Building C Programs
&
Implementing DFAs in C

PRINCETON UNIVERSITY

Agenda

Building simple C programs

- examine 4-stage build process for charcount

"DFA model" character processing programs

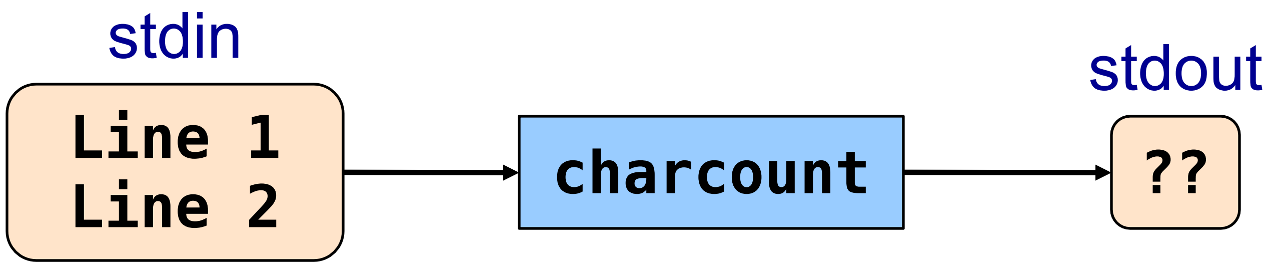
- upper: demonstrate ctype library for character data
- upper1: DFA model
- upper1: develop a C program to implement the DFA

Next time: design decisions in charcount, upper, upper1

Last time: The `charcount` Program

Functionality:

- Read all characters from standard input stream
- Write to standard output stream the number of characters read



Last time: 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;
}
```

Last time: `charcount` Building and Running

```
$ gcc217 charcount.c
$ ls
.     ..    a.out
$ gcc217 charcount.c –o charcount
$ ls
.     ..    a.out
      charcount
$
```

`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 declarations of `getchar()` and `printf()`
- Missing definitions of `getchar()` and `printf()`

`charcount` Build Process: Preprocessor

Command to preprocess:

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

Preprocessor functionality

- Removes comments
- Handles preprocessor directives

`charcount` Build Process: Preprocessor

`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 (this is A1!)

charcount Build Process: Preprocessor

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

`charcount` Build Process: Preprocessor

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
- Without comments
- Without preprocessor directives
- Contains code from `stdio.h`: **declarations** of `getchar()` and `printf()`
- Missing **definitions** of `getchar()` and `printf()`
- Contains value for `EOF`

`charcount` Build Process: Compiler

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()`

charcount Build Process: Compiler

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**
- These give compiler enough information to check subsequent calls of `getchar()` and `printf()`

`charcount` Build Process: Compiler

`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()`
- Compiler translates C code to assembly language directives and instructions progressively

`charcount` Build Process: Compiler

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()`

`charcount` Build Process: Assembler

Command to assemble:

- `gcc217 –c charcount.s`

Assembler functionality

- Translate from assembly language to machine language

`charcount` Build Process: Assembler

The result:

`charcount.o`

```
Machine language
version of the
program

No longer human
readable
```

- Machine language
- (Still!) Missing definitions of `getchar()` and `printf()`

`charcount` Build Process: Linker

Command to link:

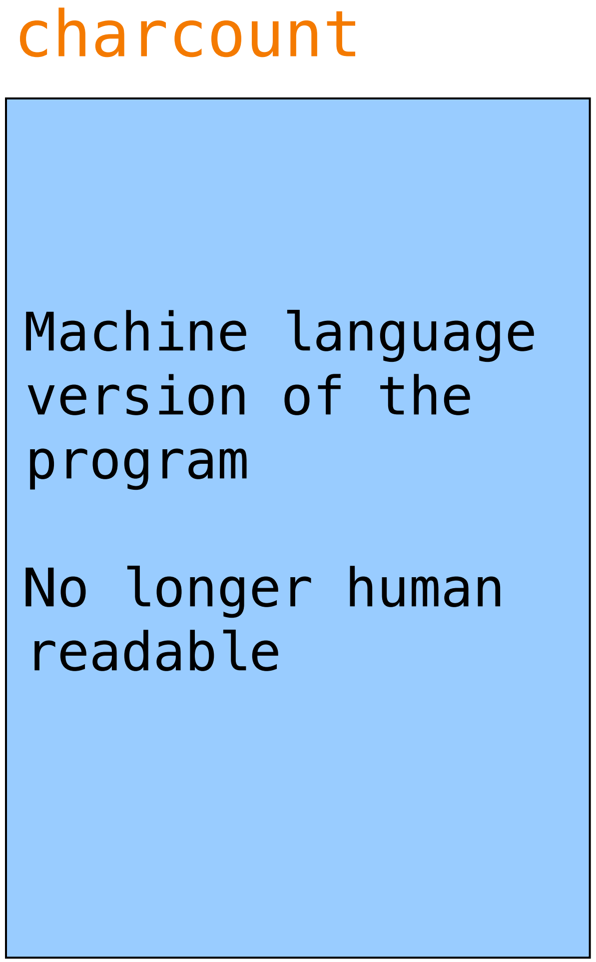
- `gcc217 charcount.o –o charcount`

Linker functionality

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

`charcount` Build Process: Linker

The result:



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

Complete! Executable!

Agenda

Building simple C programs

- examine 4-stage build process for charcount

"DFA model" character processing programs

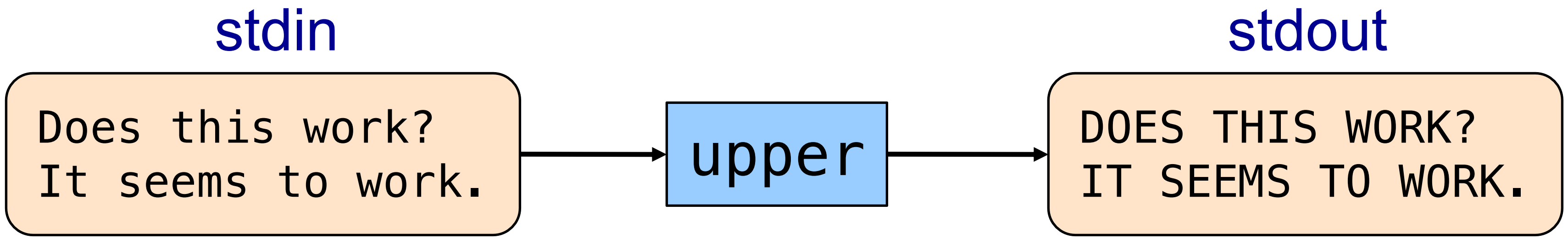
- upper: demonstrate ctype library for character data
- upper1: DFA model
- upper1: develop a C program to implement the DFA

Next time: design decisions in charcount, upper, upper1

Getting closer: `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` (starting at Version 3 … 1 and 2 next time!)

```
#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 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, which must
have the value of an
unsigned char or EOF,
falls into a certain
character  class.

...

islower() checks for a
lowercase character.
```

`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.
```

It's important to be inclusive!

What build tool will be limited (and thus complain with a warning)
if we omit the library preprocessor directive?

A: Preprocessor

B: Compiler

C: Assembler

D: Linker

```
#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;
}
```

B: Compiler
gives warning
that it hasn't seen
declaration for
`islower` or `toupper`

... but build does
ultimately succeed.

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The `upper1` program

Functionality

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

stdin

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

→ `upper1` →

stdout

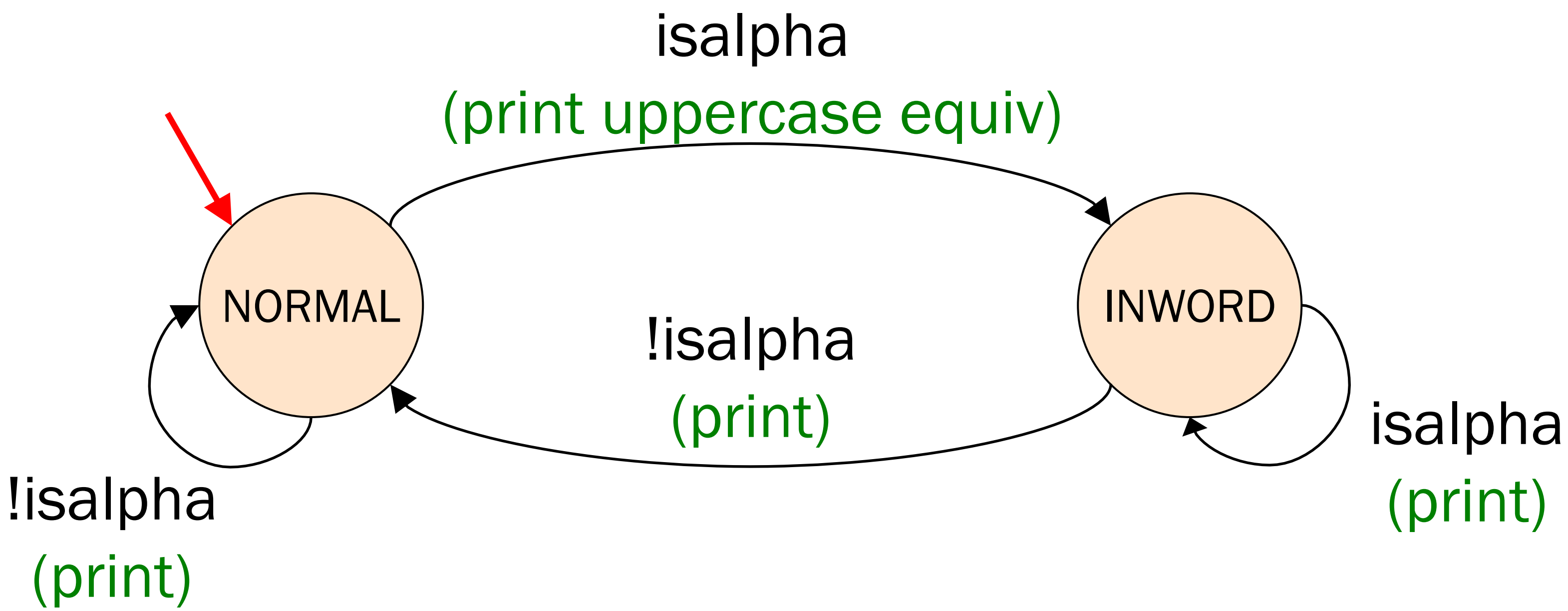
```
Cos 217 Rocks
Does This Work?
It Seems To Work.
```

What we need:

1. to recognize when we're *"in a word"* vs *"**not** in a word"*
2. to reason about what to do with that information in a systematic way

Deterministic Finite Automaton

Deterministic Finite State Automaton (DFA)



- States, one of which is designated as the start
- Transitions labeled by individual or categories of chars
- Optionally, actions on transitions

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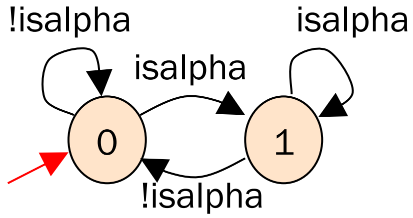
Next time: design decisions in charcount, upper, upper1

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

upper1 Version 2

```
…
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;
}
```

```c
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?

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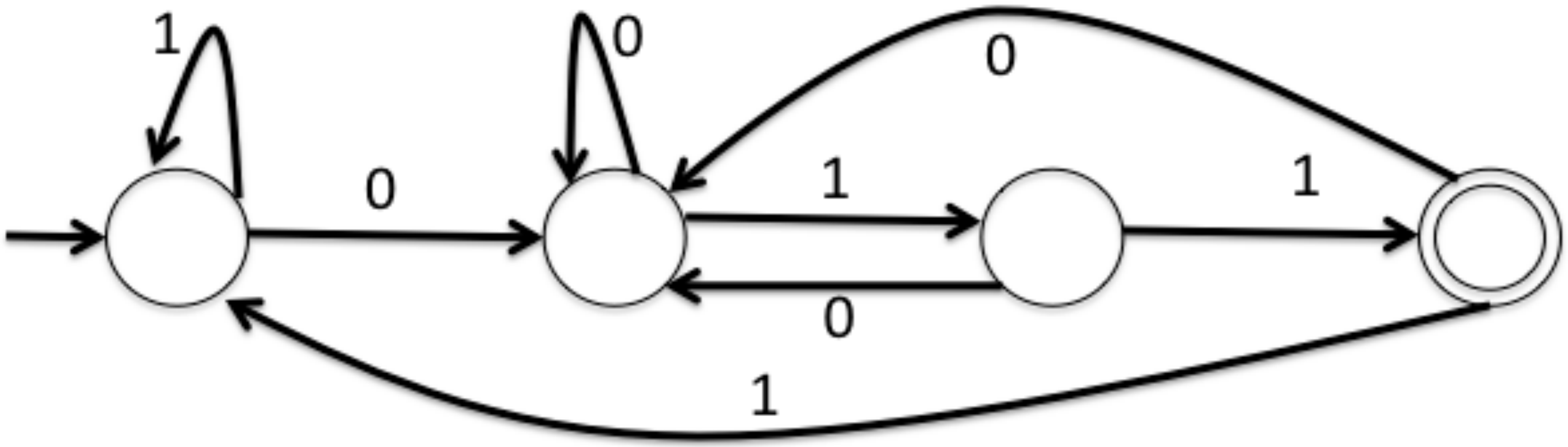
Next time: design decisions in charcount, upper, upper1

more C language design decisions and features

Sample Exam Question (Fall 2015, Exam 1)

State concisely what sequences (and only those sequences) this four-state DFA accepts. Assume all sequence characters are either ‘0’ or ‘1’, that the leftmost state is the initial state, and that the rightmost state is the only accept state. (6 points / 100)



Appendix:

Additional DFA Examples

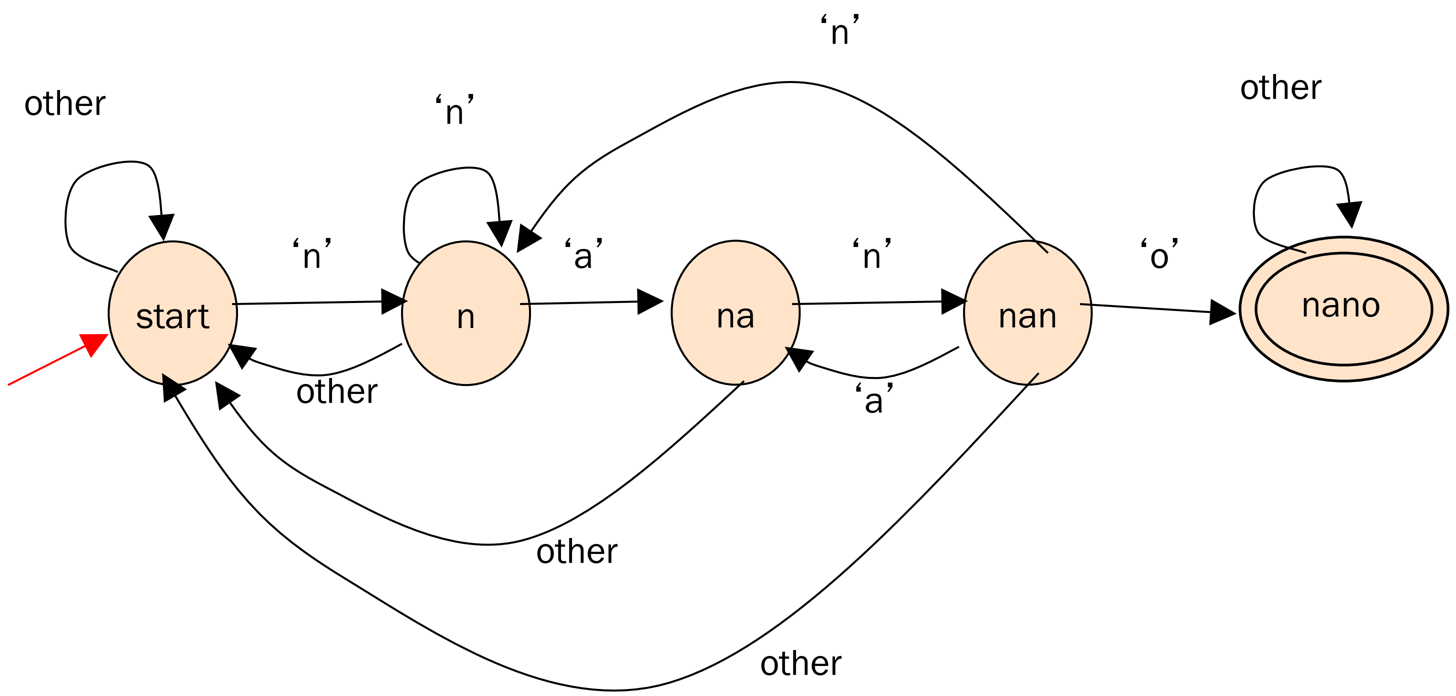
Another DFA Example

Does the string have "nano" in it?

- "banano" ⇒ yes
- "nnnnnnnanofff" ⇒ yes
- "banananonano" ⇒ yes
- "bananananashanana" ⇒ no

Double circle is accepting state

Single circle is rejecting state



Yet Another DFA Example

Old (Hard!) 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"