## 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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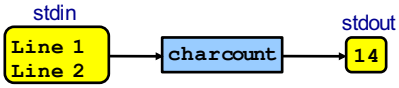
## The "charcount" Program

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

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## 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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## "charcount" Building and Running

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

What is this?
What is the effect?

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## "charcount" Building and Running

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

What is this?
What is the effect?

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## "charcount" Building and Running

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

What is this?
What is the effect?

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## "charcount" Building and Running in Detail

**Question**:

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

**Answer**: Four steps

1. Preprocess
2. Compile
3. Assemble
4. Link

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## "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()

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## (1) Preprocessing "charcount"

Command to preprocess:

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

Preprocessor functionality

- Removes comments
- Handles **preprocessor directives**

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## (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 != 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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## (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

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## (1) 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()

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## (2) 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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## (2) 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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## (2) 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

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## (2) 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()

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## (3) Assembling "charcount"

Command to assemble:
- `gcc217 -c charcount.s`

Assembler functionality
- Translate from assembly language to machine language

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## (3) Assembling "charcount"

The result:

charcount.o

```
Machine language
version of the
program

No longer human
readable
```

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

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## (4) 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

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## (4) 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!

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## Running "charcount"

Command to run:
- `./charcount < somefile`

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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;
}
```

- 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

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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 ≠ 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 stmt
- Return from main() terminates program

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

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## 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();
}
```

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## 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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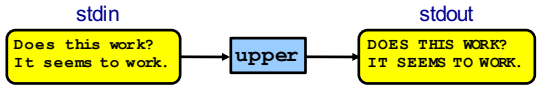
## Example 2: "upper"

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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## 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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## "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?

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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" 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?

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## 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**

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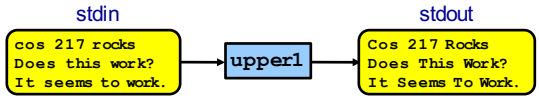
## Example 3: "upper1"

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

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## "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.
$
```

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## "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"

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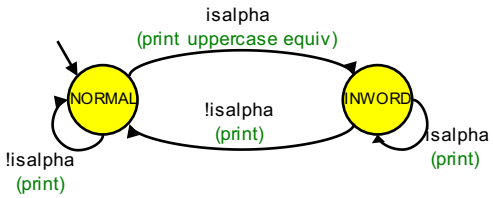
## Deterministic Finite Automaton

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

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## "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?

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## "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!**

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## Appendix:

## Additional DFA Examples

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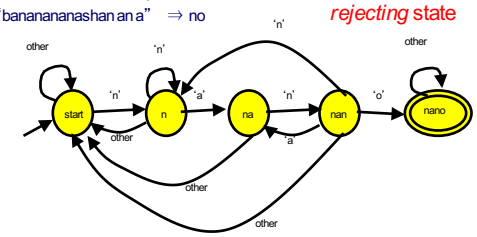
## Another DFA Example

Does the string have "nano" in it?
- "banano" ⇒ yes
- "nnnnnnnanofff" ⇒ yes
- "bananananonano" ⇒ yes
- "bananananashan an a" ⇒ no

Double circle is *accepting* state

Single circle is *rejecting* state

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## 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"

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