Princeton University

Computer Science 217: Introduction to Programming Systems

A Taste of C

Goals of this Lecture

Help you learn about:

- The basics of C
- Deterministic finite-state automata (DFA)
- Expectations for programming assignments

Why?

- Help you get started with Assignment 1
  - Required readings…
  - + coverage of programming environment in precepts…
  - + minimal coverage of C in this lecture…
  - = enough info to start Assignment 1
- DFAs are useful in many contexts
  - E.g. Assignment 1, Assignment 7

Agenda

The charcount program

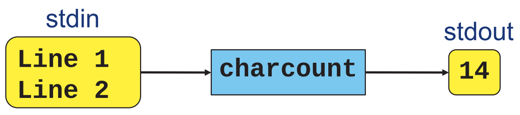
The upper program

The upper1 program

The “charcount” Program

Functionality:

- Read all chars from stdin (standard input stream)
- Write to stdout (standard output stream) the number of chars read



The “charcount” Program

The program:

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

“charcount” Building and Running

```
$ gcc217 charcount.c –o charcount
$ ./charcount
Line 1
Line 2
^D
14
$
```

What is this?
What is the effect?

“charcount” Building and Running

```
$ cat somefile
Line 1
Line 2
$ ./charcount < somefile
14
$
```

What is this?
What is the effect?

“charcount” Building and Running

```
$ ./charcount > someotherfile
Line 1
Line 2
^D
$ cat someotherfile
14
```

What is this?
What is the effect?

“charcount” Building and Running in Detail

Question:

- Exactly what happens when you issue the command
  `gcc217 charcount.c –o charcount`

Answer: Four steps

- Preprocess
- Compile
- Assemble
- Link

“charcount” Building and Running in Detail

The starting point

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- C language
- Missing definitions of getchar() and printf()

Preprocessing “charcount”

Command to preprocess:

- `gcc217 –E charcount.c > charcount.i`

Preprocessor functionality

- Removes comments
- Handles **preprocessor directives**

Preprocessing “charcount”

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Preprocessor replaces
#include <stdio.h>
with contents of
/usr/include/stdio.h

Preprocessor replaces
EOF with -1

Preprocessing "charcount"

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != -1)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Preprocessor
removes comment

Preprocessing "charcount"

The result

charcount.i

```
...
int getchar();
int printf(char *fmt, ...);
...
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != -1)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Why **int** instead of **char**?

- C language
- Missing comments
- Missing preprocessor directives
- Contains code from stdio.h
  - **Declarations** of getchar() and printf()
- Missing **definitions** of getchar() and printf()

Compiling "charcount"

Command to compile:

- **gcc217 –S charcount.i**

Compiler functionality

- Translate from C to assembly language
- Use function declarations to check calls of getchar() and printf()

Compiling "charcount"

charcount.i

```
...
int getchar();
int printf(char *fmt, ...);
...
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != -1)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- Compiler sees function declarations
- So compiler has enough information to check subsequent calls of getchar() and printf()

Compiling "charcount"

charcount.i

```
...
int getchar();
int printf(char *fmt, ...);
...
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != -1)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- Definition of main() function
- Compiler checks calls of getchar() and printf() when encountered
- Compiler translates to assembly language

Compiling "charcount"

The result: charcount.s

```
        .section ".rodata"
format:
        .string "%d\n"
        .section ".text"
        .globl main
        .type main,@function
main:
        pushq %rbp
        movq %rsp, %rbp
        subq $4, %rsp
        call getchar
loop:
        cmpl $-1, %eax
        je endloop
        incl -4(%rbp)
        call getchar
        jmp loop
endloop:
        movq $format, %rdi
        movl -4(%rbp), %esi
        movl $0, %eax
        call printf
        movl $0, %eax
        movq %rbp, %rsp
        popq %rbp
        ret
```

- Assembly language
- Missing definitions of getchar() and printf()

Assembling "charcount"

Command to assemble:

- `gcc217 –c charcount.s`

Assembler functionality

- Translate from assembly language to machine language

Assembling "charcount"

The result:

charcount.o

```
Machine language
version of the
program

No longer human
readable
```

- Machine language
- Missing definitions of getchar() and printf()

Linking "charcount"

Command to link:

- `gcc217 charcount.o –o charcount`

Linker functionality

- Resolve references
- Fetch machine language code from the standard C library (/usr/lib/libc.a) to make the program complete

Linking "charcount"

The result:

charcount

```
Machine language
version of the
program

No longer human
readable
```

- Machine language
- Contains definitions of getchar() and printf()

Complete! Executable!

Running "charcount"

Command to run:

- `./charcount < somefile`

Running "charcount"

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Computer allocates space for c and charCount in the stack section of memory

Why **`int`** instead of **`char`**?

Running “charcount”

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- Computer calls getchar()
- getchar() tries to read char from stdin
  - Success ⇒ returns char (within an int)
  - Failure ⇒ returns **EOF**

EOF is a special non-char value that getchar() returns to indicate failure

Running “charcount”

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Assuming c ≠ EOF, computer increments charCount

Running “charcount”

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

Computer calls getchar() again, and repeats

Running “charcount”

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- Eventually getchar() returns EOF
- Computer breaks out of loop
- Computer calls printf() to write charCount

Running “charcount”

Run-time trace, referencing the original C code…

charcount.c

```
#include <stdio.h>
/* Write to stdout the number of
   chars in stdin. Return 0. */
int main(void)
{  int c;
   int charCount = 0;
   c = getchar();
   while (c != EOF)
   {  charCount++;
      c = getchar();
   }
   printf("%d\n", charCount);
   return 0;
}
```

- Computer executes return stmt
- Return from main() terminates program

Normal execution ⇒ return 0 or **EXIT_SUCCESS**
Abnormal execution ⇒ return **EXIT_FAILURE**

Other Ways to “charcount”

1

```
for (c=getchar(); c!=EOF; c=getchar())
   charCount++;
```

2

```
while ((c=getchar())!=EOF)
   charCount++;
```

Which way is best?

3

```
for (;;)
{  c = getchar();
   if (c == EOF)
      break;
   charCount++;
}
```

4

```
c = getchar();
while (c!=EOF)
{  charCount++;
   c = getchar();
}
```

Review of Example 1

Input/Output
- Including **stdio.h**
- Functions **getchar()** and **printf()**
- Representation of a character as an integer
- Predefined constant **EOF**

Program control flow
- The **for** and **while** statements
- The **break** statement
- The **return** statement

Operators
- Assignment: **=**
- Increment: **++**
- Relational: **==** **!=**

Agenda

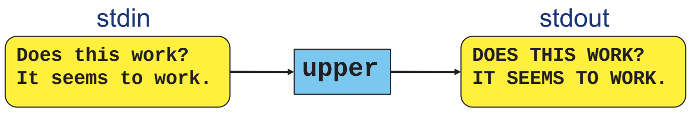
The charcount program

The upper program

The upper1 program

Example 2: "upper"

Functionality
- Read all chars from stdin
- Convert each lower case alphabetic char to upper case
  - Leave other kinds of chars alone
- Write result to stdout



"upper" Building and Running

```
$ gcc217 upper.c –o upper
$ cat somefile
Does this work?
It seems to work.
$ ./upper < somefile
DOES THIS WORK?
IT SEEMS TO WORK.
$
```

ASCII

American Standard Code for Information Interchange

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	NUL									HT	LF					
16																
32	SP	!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
48	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
64	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
80	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
96	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
112	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	

Partial map

Note: Lower case and upper case letters are 32 apart

"upper" Version 1

```
#include <stdio.h>
int main(void)
{  int c;
   while ((c = getchar()) != EOF)
   {  if ((c >= 97) && (c <= 122))
         c -= 32;
      putchar(c);
   }
   return 0;
}
```

What's wrong?

EBCDIC

Extended Binary Coded Decimal Interchange Code

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	NUL					HT										
16																
32						LF										
48																
64	SP											.	<	(	+	|
80	&										!	$	*	)	;	
96	-	/									|	,	%	_	>	?
112										`	:	#	@	'	=	"
128		a	b	c	d	e	f	g	h	i		{				
144		j	k	l	m	n	o	p	q	r		}				
160		~	s	t	u	v	w	x	y	z						
176																
192		A	B	C	D	E	F	G	H	I						
208		J	K	L	M	N	O	P	Q	R						
224	\		S	T	U	V	W	X	Y	Z						
240	0	1	2	3	4	5	6	7	8	9						

Partial map

Note: Lower case not contiguous; same for upper case

Character Literals

Examples

```
'a'       the a character
                 97 on ASCII systems
                 129 on EBCDIC systems
'\n'      newline
                 10 on ASCII systems
                 37 on EBCDIC systems
'\t'      horizontal tab
                 9 on ASCII systems
                 5 on EBCDIC systems
'\\'      backslash
                 92 on ASCII systems
                 224 on EBCDIC systems
'\''      single quote
                 39 on ASCII systems
                 125 on EBCDIC systems
'\0'      the null character (alias NUL)
                 0 on all systems
```

"upper" Version 2

```
#include <stdio.h>
int main(void)
{  int c;
   while ((c = getchar()) != EOF)
   {  if ((c >= 'a') && (c <= 'z'))
         c += 'A' - 'a';
      putchar(c);
   }
   return 0;
}
```

Arithmetic on chars?

What's wrong?

ctype.h Functions

```
$ man islower
NAME
       isalnum, isalpha, isascii, isblank, iscntrl, isdigit, isgraph,
       islower, isprint, ispunct, isspace, isupper, isxdigit –
       character classification routines

SYNOPSIS
       #include <ctype.h>
       int isalnum(int c);
       int isalpha(int c);
       int isascii(int c);
       int isblank(int c);                These functions
       int iscntrl(int c);                check whether c...
       int isdigit(int c);                falls into a
       int isgraph(int c);                certain character
       int islower(int c);                class...
       int isprint(int c);
       int ispunct(int c);
       int isspace(int c);
       int isupper(int c);
       int isxdigit(int c);
```

ctype.h Functions

```
$ man toupper
NAME
       toupper, tolower - convert letter to upper or lower case

SYNOPSIS
       #include <ctype.h>
       int toupper(int c);
       int tolower(int c);

DESCRIPTION
       toupper() converts the letter c to upper case, if possible.
       tolower() converts the letter c to lower case, if possible.

       If c is not an unsigned char value, or EOF, the behavior of
       these functions is undefined.

RETURN VALUE
       The value returned is that of the converted letter, or c if
       the conversion was not possible.
```

"upper" Final Version

```
#include <stdio.h>
#include <ctype.h>
int main(void)
{  int c;
   while ((c = getchar()) != EOF)
   {  if (islower(c))
         c = toupper(c);
      putchar(c);
   }
   return 0;
}
```

Is the **if** statement really necessary?

Review of Example 2

Representing characters

- ASCII and EBCDIC character sets
- Character literals (e.g., 'A' or 'a')

Manipulating characters

- Arithmetic on characters
- Functions such as islower() and toupper()

Agenda

The charcount program

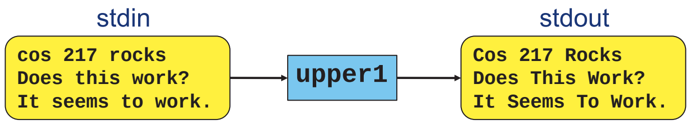
The upper program

The upper1 program

Example 3: "upper1"

Functionality

- Read all chars from stdin
- Capitalize the first letter of each word
  - "cos 217 rocks" ⇒ "Cos 217 Rocks"
- Write result to stdout



```
cos 217 rocks
Does this work?
It seems to work.
```

```
Cos 217 Rocks
Does This Work?
It Seems To Work.
```

"upper1" Building and Running

```
$ gcc217 upper1.c –o upper1
$ cat somefile
cos 217 rocks
Does this work?
It seems to work.
$ ./upper1 < somefile
Cos 217 Rocks
Does This Work?
It Seems To Work.
$
```

"upper1" Challenge

Problem

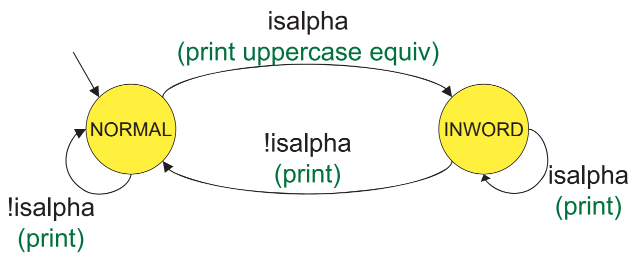
- Must remember where you are
- Capitalize "c" in "cos", but not "o" in "cos" or "c" in "rocks"

Solution

- Maintain some extra information
- "In a word" vs "not in a word"

Deterministic Finite Automaton

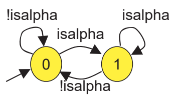
Deterministic Finite State Automaton (DFA)



- **States**, one of which is denoted the **start** state
- **Transitions** labeled by chars or char categories
- Optionally, actions on transitions

“upper1” Version 1

```c
#include <stdio.h>
#include <ctype.h>
int main(void)
{  int c;
   int state = 0;
   while ((c = getchar()) != EOF)
   {  switch (state)
      {  case 0:
            if (isalpha(c))
            {  putchar(toupper(c)); state = 1; }
            else
            {  putchar(c); state = 0; }
            break;
         case 1:
            if (isalpha(c))
            {  putchar(c); state = 1; }
            else
            {  putchar(c); state = 0; }
            break;
      }
   }
   return 0;
}
```



That’s a B.
What’s wrong?

“upper1” Toward Version 2

Problem:
- The program works, but…
- States should have names

Solution:
- Define your own named constants
- **`enum Statetype {NORMAL, INWORD};`**
  - Define an enumeration type
- **`enum Statetype state;`**
  - Define a variable of that type

“upper1” Version 2

```c
#include <stdio.h>
#include <ctype.h>
enum Statetype {NORMAL, INWORD};
int main(void)
{  int c;
   enum Statetype state = NORMAL;
   while ((c = getchar()) != EOF)
   {  switch (state)
      {  case NORMAL:
            if (isalpha(c))
            {  putchar(toupper(c)); state = INWORD; }
            else
            {  putchar(c); state = NORMAL; }
            break;
         case INWORD:
            if (isalpha(c))
            {  putchar(c); state = INWORD; }
            else
            {  putchar(c); state = NORMAL; }
            break;
      }
   }
   return 0;
}
```

That’s a B+.
What’s wrong?

“upper1” Toward Version 3

Problem:
- The program works, but…
- Deeply nested statements
- No modularity

Solution:
- Handle each state in a separate function

“upper1” Version 3

```c
#include <stdio.h>
#include <ctype.h>
enum Statetype {NORMAL, INWORD};

enum Statetype handleNormalState(int c)
{  enum Statetype state;
   if (isalpha(c))
   {  putchar(toupper(c));
      state = INWORD;
   }
   else
   {  putchar(c);
      state = NORMAL;
   }
   return state;
}

enum Statetype handleInwordState(int c)
{  enum Statetype state;
   if (!isalpha(c))
   {  putchar(c);
      state = NORMAL;
   }
   else
   {  putchar(c);
      state = INWORD;
   }
   return state;
}
```

```c
int main(void)
{  int c;
   enum Statetype state = NORMAL;
   while ((c = getchar()) != EOF)
   {  switch (state)
      {  case NORMAL:
            state = handleNormalState(c);
            break;
         case INWORD:
            state = handleInwordState(c);
            break;
      }
   }
   return 0;
}
```

That’s an A-.
What’s wrong?

“upper1” Toward Final Version

Problem:
- The program works, but…
- No comments

Solution:
- Add (at least) function-level comments

Function Comments

Function comment should describe
what the function does (from the caller's viewpoint)

- Input to the function
  - Parameters, input streams
- Output from the function
  - Return value, output streams, (call-by-reference parameters)

Function comment should **not** describe
how the function works

Function Comment Examples

Bad main() function comment

```
Read a character from stdin. Depending upon
the current DFA state, pass the character to
an appropriate state-handling function. The
value returned by the state-handling function
is the next DFA state. Repeat until end-of-file.
```

- Describes **how the function works**

Good main() function comment

```
Read text from stdin. Convert the first character
of each "word" to uppercase, where a word is a
sequence of letters. Write the result to stdout.
Return 0.
```

- Describes **what the function does** from caller's viewpoint

"upper1" Final Version

```
/*------------------------------------------------------------*/
/* upper1.c                                                   */
/* Author: Bob Dondero                                        */
/*------------------------------------------------------------*/

#include <stdio.h>
#include <ctype.h>

enum Statetype {NORMAL, INWORD};
```

Continued on next page

"upper1" Final Version

```
/*------------------------------------------------------------*/

/* Implement the NORMAL state of the DFA. c is the current
   DFA character. Write c or its uppercase equivalent to
   stdout, as specified by the DFA. Return the next state. */

enum Statetype handleNormalState(int c)
{  enum Statetype state;
   if (isalpha(c))
   {  putchar(toupper(c));
      state = INWORD;
   }
   else
   {  putchar(c);
      state = NORMAL;
   }
   return state;
}
```

Continued on next page

"upper1" Final Version

```
/*------------------------------------------------------------*/

/* Implement the INWORD state of the DFA. c is the current
   DFA character. Write c to stdout, as specified by the DFA.
   Return the next state. */

enum Statetype handleInwordState(int c)
{  enum Statetype state;
   if (!isalpha(c))
   {  putchar(c);
      state = NORMAL;
   }
   else
   {  putchar(c);
      state = INWORD;
   }
   return state;
}
```

Continued on next page

"upper1" Final Version

```
/*------------------------------------------------------------*/

/* Read text from stdin. Convert the first character of each
   "word" to uppercase, where a word is a sequence of
   letters. Write the result to stdout. Return 0. */

int main(void)
{  int c;
   /* Use a DFA approach.  state indicates the DFA state. */
   enum Statetype state = NORMAL;
   while ((c = getchar()) != EOF)
   {  switch (state)
      {  case NORMAL:
            state = handleNormalState(c);
            break;
         case INWORD:
            state = handleInwordState(c);
            break;
      }
   }
   return 0;
}
```

Review of Example 3

Deterministic finite-state automaton
- Two or more states
- Transitions between states
  - Next state is a function of current state and current character
- Actions can occur during transitions

Expectations for COS 217 assignments
- Readable
  - Meaningful names for variables and literals
  - Reasonable max nesting depth
- Modular
  - Multiple functions, each of which does one well-defined job
- Function-level comments
  - Should describe what function does
- See K&P book for style guidelines specification

Summary

The C programming language
- Overall program structure
- Control statements (**`if`**, **`while`**, **`for`**, and **`switch`**)
- Character I/O functions (**`getchar()`** and **`putchar()`**)

Deterministic finite state automata (DFA)

Expectations for programming assignments
- Especially Assignment 1

Start Assignment 1 soon!

Appendix:

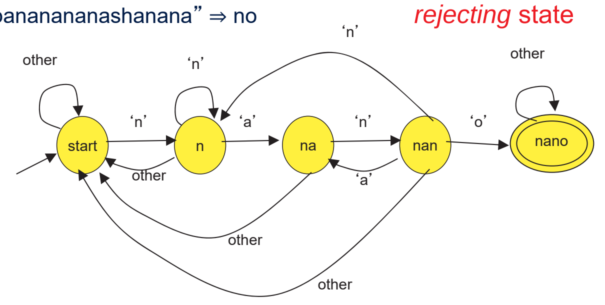
Additional DFA Examples

Another DFA Example

Does the string have “nano” in it?
- “banano” ⇒ yes
- “nnnnnnnanofff” ⇒ yes
- “bananananonano” ⇒ yes
- “bananananashanana” ⇒ no

Double circle is *accepting* state

Single circle is *rejecting* state



Yet Another DFA Example

Old Exam Question

Compose a DFA to identify whether or not a string is a floating-point literal

Valid literals	Invalid literals
“-34”	“abc”
“78.1”	“-e9”
“+298.3”	“1e”
“-34.7e-1”	“+”
“34.7E-1”	“17.9A”
“7.”	“0.38+”
“.7”	“.”
“999.99e99”	“38.38f9”