Princeton University
Computer Science 217: Introduction to Programming Systems

A Taste of C

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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

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Agenda

The charcount program

The upper program

The upper1 program

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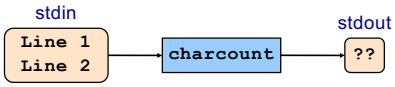
The "charcount" Program

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



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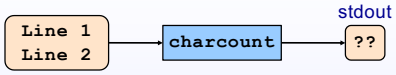
iClicker Question

Q: What is the output of `charcount` on this input?



A. 10

B. 12

C. 13

D. 14

E. 15

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;
}
```

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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;
}
```

Execution begins at **`main()`** function

- No classes, no methods in the C language

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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`**?

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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;
}
```

getchar() tries to read char from stdin

- Success ⇒ returns char (within an int)
- Failure ⇒ returns **EOF**

EOF is a special non-char value, different from all possible chars, that getchar() returns to indicate failure

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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 $c \neq EOF$, computer increments charCount

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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

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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

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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 statement
- Return from main() terminates program

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

"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" Build Process in Detail

Question:

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

Answer: Four steps

- Preprocess
- Compile
- Assemble
- Link

"charcount" Build Process 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**

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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 removes comment

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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

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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;
}
```

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

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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()

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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()

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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
.LC0:
        .string "%d\n"
        .section        .text
        .global main
main:
        stp     x29, x30, [sp, -32]!
        add     x29, sp, 0
        str     wzr, [x29,24]
        bl      getchar
        str     w0, [x29,28]
        b       .L2
.L3:
        ldr     w0, [x29,24]
        add     w0, w0, 1
        str     w0, [x29,24]
        bl      getchar
        str     w0, [x29,28]
.L2:
        ldr     w0, [x29,28]
        cmn     w0, #1
        bne     .L3
        adrp    x0, .LC0
        add     x0, x0, :lo12:.LC0
        ldr     w1, [x29,24]
        bl      printf
        mov     w0, 0
        ldp     x29, x30, [sp], 32
        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!

iClicker Question

Q: There are other ways to **charcount** – which is best?

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

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

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

D.
```
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: **== !=**

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Agenda

The charcount program

The upper program

The upper1 program

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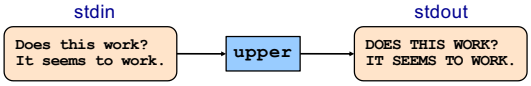
Example 2: "upper"

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



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"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.
$
```

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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

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"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?

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Character Literals

Examples

```
'a'     the a character
                97 on ASCII systems

'\n'    newline
                10 on ASCII systems

'\t'    horizontal tab
                9 on ASCII systems

'\\'    backslash
                92 on ASCII systems

'\''    single quote
                39 on ASCII systems

'\0'    the null character (alias NUL)
                0 on all systems
```

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"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 now?

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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

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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
```

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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);
       int iscntrl(int c);
       int isdigit(int c);
       int isgraph(int c);
       int islower(int c);
       int isprint(int c);
       int ispunct(int c);
       int isspace(int c);
       int isupper(int c);
       int isxdigit(int c);
```

These functions check whether c... falls into a certain character class...

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" Version 3

```
#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;
}
```

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iClicker Question

Q: Is the **if** statement really necessary?

A. Gee, I don't know. Let me check the man page!

```
#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;
}
```

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.
```

iClicker Question

Q: Is the **if** statement really necessary?

A. Yes, necessary for correctness.

B. Not necessary, but I'd leave it in.

C. Not necessary, and I'd get rid of it.

```
#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;
}
```

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()

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Agenda

The charcount program

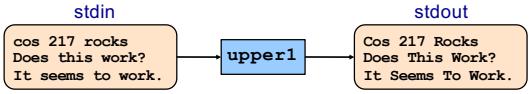
The upper program

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



"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

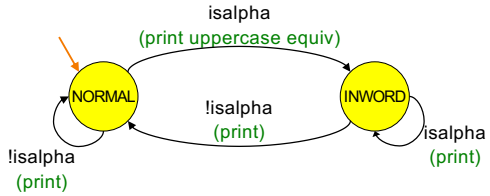
- Must remember where you are
- Capitalize "c" in "cos", but not "o" in "cos" or "c" in "rocks"

Solution

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

Deterministic Finite Automaton

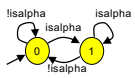
Deterministic Finite State Automaton (DFA)



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

"upper1" Version 1

```
#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

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"upper1" Version 2

```
#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?

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"upper1" Toward Version 3

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

Solution:
- Handle each state in a separate function

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"upper1" Version 3

```
#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;
}
```

```
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?

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"upper1" Toward Final Version

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

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

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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

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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

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"upper1" Final Version

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

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

enum Statetype {NORMAL, INWORD};
```

Continued on next page

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"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

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"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

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"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;
}
```

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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

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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!

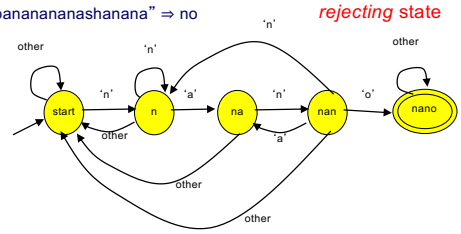
Appendix:
Additional DFA Examples

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
- "-34"
- "78.1"
- "+298.3"
- "-34.7e-1"
- "34.7E-1"
- "7."
- ".7"
- "999.99e99"

Invalid literals
- "abc"
- "-e9"
- "1e"
- "+"
- "17.9A"
- "0.38+"
- "."
- "38.38f9"