) + - *
  ```
  one-letter identifiers one-digit constants

- **A lexical analyzer usually discards white space: blanks, tabs, newlines, etc.**

- **Lexical analyzers can be described by and implemented with *finite-state machines***

Syntax Analysis

- **A *context-free grammar* specifies how tokens can be formed into valid 'sentences'**

  Grammar rules or 'productions' specify how to generate all valid sentences

  1. *pgm* $\rightarrow$ *expr*

  2. *expr* $\rightarrow$ *expr* + *expr*
  3. *expr* $\rightarrow$ *expr* - *expr*
  4. *expr* $\rightarrow$ *expr* * *expr*
  5. *expr* $\rightarrow$ (*expr*)
  6. *expr* $\rightarrow$ identifier
  7. *expr* $\rightarrow$ constant

  pgm expr **are 'nonterminals' — they describe *classes* of valid sentences**
  + - * ( ) identifier constant are terminals or tokens — the basic vocabulary

1	*pgm* $\Rightarrow$ *expr*
3	$\Rightarrow$ *expr* - *expr*
5	$\Rightarrow$ (*expr*) - *expr*
4	$\Rightarrow$ (*expr* * *expr*) - *expr*
6	$\Rightarrow$ (a * *expr*) - *expr*
5	$\Rightarrow$ (a * (*expr*)) - *expr*
2	$\Rightarrow$ (a * (*expr* + *expr*)) - *expr*
6	$\Rightarrow$ (a * (b + *expr*)) - *expr*
7	$\Rightarrow$ (a * (b + 2)) - *expr*
5	$\Rightarrow$ (a * (b + 2)) - (*expr*)
2	$\Rightarrow$ (a * (b + 2)) - (*expr* + *expr*)
6	$\Rightarrow$ (a * (b + 2)) - (c + *expr*)
7	$\Rightarrow$ (a * (b + 2)) - (c + 9)

Parsers

- A ***parser*** determines if a sentence can be generated by the grammar rules

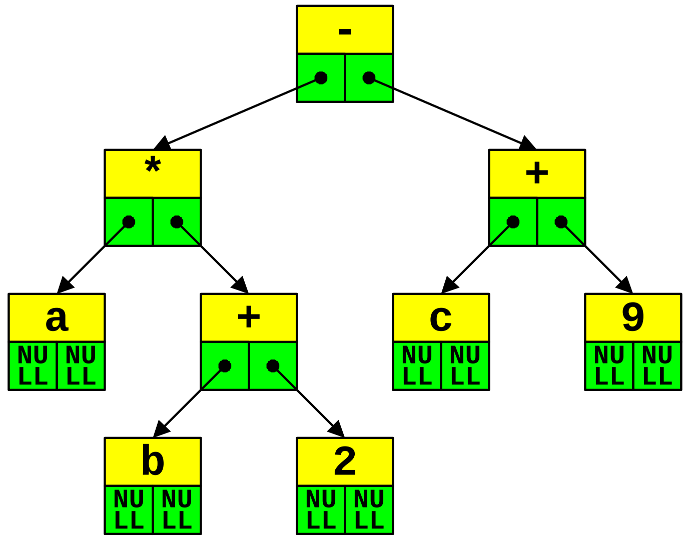
  Proves that the sentence is syntactically valid

- A parser may also build an ***abstract syntax tree*** to represent the sentence

  `(a * (b + 2)) - (c + 9)`

  Internal nodes hold terminal symbols that denote operators: + - *

  Leaf nodes hold terminal symbols that denote variables or constants: a b c 2 9



- A 'recursive-descent' parser has a function for each nonterminal

  'Matches' terminals in input

  Calls other nonterminal functions — including itself — to apply the rules

- Parsers can be described by and implemented with ***pushdown automata***

Code Generation

- **A *code generator* traverses the abstract syntax tree and emits code, e.g., TAL, or TOY instructions**

```
% lcc -I/u/cs126/include compile.c /u/cs126/lib/libmisc.a
% a.out 5 6 7 "(a * (b + 2)) - (c + 9)"
00:  0005
01:  0006
02:  0007
1A:  9100                R1 <- M[R0+0]
1B:  9201                R2 <- M[R0+1]
1C:  B302                R3 <- 2
1D:  1223                R2 <- R2 + R3
1E:  3112                R1 <- R1 * R2
1F:  9202                R2 <- M[R0+2]
20:  B309                R3 <- 9
21:  1223                R2 <- R2 + R3
22:  2112                R1 <- R1 - R2
23:  4102                print R1
24:  0000                halt
1A
```

- **This compiler — and only this one — bypasses assembly, linking, and loading**

```
% a.out 5 6 7 "(a * (b + 2)) - (c + 9)" | /u/cs126/toy/toy
ab2+*c9+-
Toy simulator $Revision: 1.14 $
0018
```


A Simple Compiler

- **Lexical analyzer: returns characters as tokens**

`int get(char set[])`	**returns the next token, advances the input**
`int look(void)`	**peeks at the next nonblank character**

- **Parser: returns an abstract syntax tree (AST)**

`Tree *expr(void)`	**parses an *expr*, returns its AST**
`Tree *pgm(char *string)`	**initializes lexer, parses a *pgm*, returns its AST**

```
struct tree {
    int op;
    struct tree *left, *right;
};
typedef struct tree Tree;

Tree *maketree(int op, Tree *left, Tree *right) {
    Tree *t = emalloc(sizeof (Tree));

    t->op = op;
    t->left = left; t->right = right;
    return t;
}
```

- **Code generator: emits TOY instructions**

`int codegen(Tree *t, int dst, int loc)`

emits TOY code for AST `t` starting at `loc`

Lexical Analysis

- **Globals hold the 'state' of lexical analysis: input and current input position**

```
char *input;      /* the "source code" */
int pos;          /* current position in input */
```

  `input[pos]` holds the next character in the input

- **The next token is the next non-whitespace character, which must be in `set`**

```
int get(char set[]) {
    while (isspace(input[pos]))
        pos++;
    if (input[pos] != '\0' && strchr(set, input[pos]) != NULL)
        return input[pos++];
    error("syntax error: expected one of '%s'\n", set);
    return 0;
}
```

- **The parser must peek ahead one character to determine its next action**

```
int look(void) {
    while (isspace(input[pos]))
        pos++;
    return input[pos];
}
```

Parsing

- **The parsing functions for *expr* and *pgm* echo their grammar rules**

```
Tree *expr(void) {
    Tree *t;

    if (look() == '(') {             /* expr → ( expr ) */
        get("("); t = expr(); get(")");
    } else if (isdigit(look()))   /* expr → constant */
        t = maketree(get("0123456789"), NULL, NULL);
    else                             /* expr → identifier */
        t = maketree(get("abcdefghijklmnopqrstuvwxyz"), NULL,NULL);
    if (look() != '\0' && strchr("+-*", look()) != NULL) {
        int op = get("+-*");      /* expr → expr [+-*] expr */
        t = maketree(op, t, expr());
    }
    return t;
}

Tree *pgm(char *string) {
    Tree *t;

    input = string;              /* initialize lexical analyzer */
    pos = 0;
    t = expr();                  /* pgm → expr */
    if (look() != '\0')
        error("expected end of input\n");
    return t;
}
```

Reverse Polish Notation

- A postorder traversal of the AST yields a ***reverse Polish*** rendition of the expression

```
void postorder(Tree *t) {
    if (t != NULL) {
        postorder(t->left);
        postorder(t->right);
        fprintf(stderr, "%c", t->op);
    }
}
```

(a * (b + 2)) - (c + 9)   **a b 2 + * c 9 + -**

- Reverse Polish can be ***evaluated***: a ***stack*** holds operands and intermediate values

	Stack→	R1	R2	R3
a b 2 + * c 9 + -	5	5		
a b 2 + * c 9 + -	5 6	5	6	
a b 2 + * c 9 + -	5 6 2	5	6	2
a b 2 + * c 9 + -	5 8	5	8	
a b 2 + * c 9 + -	40	40		
a b 2 + * c 9 + -	40 7	40	7	
a b 2 + * c 9 + -	40 7 9	40	7	9
a b 2 + * c 9 + -	40 16	40	7	16
a b 2 + * c 9 + -	24	24		

- Instead of evaluating the expression, generate code, using ***registers*** for the stack

Code Generation

- ***codegen*** **emits code to evaluate an AST into register `dst`, assuming higher numbered registers are free**

```
int codegen(Tree *t, int dst, int loc) {
    if (isalpha(t->op)) {
        int addr = t->op - 'a';
        printf("%02X: 9%X%X%X\tR%d <- M[R%d+%d]\n", loc++,
            dst, 0, addr, dst, 0, addr);
    } else if (isdigit(t->op))
        printf("%02X: B%X%02X\tR%d <- %d\n", loc++,
            dst, t->op - '0', dst, t->op - '0');
    else {
        loc = codegen(t->left, dst, loc);
        loc = codegen(t->right, dst + 1, loc);
        printf("%02X: %X%X%X%X\tR%d <- R%d %c R%d\n", loc++,
            strchr("+1-2*3", t->op)[1] - '0', dst,
            dst, dst + 1, dst, dst, t->op, dst + 1);
    }
    return loc;
}
```

Variables a..z are stored in locations $0..19_{16}$

`loc` is the location counter: the address of the next instruction emitted

codegen **returns an updated value of *loc* for use by subsequent traversals**

The Main Program

- **The final touches**

  Arguments 1..`argc-2` are the initial values of the corresponding variables

  Argument `argc-1` is the 'source program'

  Starting address is $26_{10} = 1A_{16}$

```
int main(int argc, char *argv[]) {
    Tree *e;
    int i, loc = 0;

    for (i = 1; i < argc - 1; i++)
        printf("%02X: %04X\n", loc++, atoi(argv[i]));
    if (i < argc) {
        e = pgm(argv[i]);
        postorder(e);
        fprintf(stderr, "\n");
        loc = codegen(e, 1, 26);
        printf("%02X: 4102\tprint R%d\n", loc++, 1);
        printf("%02X: 0000\thalt\n", loc);
        printf("%02X\n", 26);
    }
    return 0;
}
```

  See page 19-5 for an example of use

Lecture 20. Operating Systems

- **An *operating system* provides a *virtual machine*: A high-level abstraction of an ugly low-level machine**
- **An OS provides *resources* and *services***

  Memory management: Each user appears to have all the memory

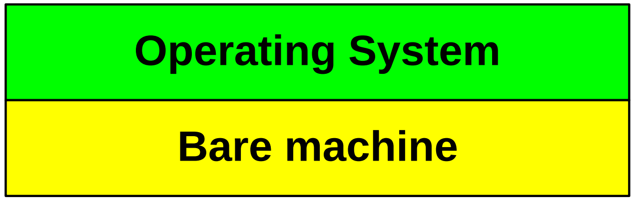
  Concurrency: Many users appear to compute simultaneously

  Protection: User *A* can't crash *B*'s program or access *B*'s files

  File system: Files appear as streams of bytes, files have names, directories, random access

  Interaction: X window system, window manager, mouse

multiple users
processes
file system
window system
…



no users
one 'process'
flat array of disk blocks
I/O bus, interrupts
…

  Network access: The World Wide Web, remote file systems and printers

- **Programs communicate with the OS via *system calls*, e.g. TOY opcode 4**

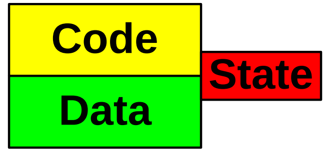
  $\underline{4}402_{16}$ **prints the contents of R_4**

  Each OS has its own (usually large) system call vocabulary

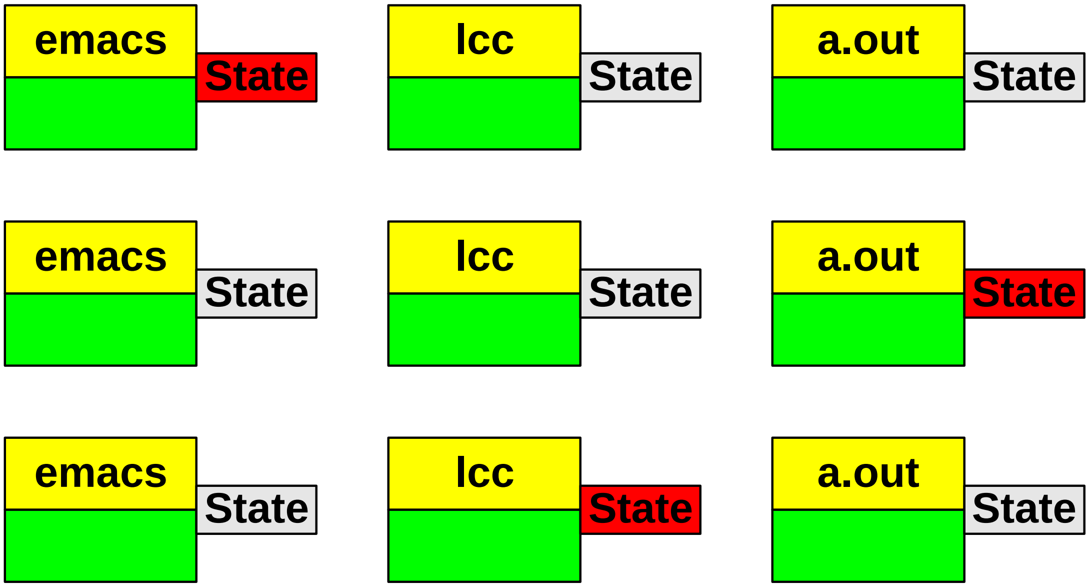
Multiprogramming

- A *process* is an executing *instance* of a program

  State includes registers, PC, memory management information



- The OS, a.k.a. kernel, *multiplexes* the processor between the processes, switching between processes at each *interrupt*



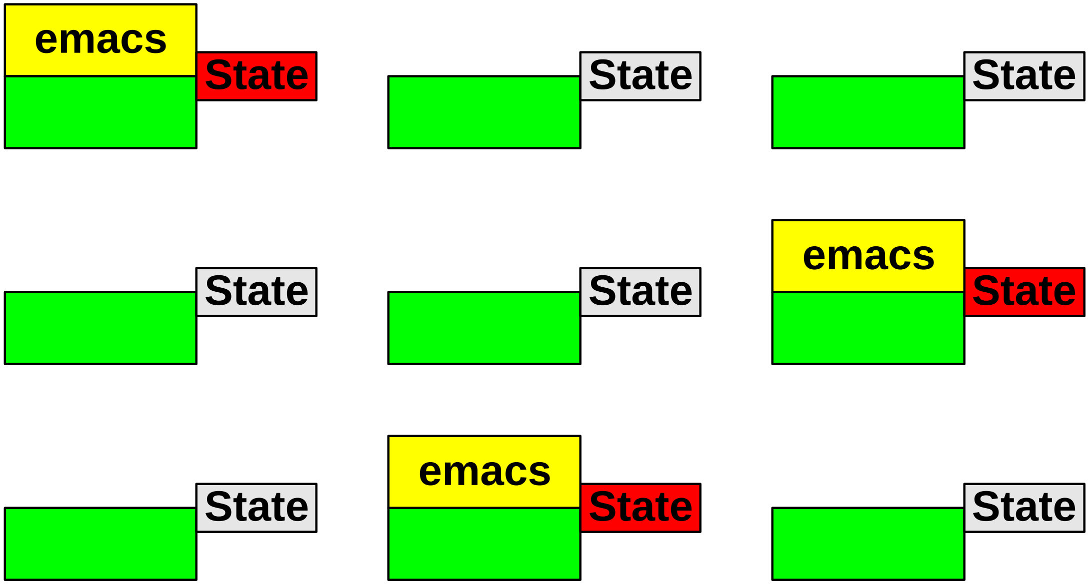
- When a periodic *clock interrupt* occurs (≈ every 1/60 second), do a *context switch*

  Stop
  Store the registers, PC, etc. in the current process's state
  Load the registers, PC, etc. from the new process's state
  Continue ('dismiss the interrupt')

Reentrant Programs

- A ***reentrant program*** does not modify its own code; it changes only its data
- One copy can be shared among many processes; each process has it own data

  Three processes running `emacs`



  Reentrant programs use less memory

- What about the ***addresses*** in each process?

Virtual Memory

- **Problem 1**

  Several programs need to use the same memory

  Direct solution: Divide up the memory

- **Problem 2**

  If the OS can load program anywhere in memory, what is its starting address?

  Direct solutions: Have OS adjust relocatable addresses upon loading
  Use only _*position-independent code*_ (impossible in TOY)

- **Problem 3**

  One program needs more memory than the machine has, or more than is left

  Direct solution: 'Overlay' unused functions with other functions

- **'Better' solution to all these problems**

  Each program assumes access to the entire memory — its _*virtual address space*_

  Hardware helps OS associate a small part of _*physical address space*_ with each process, keep some of the virtual address space on disk

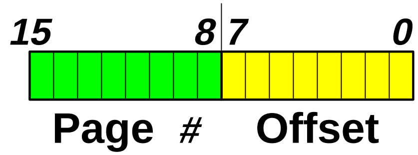
Paging

- ***Paging*** **is the predominant method for implementing virtual memory**
- **Maximum *effective address* determines the virtual address space size**
- **Divide physical memory and virtual memory into fixed-size 'pages'**

  Use a power of 2

  Leading address bits give the page number

  Trailing address bits give the offset in that page

  Example: 16-bit addresses, 8-bit page #s, 256-byte pages

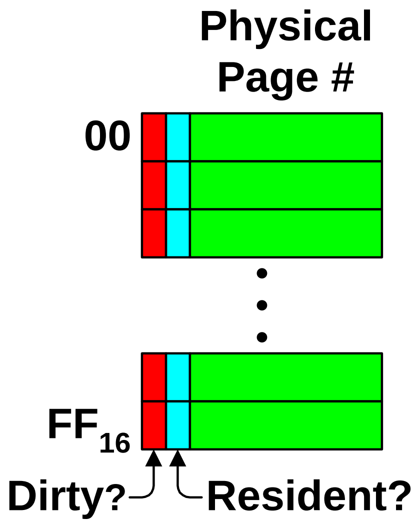
- **Build hardware to map all addresses through a *page table***

  Indexed by virtual page #

  Maps virtual page # $\rightarrow$ physical page #

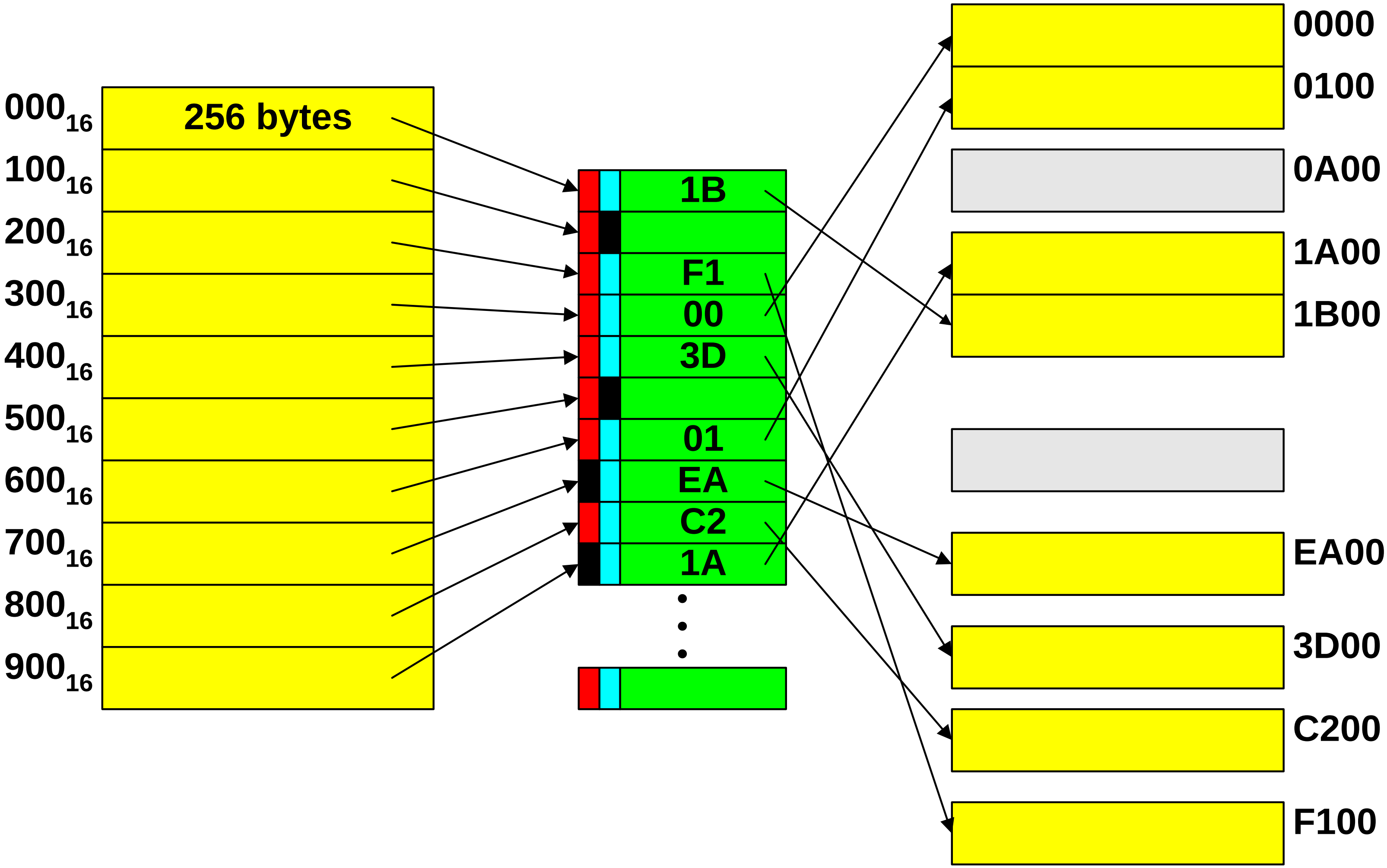
  Indicates whether page is in memory or on disk

  Indicates whether in memory page is 'dirty' or clean

- **Keep virtual memory for each program on disk**

Paging, cont'd



- **Each page read in from disk has to replace another page: Use page replacement strategies, such as *L*east *R*ecently *U*sed**

Size of Virtual Memory

- **16 bits is not enough**
- **24 bits is not enough**
- **32 bits is not enough!**
- **Is 64 bits enough?**

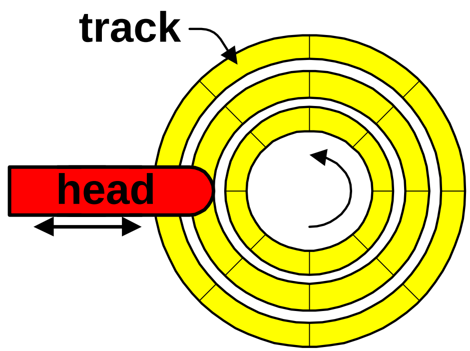
  18,446,744,073,709,551,616 $>$ 10^{19} addresses
- **64-bit address space needs more sophisticated paging strategy and hardware**

  Page table would be too big: 2^{13} $=$ 8Kbyte pages needs 2^{51} page-table entries

  Associative page tables, multilevel page tables
- **Some big numbers**

10^{20}	**Number of grains of sand on a beach**
10^{27}	**Number of oxygen atoms in a thimble**
$2^{256} > 10^{77}$	**Number of electrons in the universe**

File Systems



- **Disks are messy: Rotating cylinders with movable heads**

  Rotational latency: Wait for the ‘track’ to appear under the head

  Seek time: Wait for the head to move in/out to the cylinder

  At best, a disk is an array of fixed-size blocks

- **A *file system* provides high-level features on low-level disks**

  Directories

  Named files

  Read/write arbitrary number of bytes

  Random access

  Automatic growth

UNIX File System

- Disk, array of fixed size blocks, is divided into 3 regions

  Root block: File system parameters *M*, *N*, list of free data blocks

  ‘Inode’ blocks: Hold ‘information’ nodes, one per file or directory

  Data blocks: Hold the data, file names in directories

- Inode blocks each hold *k* inodes numbered 0 to *k*–1, so a file system can hold $k \times M$ files/directories

- An inode holds everything about a file, ***<u>except</u>*** its name

  Type: directory or file

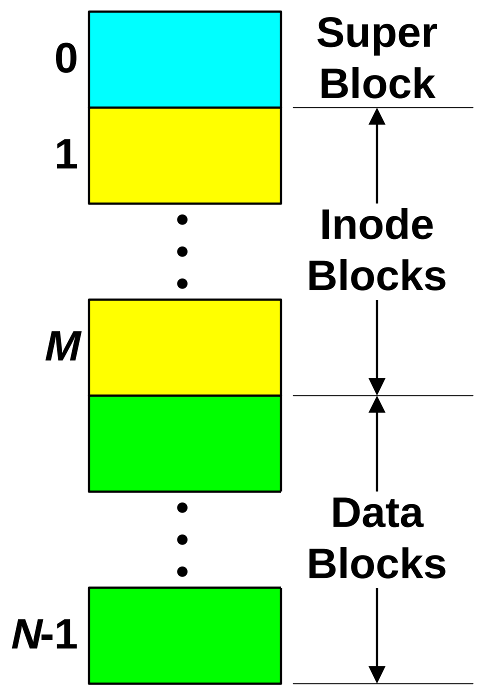
  Size in bytes

  Block numbers of its data blocks or indirect blocks

  Number of directories pointing to the file

  Times of creation, last modification

- A ***<u>directory</u>*** is just list of (file name, inode number) pairs



File Layout

- **Small file: Inode points to 10 data blocks**

  For 1Kbyte data blocks, handles files ≤ 10 Kbyte

- **Medium-size file: Inode points to 10 'indirect' blocks that point to data blocks**

  With 4-byte block #s, handles files ≤ $10 \times 256 \times 1024 = 2{,}621{,}440 = 2.5$ Mbyte

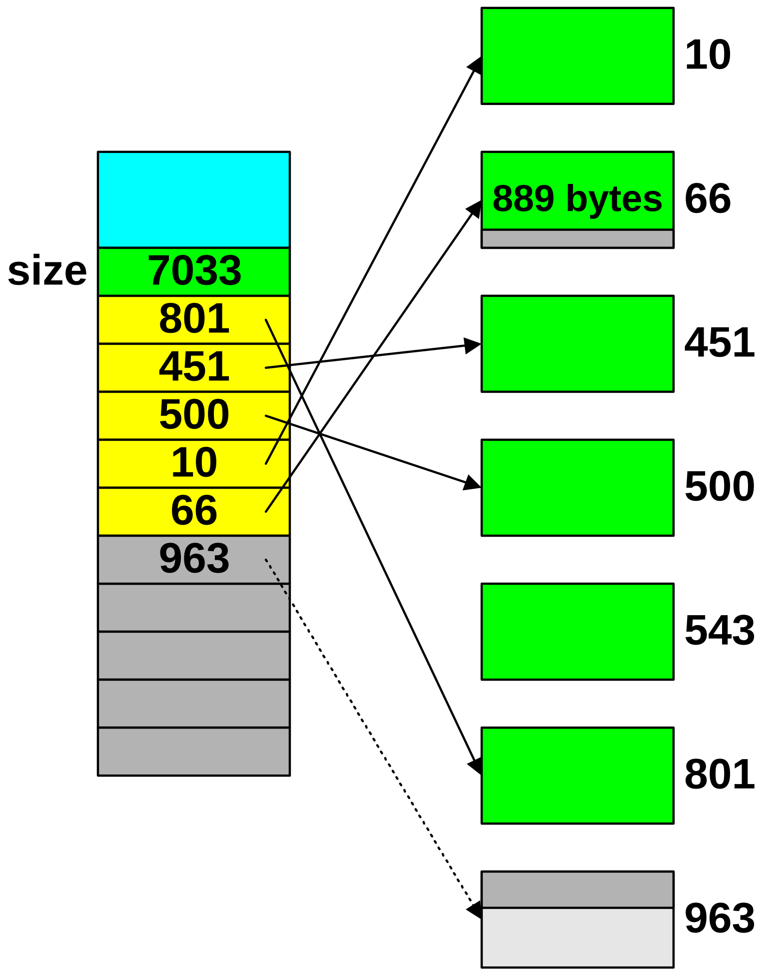
- **Large files: Entries in last indirect block point to other indirect blocks**

  Handles files ≤ $(9 + 256) \times 256 \times 1024 = 69{,}468{,}160 = 66.25$ Mbyte

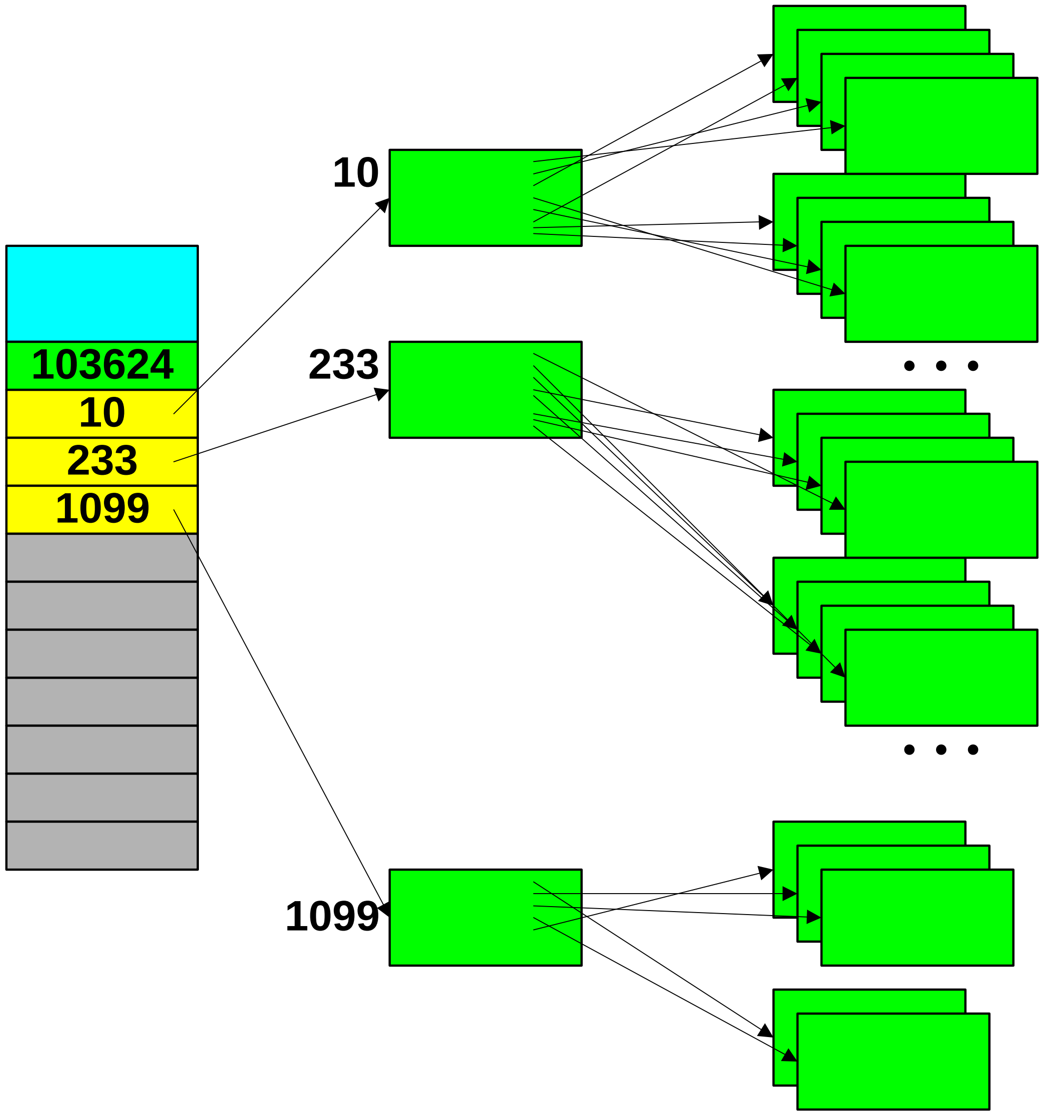
- **Huge files: Inode points to 10 indirect blocks that each point to 256 indirect blocks**

  Handles files ≤ $10 \times 256 \times 256 \times 1024 = 671{,}088{,}640 = 640$ Mbyte

- **Adjust block size/inode size to span larger disks**



Typical Medium-Size File



Lecture 21. Regular Expressions

- A ***regular expression*** describes a set of strings by giving a ‘pattern’ for them

c	Any nonspecial character matches itself	`A`
`.`	Any single character	`x`
c	Special character *c*	`\.`
[...]	Any character in ..., including ranges	`[a-z0-9]`
[^...]	Any character *not* in ..., including ranges	`[^0-9]`
R_1R_2	Whatever matches R_1 followed by R_2	`[A-Z]_`
*R**	Zero or more occurrences of *R*	`[a-z][a-z]*`

- Tokens in most programming languages can be described by regular expressions

`[1-9][0-9]*`	Decimal constants in C
`0[0-7]*`	Octal constants in C
`[0-9][0-9]*\.[0-9]*`	Floating constants in C
`[A-Za-z_][A-Za-z_0-9]*`	C identifiers
`"[^"\n]*"` `'"[^"\n]*"'`	String literals in C (quoted for the shell)

egrep

- **Many UNIX tools support searching for patterns described by regular expressions**

egrep, grep, fgrep	**Search for lines matching regular expressions**
ed, vi, emacs	**Text editors**
sed	**Stream editor**
awk	**String-processing language**
More …	

- **egrep prints those lines that match the regular expression**

```
% cd /u/cs126/examples
% egrep emalloc *.c
compile.c:   Tree *t = emalloc(sizeof (Tree));
intlist.c:   struct intnode *p = emalloc(sizeof (struct intnode));
intlist.c:   struct intnode *p = emalloc(sizeof (struct intnode));
lookup.c:    ptr = emalloc(size*sizeof (char *));
lookup2.c:       struct node *p = emalloc(sizeof (struct node));
sort2.c:     ptr = emalloc(size*sizeof (int));
sort3.c:     ptr = emalloc(n*sizeof (int));
sublistn.c:  array = emalloc(size*sizeof (int));
sublistn2.c: array = emalloc(size*sizeof (int));
sublistn3.c: array = emalloc(size*sizeof (int));
```

egrep, cont'd

- **`/usr/dict/words` contains ≈ 25,143 words**

```
% egrep hh /usr/dict/words
beachhead
highhanded
withheld
withhold
```

How many words have 3 a's one letter apart?

```
% egrep .a.a.a /usr/dict/words | wc -l
50
% egrep .u.u.u /usr/dict/words
cumulus
```

- **`egrep` supports extended regular expressions**

^	**Beginning of line**	
$	**End of line**	
***R*+**	**One or more occurrences of *R***	`[0-9]+`
***R*?**	**Zero on one occurrence of *R***	`[0-9]*\.?[0-9]+`
$R_1 \| R_2$	**Whatever matches R_1 or R_2**	`[A-Z]|_+`
(*R*)	**Grouping**	

egrep, cont'd

- **egrep as a simple spelling checker: Specify plausible alternatives you know**

```
% egrep "n(ie|ei)ther" /usr/dict/words
neither
```

- **Find big files; du -ka prints file sizes in 1Kbyte blocks**

```
% du -ka /etc | egrep '^[5-9][0-9][0-9]'
552     /etc/fs/nfs/mount
553     /etc/fs/nfs
837     /etc/fs
850     /etc/lp/printers
883     /etc/lp
```

500 and up

- **Find all lines with signed numbers**

```
% egrep '[-+][0-9]+\.?[0-9]*' *.c
bsearch.c:           return -1;
compile.c:               strchr("+1-2*3", t->op)[1] - '0', dst,
convert.c:Print integers in a given base 2-16 (default 10)
convert.c:           sscanf(argv[i+1], "%d", &base);
...
strcmp.c:            return -1;
strcmp.c:            return +1;
```

- **egrep has its limits: It cannot match all lines that contain a number divisible by 5**

Formal Languages

- A ***language*** is a (possibly infinite) set of strings over a finite alphabet
- A regular expression describes a language: The set of all strings it 'matches'
- A ***regular language*** is any language that can be described by a regular expression
- Essential aspects of regular expressions can be specified with only

0 or 1	The alphabet
$R_1 R_2$	R_1 followed by R_2
$R_1 + R_2$	R_1 or R_2 (same as `egrep`'s |)
(R)	Grouping
R*	Kleene closure: 0 or more Rs (10)* (0+011+101+110)* (01*01*01*)*

- What languages over { 0 1 } are regular? All but one below are regular

Bit strings
whose number of 0's is a multiple of 5
that begin with 0 and end with 1
with more 1's than 0's
with no consecutive 1's
for a binary number that is a multiple of 2
for a binary number that is multiple of 5

- It is possible to cast ***any*** computation as a language problem

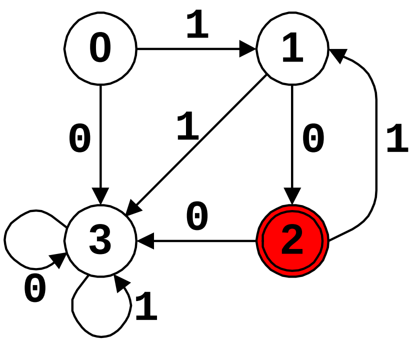
Finite State Automata

- A ***finite state automata***, an FSA, is another representation for regular languages
- A FSA is a simple machine with *N* states (0 to *N*–1)

  Start in state 0
  Read a bit
  Move to a new state depending on the bit and the current state
  Stop after reading last bit
  Accept if FSA is in one of its ***final states***, *Reject* otherwise

- An FSA ‘recognizes’ its input: ‘Decides’ if the input is in the FSA’s regular language

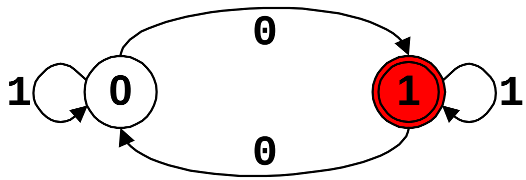
10(10)*



Transition table

	0	1
0	3	1
1	2	3
2	3	1
3	3	3

Odd number of 0s



10101010?

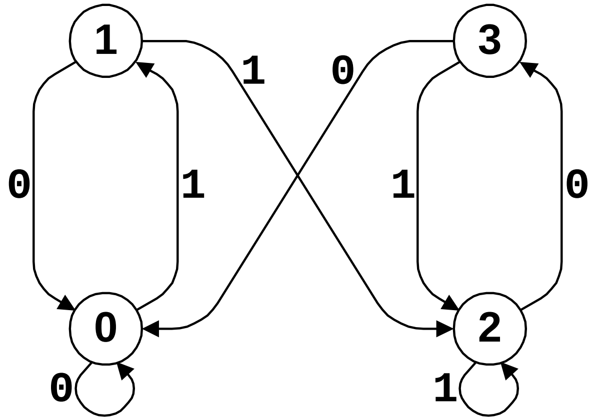
0001110?

- There is a one-to-one correspondence between FSAs and regular expressions
- It is possible to construct FSAs ***automatically*** from regular expressions

‘Bounce’ Filter

- **Flip isolated 0s and 1s in a bitstream**

  Input: `0 1 0 0 0 1 1 0 1 1`
  Output: `0 0 0 0 0 1 1 1 1 1`



- **State interpretations**
  1. **At least two consecutive 0s**
  2. **Sequence of 0s followed by a single 1**
  3. **At least two consecutive 1s**
  4. **Sequence of 1s followed by a single 0**
- **Do ‘output’ by monitoring the state transitions**

Simulating FSAs

```
int main(int argc, char *argv[]) {
    int i = 0, zero[100], one[100], final[100];
    for (i = 0; i < 100; i++)
        if (scanf("%d%d%d", &zero[i], &one[i], &final[i]) != 3)
            break;
    for (i = 1; i < argc; i++) {
        int state = 0;
        char *input = argv[i];
        for ( ; *input != '\0'; input++)
            if (*input == '0')
                state = zero[state];
            else
                state =  one[state];
        if (final[state])
            printf("%s: accepted\n", argv[i]);
        else
            printf("%s: rejected; ended in state %d\n",
                argv[i], state);
    }
    return 0;
}
```

```
% cat fsainput
3 1 0
2 3 0
3 1 1
3 3 0
```

```
% lcc fsa.c
% a.out 10101010 10 101011 <fsainput
10101010: accepted
10: accepted
101011: rejected; ended in state 3
```

FSAs Can’t ‘Count’

- **Theorem: No finite state machine can decide whether or not its input has the same number of 0s and 1s**

- **Proof**

  Suppose an *N*-state machine can determine if its input has equal number of 0s 1s

  Give it *N*+1 0s followed by *N*+1 1s

  Some state *must* be visited a least twice

  So, the machine would accept the same string *without* the intervening 0s

  And that string doesn’t have the same number of 0s and 1s. Contradiction ∎

  0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1

- **Need more powerful machines than FSAs**

  How much more powerful? Language hierarchy

Regular	Finite-state automata
Context-free	Pushdown automata (can count 2 things)
Context-sensitive	Linear-bounded automata
Type 0	Turing machines

  Take COS 487, Theory of Automata and Computation

Lecture 22. Hard Problems

- **Important properties of algorithms**

***Finite*:**	**Guarranteed to terminate**
***Deterministic*:**	**Always produces the same output for the same input**

- ***Efficient* algorithms execute in times that are no more than *polynomial* in the size of their inputs, *N***

  N, N^2, $N + N^4$, etc.

- ***Inefficient* algorithms execute in times that are at least *exponential* in *N***

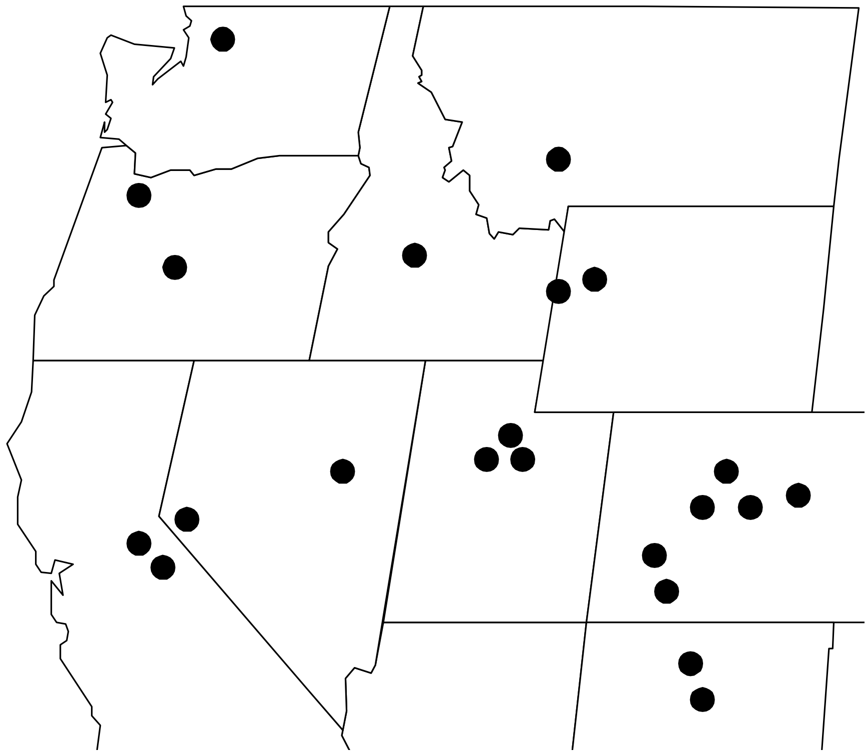
  2^N, 10^N, $N!$, etc.

- **Some apparently simple problems have no known efficient solutions**

Traveling Salesman	**Find the minimum-cost tour of *N* cities**
Scheduling	**Schedule *N* jobs of varying length on two machines to finish by a given deadline**
Sequencing	**Arrange *N* 4-letter fragments cut from a long string (with overlaps) into the original string (DNA sequencing)**
Satisfiability	**Assign true/false values to *N* logical variables so that a given logical formula is true**

The Traveling Skibum Problem

- **Visit *N* ski areas in the order that minimizes cost, e.g., distance**
- **To find an optimal tour, try all of them**



```
void visit(int k) {
    if (k == 1)
        checklength();
    else {
        int i;
        for (i = 0; i < k; i++) {
            swap(i, k - 1);
            visit(k - 1);
            swap(i, k - 1);
        }
    }
}
```

visit(n);

- **Takes *N*! steps; no computer can run this for $N = 100$, because $100! \approx 10^{157}$**
- **Use *<u>heuristics</u>* to get good, but not optimal solutions, to hard problems**

  TSP: **Choose the 'nearest neighbor' as the next ski area on the tour**

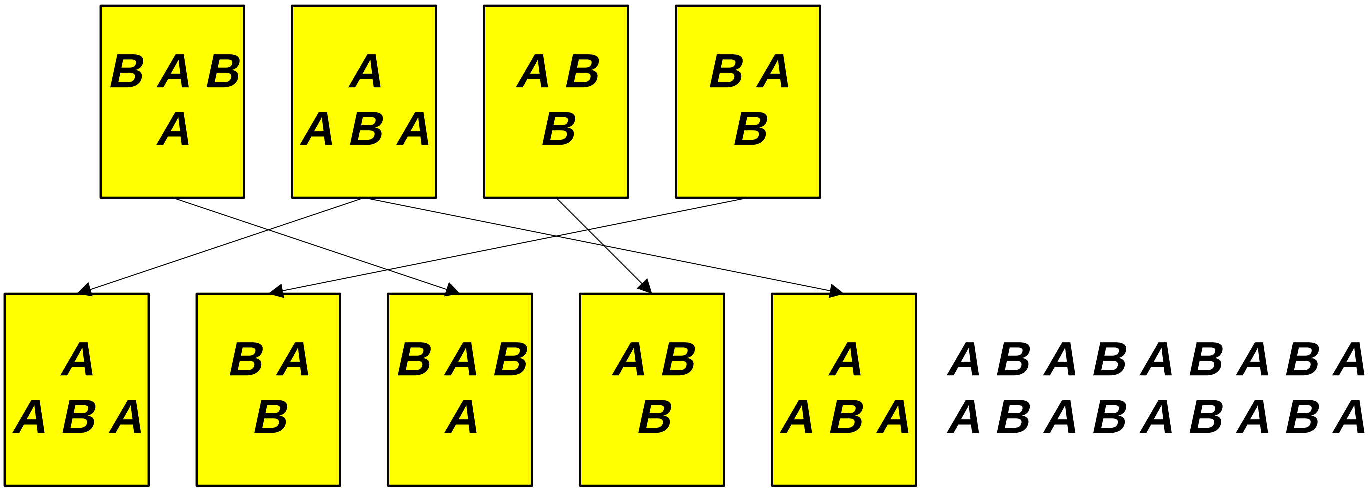
- **Hard problems can be your friends: Use encryption to send secret messages**

Unsolvable Problems

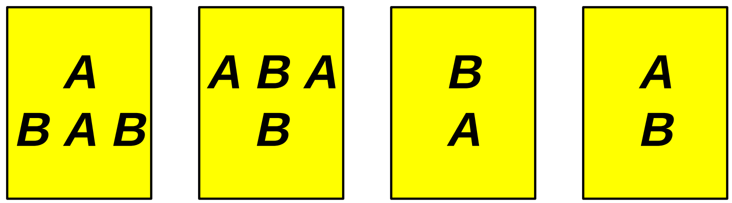
- **Oh oh… Are some problems *unsolvable*?**
- **Example: Post's Correspondence Problem**

  ***N* types of cards, each with a top string and a bottom string**

  Using as many of each card as needed, arrange them so that the top and bottom strings are identical (or say it's impossible)



- **There's no solution for the cards**
- **The bad news: Post's Correspondence Problem is unsolvable; you cannot write a program that determines if there is a solution for a given set of cards**



The Halting Problem

- **Write a C program that**

  Reads another C program, *P*

  Reads *P*'s input

  Determines whether or not *P* loops forever; that is, whether or not *P* halts

```
while (x != 1)
    if (x > 2) x -= 2; else x += 2;
```

<u>7</u> 5 3 1 — ***P* halts**

<u>8</u> 6 4 2 4 2 4 … — ***P* loops on even inputs**

```
while (x != 1)
    if (x%2 != 0) x = 3*x + 1; else x /= 2;
```

<u>7</u> 22 11 34 17 52 26 13 40
20 10 5 16 8 4 2 1 — **does *P* halt for all odd integers?**

<u>8</u> 4 2 1 — ***P* halts**

The Halting Problem, cont'd

- **Theorem: The Halting Problem is unsolvable**
- **Proof by contradiction**

  Assume there is a program, `HALTS(`*P*,*y*`)`, that takes two inputs, a program *P* and its input *y*. If *P*(*y*) halts, `HALTS(`*P*,*y*`)` stops and prints 'Yes'; if *P*(*y*) does not halt, `HALTS(`*P*,*y*`)` stops and prints 'No'

  Build another program, `CONFUSE(`*x*`)`, that takes a legal C program *x* as input. If `HALTS(`*x*,*x*`)` prints 'Yes', `CONFUSE(`*x*`)` loops forever; if `HALTS(`*x*,*x*`)` prints 'No', `CONFUSE(`*x*`)` stops.

  Now, call `CONFUSE(CONFUSE)`:

    If `HALTS(CONFUSE,CONFUSE)` prints 'Yes', `CONFUSE(CONFUSE)` loops

    If `HALTS(CONFUSE,CONFUSE)` prints 'No', `CONFUSE(CONFUSE)` stops

  But `CONFUSE` can't do both! So, `HALTS` cannot exist ▮

- **Maybe C programs are too hard; what about TOY programs?**

  If the Halting Problem can be solved for TOY programs, it can be solved for C

  Use a C compiler to translate C programs to TOY code

- **Ditto for simple, abstract machines — for any machine that can *simulate* others**

More Integers or Reals?

- **Just how many unsolvable problems are there?**
- **A simpler question: Are there more integers or more even integers?**

0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**…**
0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**…**

There's a 1-to-1 correspondence, none missing, so there are as many integers as even integers!

- **Are there more integers or more reals? Try the same technique: Make a 1-to-1 correspondence between integers and reals, listing the reals in *any* order**

0	**0.*1*00100110000100101010010101…**
1	**0.0*0*0100100100101001001000101…**
2	**0.11*1*1111111111111111111111111…**
3	**0.000*1*000000001000100010000010…**
4	**0.1000*0*000000000000000000000000…**
5	**0.11100*0*111000111000111000111…**

This *diagonalization* shows there's at least one real not on the list! 0.010011… the *complement* of the bits on the diagonal above

There are infinitely more reals than integers

- **All possible programs correspond to the integers, all possible functions correspond to the reals: *Most* functions are not computable!**

Implications

- **Practical**
  - **Computing has its limitations; work within them**
  - **Recognize and avoid unsolvable problems**
  - **Recognize hard problems, don't try for optimal solutions**
  - **Use heuristics for hard problems**
  - **Abstract structures reveal much about practical problems**
- **Philosophical (Buyer beware: Consult a 'real' philosopher for the truth)**
  - **We 'assume' that step-by-step reasoning can solve any technical problem**
  - **'Not quite' says the Halting Problem**
  - **Anything that is 'like a computer' suffers the same flaw**
    - **Physical machines**
    - **Human brain?**
    - **Matter?**

Lecture 23. Viruses and Secret Messages

- **Remember `sum.toy`?**

```
0E                                               starting address
0E:  B001     R0 <- 01                           R0 holds 1
0F:  B10A     R1 <- 0A                           R1 is n
10:  B201     R2 <- 01                           R2 is i
11:  B300     R3 <- 00                           R3 is sum
12:  2110     R1 <- R1 - R0                      n--
13:  6118     jump to 18 if R1 < 0               if (n < 0) goto End
14:  1332     R3 <- R3 + R2                      sum += i
15:  1220     R2 <- R2 + R0                      i++
16:  2110     R1 <- R1 - R0                      n--
17:  5013     jump to 13                         goto Top
18:  4302     print R3                           print sum
19:  0000     halt
```

```
% /u/cs217/bin/toy /u/cs217/toy/sum.toy
0037
```

- **Suppose an unknown source *modifies* `sum.toy` by appending the following code**

```
87:  8088     R0 <- 88          % /u/cs217/bin/toy /u/cs217/toy/sum.toy
88:  B108     R1 <- 08          8888
89:  F201     R2 <- R0<<R1      0037
8A:  C002     R0 <- R0^R2
8B:  4002     print R0
8C:  500E     jump to 0E
87
```

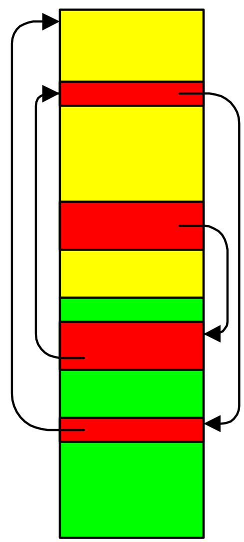
`sum.toy` is infected with the '8888' virus

Infection Routes

- If a virus *V* can find a ***writable executable file*** *P*, it may be able to embed itself in *P*

  infect(*P*,*V*) A copy of *P* with *V* embedded so *V* gets initial control

  V's execution can be arbitrarily complex, perhaps involving self-modifying code to cover its tracks



- When infect(*P*,*V*) runs, *V* can do anything *P* can do, perhaps without visible effects

  Print '8888'

  Print

  `login:`

  On some other computer and wait for a user id; then print

  `Password:`

  Snarf the password entered, spawn another process running `/bin/login`, and leave town with a fresh user id and password; user just sees

  `login:`

  Scramble/delete your files

  Spawn a separate process running itself and find other executable files to infect

Detecting Viruses

- **Given a program *P*, how can you tell if it's infected? You can't**
- **Virus detection software looks for occurrences of *specific* viruses**

  e.g.,

  Is the instruction at location $87_{16} = 8088_{16}$? 'Infected with the 8888 virus'

  Oh oh… Viruses embed themselves in different ways and at different locations

  Must update virus detection software on a regular basis (daily?)

  Virus detection software does not solve the general problem 'is *P* infected?'
- **Suppose you have two versions of supposedly the same program, P_1 and P_2**

  Which one of P_1 or P_2 is infected?

  Do P_1 and P_2 produce the same output? (Even if one is infected)

  Both are *unsolvable* problems alà the Halting Problem
- **Is there any hope?**

  Intractable problems — those with only exponential-time algorithms — come to the rescue

Fingerprints

- **Suppose that given a file *P*, H(*P*) is a relatively small number that 'characterizes' *P***

  H(`/u/cs126/examples/compile.c`) = $364BFFB1_{16}$

  H provides a *fingerprint* of `/u/cs126/examples/compile.c`

  Accept P_2, a copy of *P*, only if H(P_2) = $364BFFB1_{16}$

- **H must be a *one-way hash function* with the following properties**

  Given *P*, it must be *easy* to compute H(*P*)

  Given H(*P*) , it must be *computationally infeasible* to reconstruct *P*

  Given *P* and a virus *V*, it must be computationally infeasible to arrange for H(infect(*P*,*V*)) = H(*P*); that is, to find two bit strings with equal fingerprints

- **Good one-way hash functions produce fingerprints with at least 128 bits**

  MD5(`compile.c`) `979a7c5c ae9f12e2 702fc6ad 9ad4493a`

  SHA(`compile.c`) `85025ddc bb5c8da7 44598fe0 d8b5e16d a75cb560`

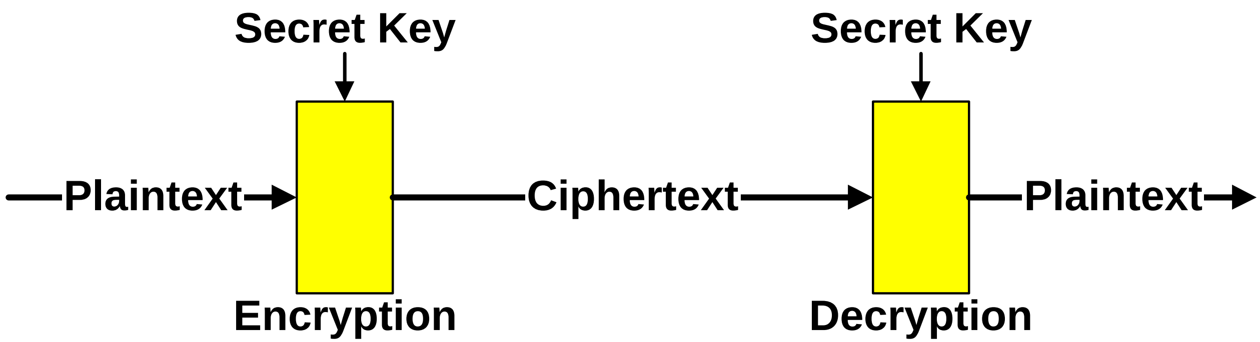
Fingerprints on the Internet

```
% ftp ftp.cs.princeton.edu
ftp> cd /pub/packages/cii
ftp> ls
README
cii10.tar.gz
cii10.tar.Z
cii10.zip
ftp> get README |more
…
The distribution directory contains the following files and
directories. MD5 fingerprints for the files in this directory are
listed below.
…
MD5 (cii10.tar.Z) = ba5b3c3b6c43061e4519c85f103be606
MD5 (cii10.tar.gz) = e3769aeca75ec52427e1b807e02aae3e
MD5 (cii10.zip) = fa71f475c97a4bfae66767012367c77f
Sat Aug 24 13:15:49 EDT 1996
ftp> get cii10.zip
ftp> quit
% md5 cii10.zip
MD5 (cii10.zip) = fa71f475c97a4bfae66767012367c77f
```

- **This isn't foolproof — intruders can intercept Internet packets and substitute different fingerprints**

Cryptography

- A ***cryptosystem*** keeps secret messages (and files) from prying eyes



'Please send money' **24 F8 A7 86 63 2E 28 0A 68 25 B1 73 5F E0 70 99 E2** **'Please send money'**

Key: 01 23 45 67 89 AB CD EF

- **Modern cryptosystems exclusive-OR key with plaintext:** $C = P \wedge K$

```
void encrypt(char *buf, int len, char *key, int keylen) {
    int i = 0;

    for (i = 0; len-- > 0; i = (i + 1)%keylen)
        *buf++ ^= key[i];
}
```

Works for encryption *and* decryption: $C \wedge K = (P \wedge K) \wedge K = \mathrm{P} \wedge (K \wedge K) = P \wedge 0 = P$**!**

Watch out! Sending many 0s in plaintext gives attackers pure key: $C = 0 \wedge K = K$

Cryptography, cont’d

- **Repeated use of a relatively short key isn’t secure; most systems use the key to generate a long stream of pseudo-key, which is XOR’d with the plaintext**
- **Assume the worst: Attackers know the algorithm, the length of the key, and have the ciphertext**
- **Security rests on the strength of the algorithm and the security of the *key***
- **Best systems force attackers to use *inefficient* algorithms, which require trying try all 2^n n-bit keys; just use large n**
- **Designing secure cryptosystems sounds easy, but it’s not; don’t trust amateurs!**
- **Key distribution is just as hard as encryption: What’s the best way to exchange keys with your trusted correspondents and keep them secret? There isn’t one…**
- **For lots of details, read B. Schneier, *Applied Cryptography: Protocols, Algorithms, and Source Code* in C, 2nd ed., Wiley, 1996**

Public-Key Cryptosystems

- ***Public-key*** **cryptosystems avoid the key distribution problem by using** ***two keys***

  Everyone knows your public key, P

  Only you know your secret key, S

  To send M**:** **Send** $P_{drh}(M)$ **via any medium**

  To read M**:** **I read** $S_{drh}(M)$

- **List public keys in the phone book, or its equivalent**

```
% finger -l drh@cs.princeton.edu
...
-----BEGIN PGP PUBLIC KEY BLOCK-----
Version: 2.6.1
mQBNAi1uT8gAAAECAK8TOxmBQ6XhoJXrGPtDKzhZkIqSRh3pMimt8nUh1nSfByec
KittyH02STppLwncD47j8KK6Cm5hriyzusnX/hkABRG0JkRhdmlkIFIuIEhhbnNv
biA8ZHJoQGNzLnByaW5jZXRvbi5lZHU+
=JFCd
-----END PGP PUBLIC KEY BLOCK-----
```

- **For all public-key algorithms**

  $S(P(M)) = M$ **for all** M
  All S**,** P **pairs must be distinct**
  Deriving S **from** P **must be as hard as reading** M
  $P(M)$ **and** $S(M)$ **must be efficient**

RSA Public-Key Cryptosystem

- **The RSA cryptosystem uses arithmetic on very large integers**

  P **is** ***N*, *p***

  S **is** ***N*, *s*** **where** $N \approx 200$ **digits,** ***p*** **and** $s \approx 100$ **digits**

- **To choose *N*, *p*, *s***

Pick 3 100-digit *secret* prime numbers, *x*, *y*, *s* The largest is *s*	$x = 47$, $y = 79$, $s = 97$
$N = x \times y$	$N = 47 \times 79 = 3713$
Choose *p* so that $(p \times s) \bmod ((x-1)(y-1)) = 1$	$p \times 97 \bmod (46 \times 78) = 1$ $37 \times 97 \bmod 3588 = 1$ $3589/3588 = 1$ **remainder 1**

- **Attackers see only *N* and *p***

  To find *s*, attackers must *factor* *N* into its prime factors *x* and *y*

  It is *believed*, but not proven, to be infeasible to factor *N* if it's sufficiently large

  Factoring 200-digit numbers probably takes $\approx 10^9$ **years**

- **Are there enough primes for everyone? Yes:** $\approx 10^{150}$ **primes with** ≤ 512 **bits (**≈ 155 **decimal digits)**

RSA Encryption

- **To *encrypt* M, use N and the *public* key, p**

  Encode M in numbers $< N$

  For each M_i, $C_i = M_i^p \bmod N$ the remainder of M_i^p when divided by N

  For $N = 3713$, $p = 37$, $s = 97$

M	**Please send money**								
	P l	e a	s e	_ s	e n	d _	m o	n e	y _
Encode:	1612	0501	1905	0019	0514	0400	1315	1405	2500
Encrypt:	2080	0057	1857	3706	1584	0888	2067	0591	1277

$1612^{37} =$ 47,044,232,358,938,497,020,498,996,761,564,680,247,331,818, 462,325,046,870,527,453,082,869,350,611,474,961,064,423,374, 436,277,844,788,137,937,637,623,201,792

$1612^{37} \bmod 3713 = 2080$, etc.

RSA Decryption

- To ***decrypt*** ***M***, use ***N*** and the ***private*** key, ***s***

  For each C_i, $M_i = C_i^s \bmod N$

  Decode numbers to reveal *M*

  For $N = 3713$, $p = 37$, $s = 97$

	Please send money
***C*:**	`2080 0057 1857 3706 1584 0888 2067 0591 1277`
Decrypt:	`1612 0501 1905 0019 0514 0400 1315 1405 2500`

$57^{97} =$ **208,862,754,025,291,103,893,549,722,030,506,307,840,035,159,185,066,358,136,864,739,390,751,752,973,213,714,581,100,145,330,888,003,488,562,198,990,224,718,358,613,240,589,340,493,287,521,060,551,858,632,460,253,869,992,608,057**

$57^{97} \bmod 3713 = 501$

Decode:	`1612 0501 1905 0019 0514 0400 1315 1405 2500`
	`P L  E A  S E  _ S  E N  D _  M O  N E  Y _`

- **This example is from R. Sedgewick, *Algorithms in C*, Addison-Wesley, 1990**
- **For details on multiple-precision arithmetic, see D. R. Hanson, *C Interfaces and Implementations*, Addison-Wesley, 1997**

PGP

- **PGP — Pretty Good Privacy — is widely used public-key cryptosystem available for PCs, UNIX systems, etc.**

```
you% cat | pgp -fea drh
Pretty Good Privacy(tm) 2.6.2 - Public-key encryption for the masses.
Can I have more time on the current
programming assignment?
--frazzled in Princeton
^D
-----BEGIN PGP MESSAGE-----
Version: 2.6.2
hEwDriyzusnX/hkBAgChqSkxFkFwyMFyCwrcl87jHzXshOdrDQYTDQbRwwVcGZIy
A83TTPYzFGU3yHHnNVWQHAejJDRJRHPaEXRNEUiPpgAAAGjcN7B2zmqgvJeW1iR2
dTOVQtmusN9Ez32CdYD8ub/3b7smX8q+NCBm13/83TexSgyudPaqPoifd7q0N96z
kL4tSAmcJHwfzyiM/RJ+2p41YgcgAqFgaB2NTHaowYQXpG4qNg3nMSTxOg==
=5u0S
-----END PGP MESSAGE-----

you% cat | pgp -fea drh | mail drh@cs

drh% inc
Incorporating new mail into inbox...
  92+ 09/04 To:drh@fs.CS.Prin  <<-----BEGIN PGP MESSAGE-----
drh% show | pgp -fd
Can I have more time on the current
programming assignment?
--frazzled in Princeton
```