

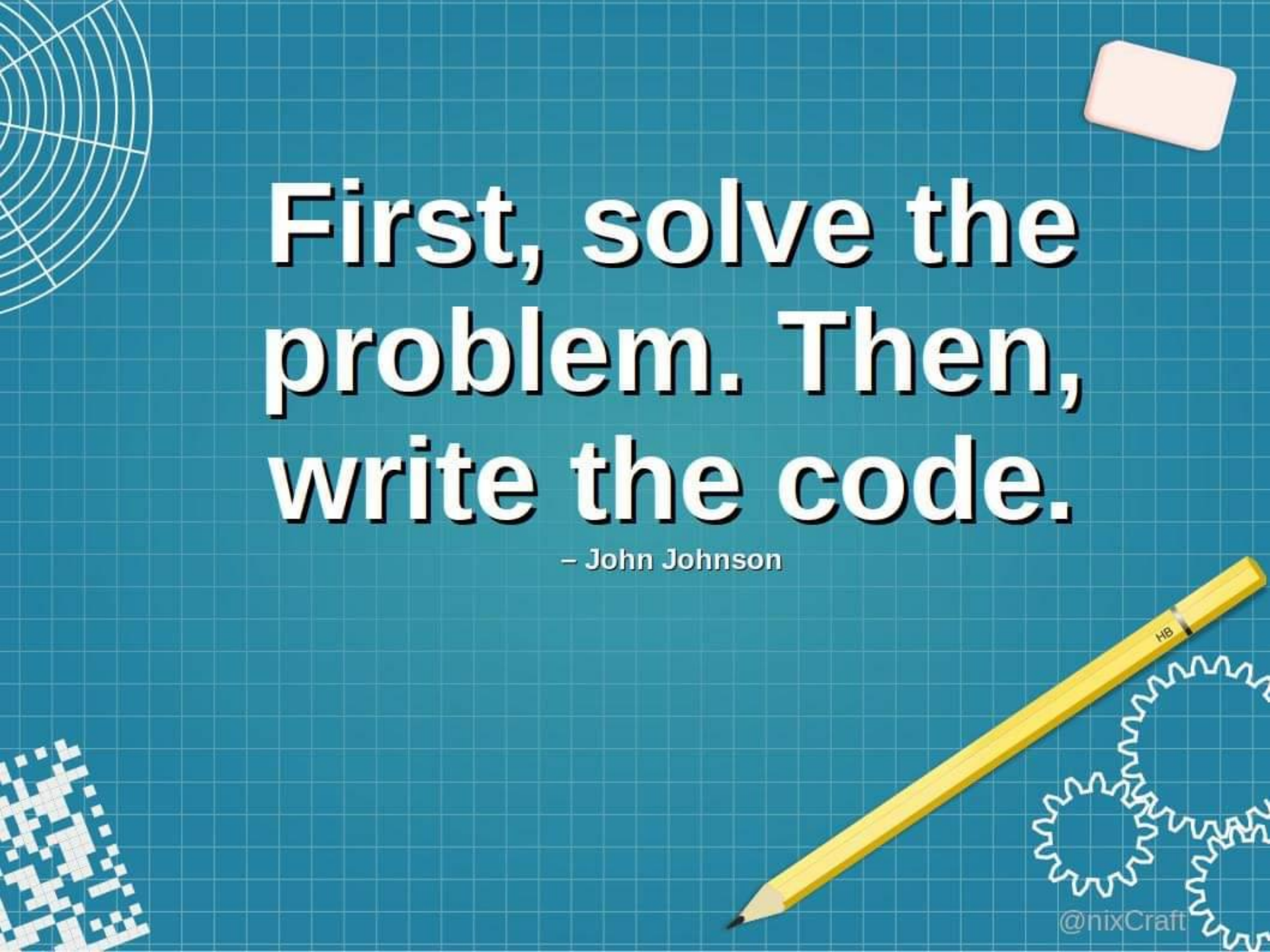
Automata and machines

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UNIMORE
UNIVERSITÀ DEGLI STUDI DI
MODENA E REGGIO EMILIA

High Performance
Real Time **Lab**



**First, solve the
problem. Then,
write the code.**

– John Johnson



Industrial embedded systems

What they do

- › Monitor physical properties of the system/plant (via *sensors*)
- › Might perform some control, or part of, control algos
- › Via *actuators*

Control can be

- › Continuous in time
 - › Discrete in time
- ➔ Control theory



Industrial controls in a nutshell



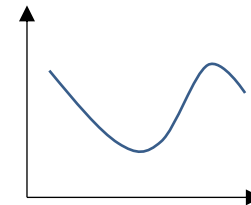
In their generic form,

$$F: \{S, I\} \rightarrow \{O\}$$

computed ...when?

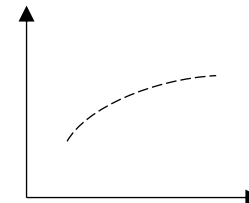
If continuous

- › Physical properties and actuators are continuous in time
- › $F(t)$ continuous
- › Combinatorial logic/analogic systems



If discrete

- › Computed at pre-determined instance in time
- › Event-driven (e.g., timeout, interrupt)
- › Sequential logics/digital systems





Finite state automations for discrete controls

E.g., an elevator, reacts to multiple events

- › Typically in idle state
- › If you are press the button, the door opens
- › You select the floor, doors close
- › Then, it reaches the floor (feat. velocity control)
- › Then, it opens the door, which subsequently closes after X seconds

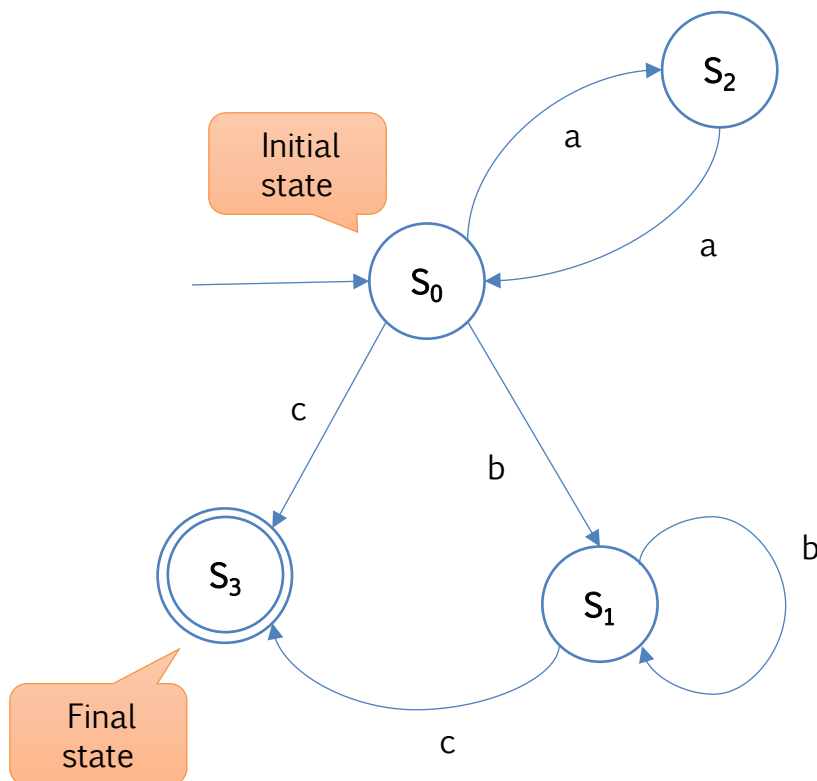
This behavior is controlled by a **finite state automations/machine**



Finite State Automations/Machines

Problem

- › Identify even sequences of a (even empty), followed by one, or more, or no, b , ended by c



Given an alphabet V ,

...that identifies a language (we'll see)..

define FSA as

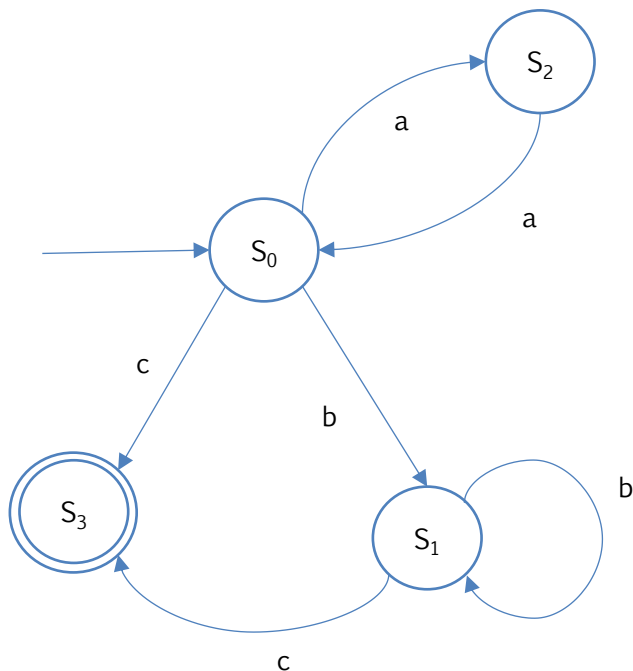
- › S : a non-empty states set
- › $s_0 \in S$: initial state
- › $S_f \subseteq S$: final states set
- › $t: S \times V \rightarrow S$: states transaction func



FSMs and languages

Let $V^* = \{v, w, \dots\}$ contain all the combinations of words using V symbols

- › Including the empty word ε
- › For instance, ac , $aabbc$, $abbabbbc$ belong to V^*
- › (note that, we can associate words in V^* to inputs, or combination of them)



A **language** L is a subset of V^*

(abbabbbc does **not** belong
to L , as previously defined)

*"Identify even sequences of a (even empty),
followed by one, or more, or no, b, ended by c"*



State transaction function

$$\triangleright \text{sfn}(s_0, b) = s_1 \quad | \quad s_0 \xrightarrow{b} s_1$$

- $\triangleright s_y$ is reachable by s_x if there exists a path from s_x to s_y
 - a combination of alphabet symbols l (letters in our case), aka: token

$$\text{sfn}: S \times V \rightarrow S$$

$$\rightarrow^* : S \times V^* \times S : s_x \xrightarrow{w^*} s_y$$

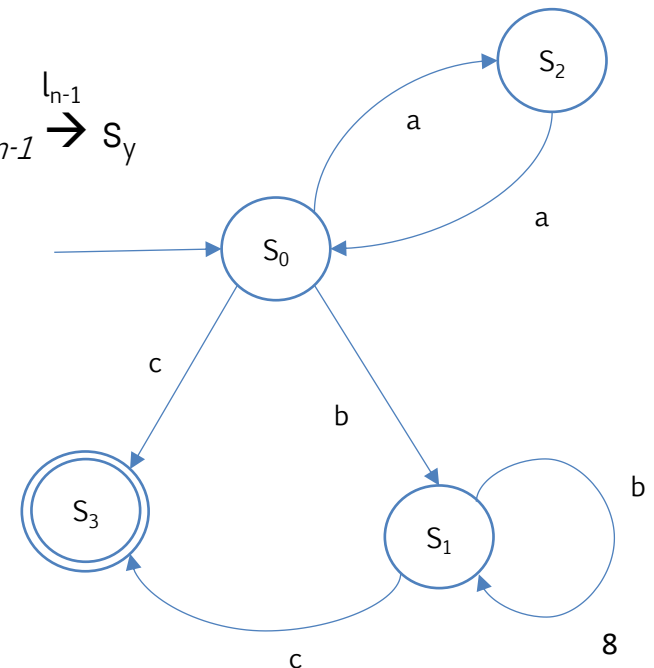
iff

$$w = l_1 l_2 \dots l_n \quad \exists s_t, s_u, \dots, s_n : s_x \xrightarrow{l_1} s_t \xrightarrow{l_2} s_u \dots s_{n-1} \xrightarrow{l_{n-1}} s_y$$

$$\xrightarrow{w^*} s_2 \rightarrow s_1$$

$$w = aab$$

$$\exists s_1, s_2, \dots, s_n : s_2 \xrightarrow{a} s_0 \xrightarrow{a} s_2 \xrightarrow{a} s_0 \xrightarrow{b} s_1$$





Exercise

Let's
code!

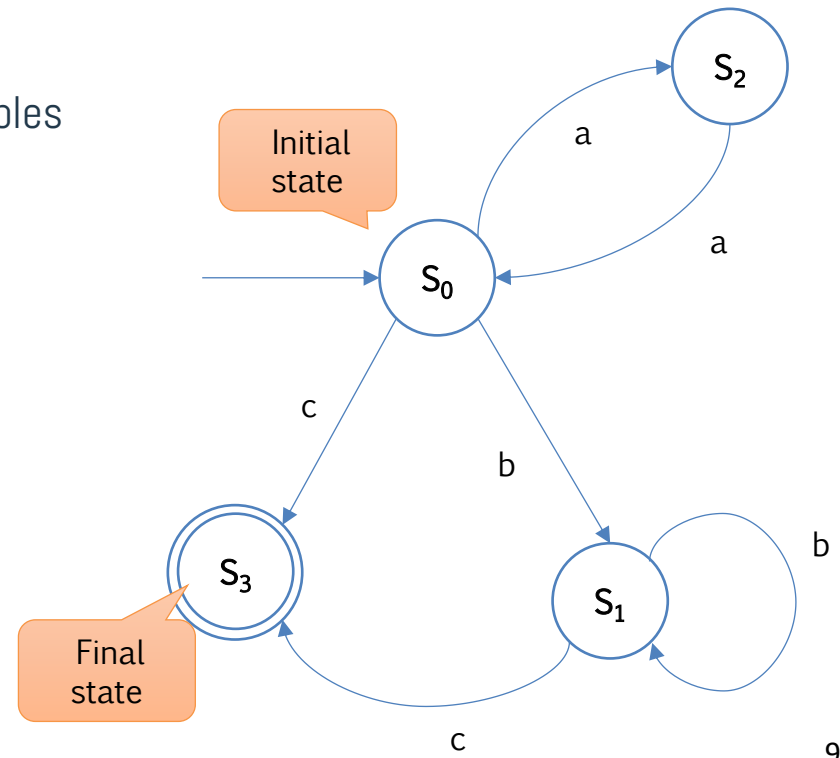
Implement the automata that understands whether a words is from L

*"Identify even sequences of a (even empty),
followed by one, or more, or no, b, ended by c"*

Use the language that you want

- › You just need IFs, CASE-SWITCH, recursion, tables
- › Receive the target word from stdin
- › Hint: start simple...

What's missing?





Exercise

Let's
code!

Implement the automata that understands whether a words is from L

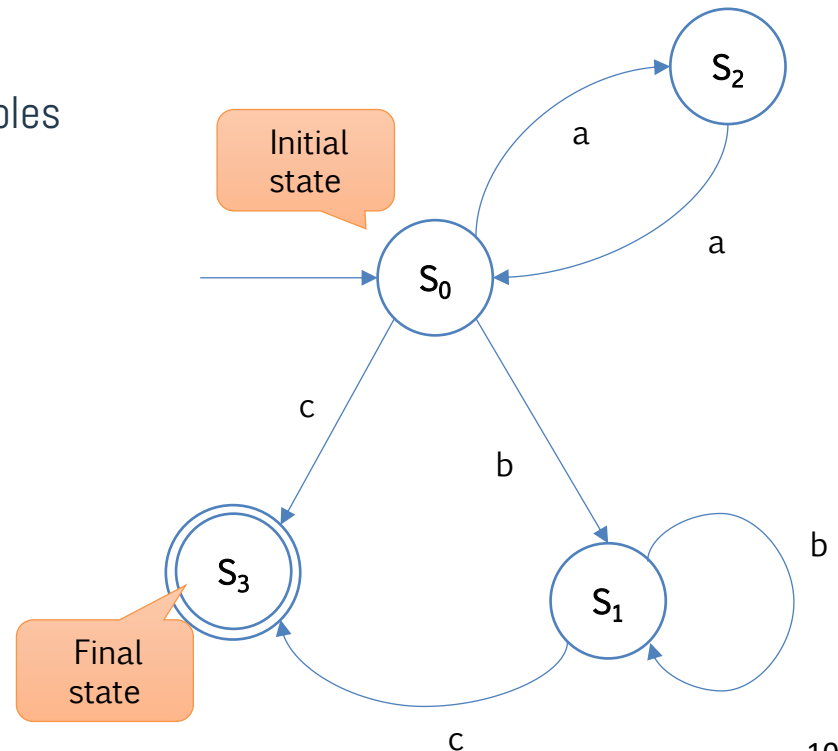
*"Identify even sequences of a (even empty),
followed by one, or more, or no, b, ended by c"*

Use the language that you want

- › You just need IFs, CASE-SWITCH, recursion, tables
- › Receive the target word from stdin
- › Hint: start simple...

What's missing?

- › In case of error => default error state
- › Typically implicit in state diagrams





Grammars

- › A standard way of representing languages (Noam Chomsky, 1950)

$$G = \langle VT, VN, P, S \rangle$$

- › VT : terminal symbols $\subseteq V$
- › VN : non-terminal symbols $\subseteq V$ (aka: syntax categories)
- › P : production rules $P \subseteq VN \times (VN \cup VT)$
- › $S \in VN$: initial symbol

VT and VN disjoint

$$VT \cap VN = \emptyset$$

VT and VN are V

$$VT \cup VN = V$$

A language L_G generated by grammar G is the set of V^* elements
derived by start symbol S through productions in P



Backus-Naur Form

- › Productions rules have form

$$\alpha ::= \beta, \alpha \in VN \beta \in V$$

- › $x \in VN$ have the form $\langle \text{name} \rangle$
- › $|$ specifies an option

```
VT = { il, gatto, topo, sasso, mangia, beve }
```

```
VN = { <frase>, <soggetto>, <verbo>, <compl-ogg>, <articolo>, <nome> }
```

```
S = <frase>
```

```
P = {  
  <frase> ::= <soggetto> <verbo> <compl-ogg>  
  <soggetto> ::= <articolo> <nome>  
  <articolo> ::= il  
  <nome> ::= gatto | topo | sasso  
  <verbo> ::= mangia | beve  
  <compl-ogg> ::= <articolo> <nome>  
}
```

Automata states



Another example

› Natural numbers

```
VT = { 0, 1, ..., 9 }
```

```
VN = { <num>, <cifra>, <cifra-non-nulla> }
```

```
S = <num>
```

```
P = {
```

```
  <num> ::= <cifra>|<cifra-non-nulla>{<cifra>}
```

```
  <cifra> ::= 0|<cifra-non-nulla>
```

```
  <cifra-non-nulla> ::= 1|2|3|4|5|6|7|8|9
```

```
}
```

“Recursion”
Extended BNF

› Challenge: extend it with sign (+, -)!



Another example: solution

› Natural numbers

```
VT = { 0, 1, ..., 9, +, - }
```

```
VN = { <int>, <num>, <cifra>, <cifra-non-nulla> }
```

```
S = <int>
```

```
P = {
```

```
  <int> ::= [+|-] <num>
```

```
  <num> ::= <cifra> | <cifra-non-nulla> {<cifra>}
```

```
  <cifra> ::= 0 | <cifra-non-nulla>
```

```
  <cifra-non-nulla> ::= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
```

```
}
```

› Challenge: extend it with sign (+, -)!



In reality...

- › We only give production rules: VN, VT, S are implicitly defined..

```
P = {  
  <frase> ::= <soggetto> <verbo> <compl-ogg>  
  <soggetto> ::= <articolo> <nome>  
  <articolo> ::= il  
  <nome> ::= gatto | topo | sasso  
  <verbo> ::= mangia | beve  
  <compl-ogg> ::= <articolo> <nome>  
}
```

Let's
code!

Want to try?

- › Implement a machine that recognizes whether a sentence (aka: **a word of the Language L**) is legal for that language
- › ("our" words are symbols of L)



Hierarchy of machine types

- › Base (combinatorial) machine
- › Finite state machines – FSM
- › FSM with stack (PDA)
- › Turing machine





Base combinatorial machine

$\langle I, O, mfn \rangle$

I : (finite) set of Input symbols

O : (finite) set of output symbols

$mfn: I \rightarrow O$ machine function

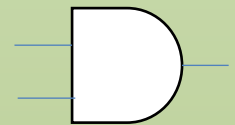
- › E.g., Logical ports, gates
- › Suitable for continuous control
- › Non suitable if you need state/memory
 - Need to model all possible cases!

Example: logical AND

$I = \{ \{0,1\} \times \{0,1\} \}$

$O = \{0,1\}$

mfn defined by a table



	0	1
0	0	0
1	0	1



Finite state machine

$\langle I, O, S, mfn, sfn \rangle$

I : (finite) set of Input symbols

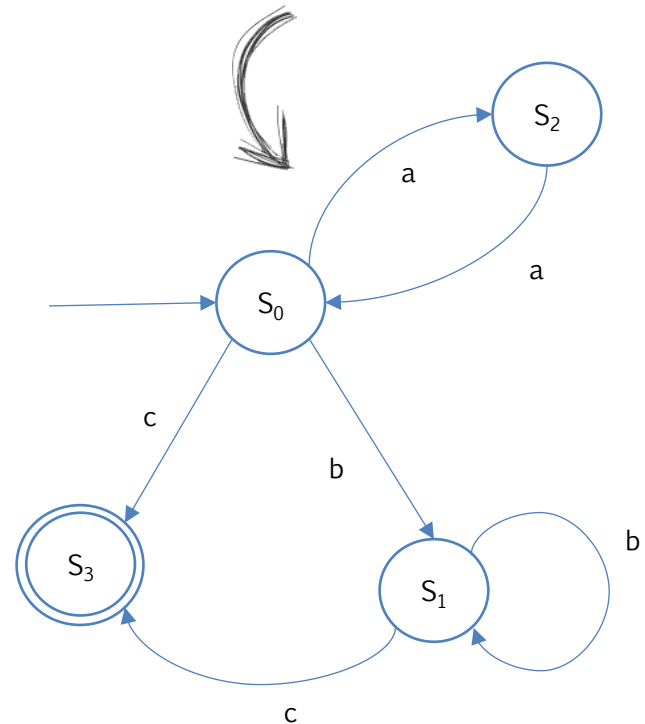
O : (finite) set of output symbols

S : (finite) set of states

$mfn: I \times S \rightarrow O$ machine function

$sfn: I \times S \rightarrow S$ state function

- › Partly already seen
- › Has memory
 - Memory is a limitation
- › Here, I show only the SFN





Finite state machine with stack

$\langle I, O, A, S, \text{mfn}, \text{sfn} \rangle$

I : (finite) set of Input symbols

A : (finite) set of stack alphabet symbols

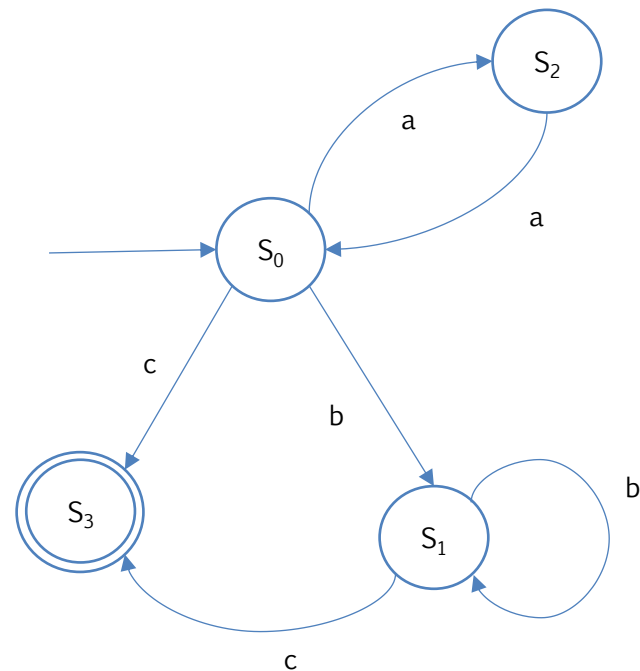
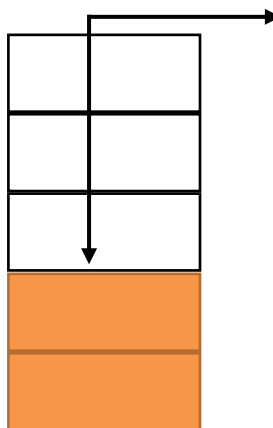
O : (finite) set of output symbols

S : (finite) set of states

$\text{mfn}: I \times S \times A \rightarrow O$ machine function

$\text{sfn}: I \times S \times A \rightarrow S$ state function

- › Also known as Push-Down Automata (PDA)
- › Uses a stack
- › We'll see them...





Turing machine

$\langle A, S, mfn, sfn, dfn \rangle$

A : (finite) set of in/out symbols

S : (finite) set of states

$mfn: A \times S \rightarrow A$ machine function

$sfn: A \times S \rightarrow S$ state function (inc. HALT)

$dfn: A \times S \rightarrow \{ \text{left}, \text{right}, \text{none} \}$
direction function

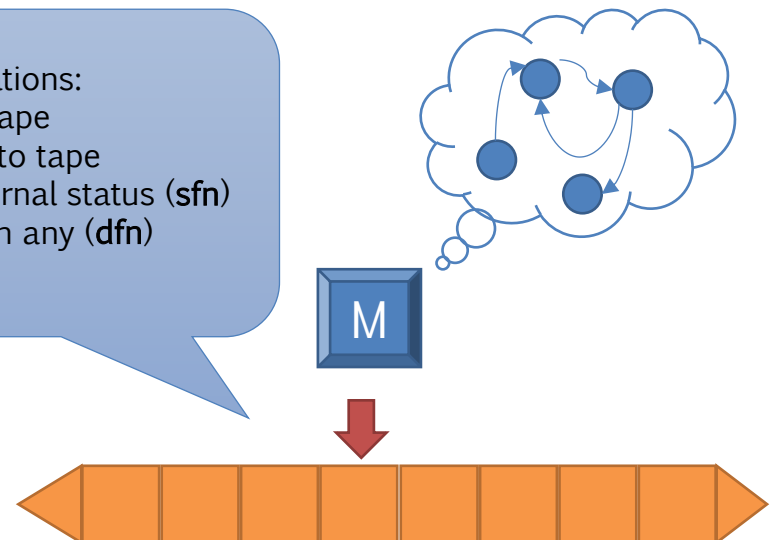
› Unlimited memory

Possible operations:

- Read from tape
- Write (**mfn**) to tape
- Change internal status (**sfn**)
- Move tape in any (**dfn**) direction

Church-Turing thesis

A function on the natural numbers can be calculated by an effective method if and only if it is computable by a Turing machine





A Universal Turing Machine

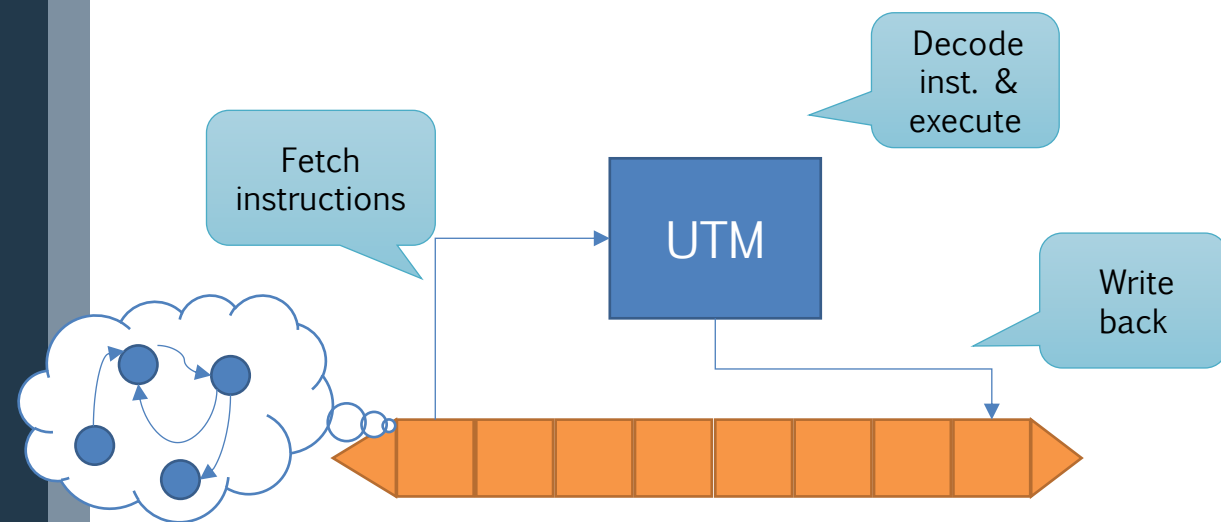
- › In TM, the algorithm is inside the machine M, we write results in the tape

What if instruction as well is in the tape?

- › We have a programmable machine, with a memory
- ›does this remind something?

Which are the catch? What do we miss?

- › Ok, the infinite tape makes it infeasible
- › ..but what else?

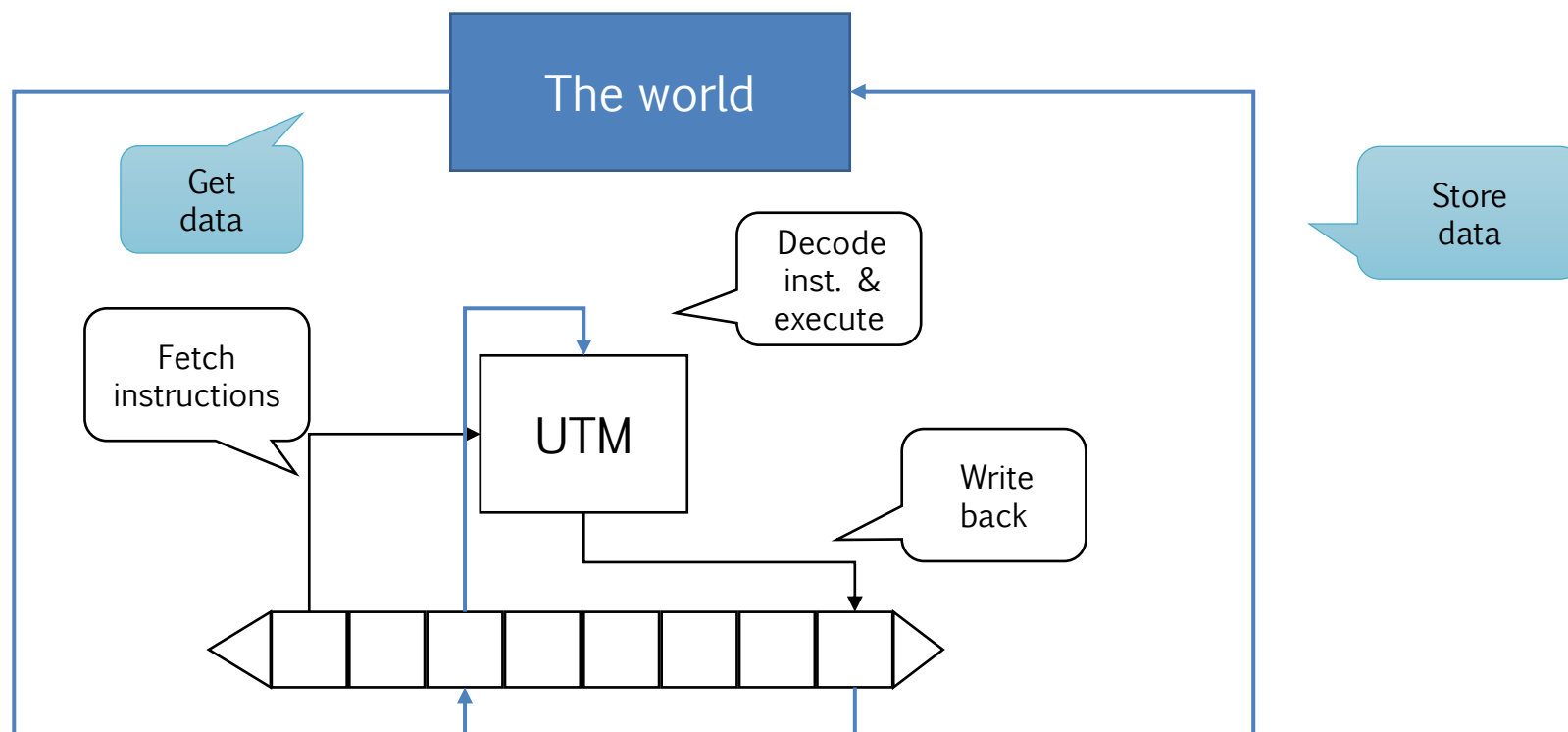




The Van Neumann Machine

We also need to model the interaction with the environment!

- › Aka: I/O (HD/SSD is also I/O)
- › Where data comes from!
- › It is a real machine: we can **build** it



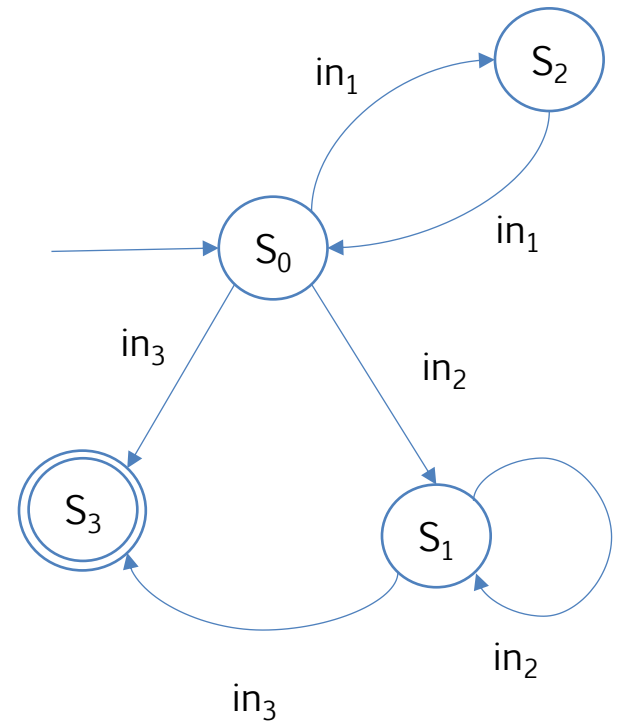


How to implement a FSM



A generic FSM

- › Till now, we only saw machines that can recognize a **word** from a language
 - I say “word”, you might want to understand “sentence”
- › Let's now see how a machine can actually **produce** an output





The Machine of Mealy

- › When crossing an edge, produce an output

$\langle I, O, S, mfn, sfn \rangle$

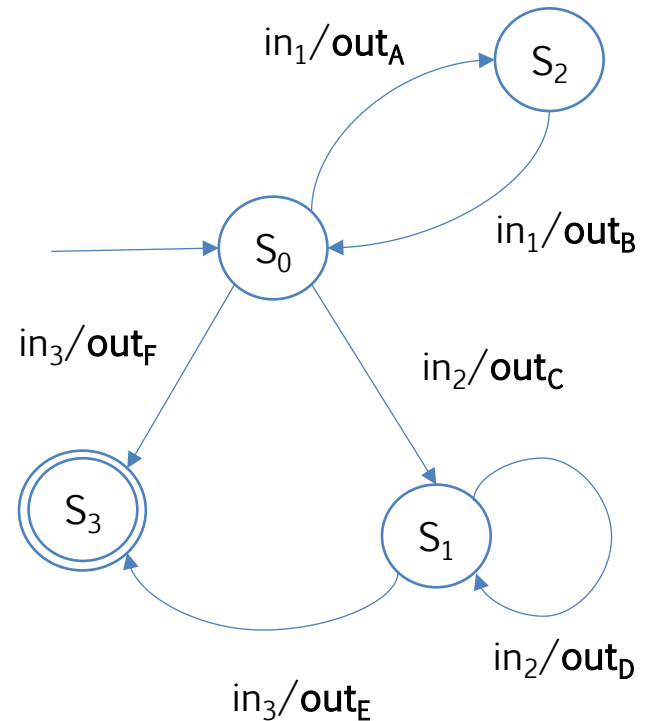
I : (finite) set of Input symbols

O : (finite) set of output symbols

S : (finite) set of states (s_0 initial state)

$mfn: I \times S \rightarrow O$ machine/output function

$sfn: I \times S \rightarrow S$ state transition function





The Machine of Moore

- › When in a state an edge, produce an output

$\langle I, O, S, mfn, sfn \rangle$

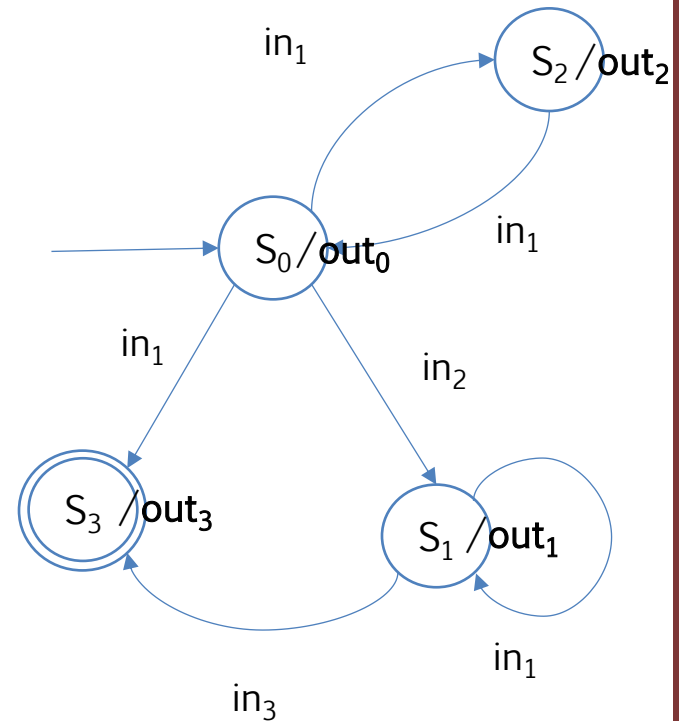
I : (finite) set of Input symbols

O : (finite) set of output symbols

S : (finite) set of states (s_0 initial state)

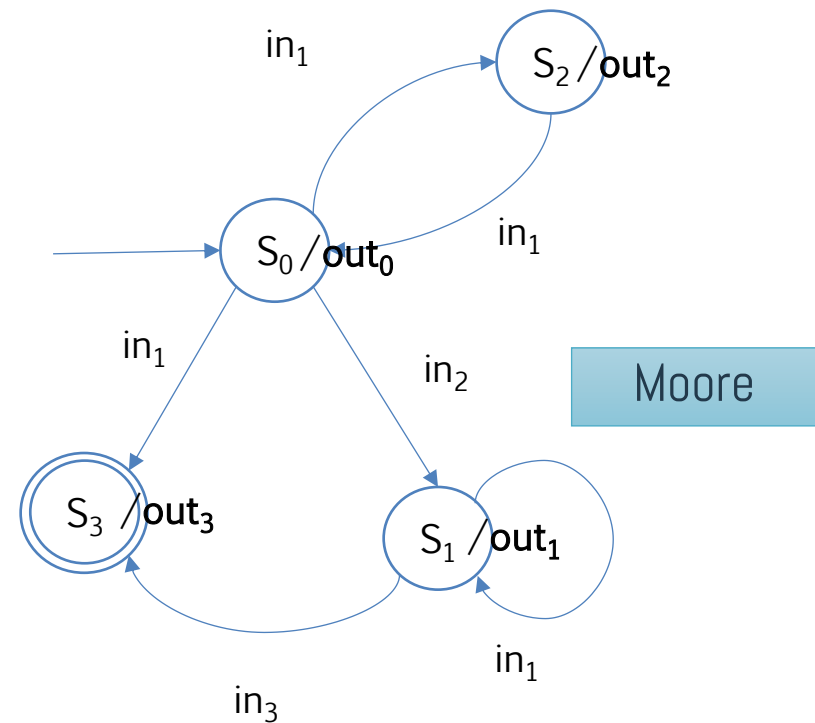
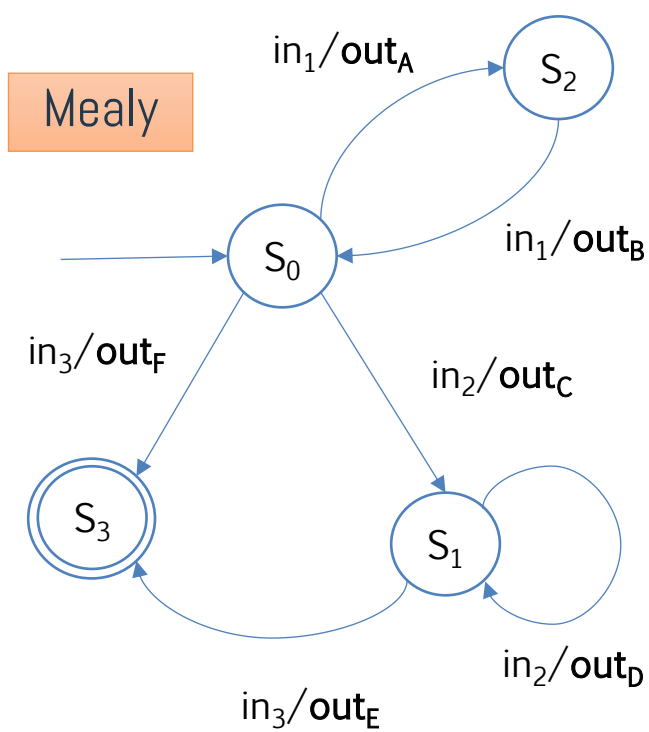
$mfn: S \rightarrow O$ machine/output function

$sfn: I \times S \rightarrow S$ state transition function





What's the difference?



Note: both these machines (Mealy/Moore), have an equivalent machine of the other type, but the two machines here are NOT equivalent!!



What's the difference?

Mathematically equivalent

- › One can be transformed in another

..but..

- › Mealy can potentially have different outs, to different inputs/transitions
 - Less states, if output depends on inputs one can add an edge to the machine
- › Moore potentially keeps the output stable for all the state
 - Moore requires more states, in case out depends on input and not only on state



Exercise

Let's
code!

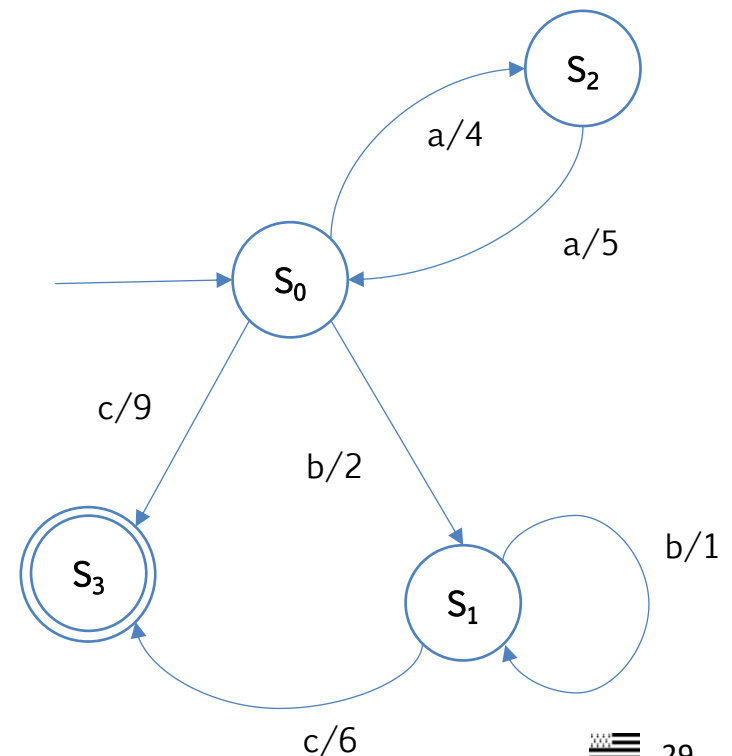
- › Implement the automata that understands whether a words is from L

*"Identify even sequences of a (even empty),
followed by one, or more, or no, b, ended by c"*

- › ..and writes the corresponding number
(I choose them randomly)
- › Mealy? Moore? You choose
 - Here, I show Mealy

Hint

- › If not already done, use tables
for state/output transactions





What else?

Several tools to support the design

- › Matlab Stateflow, UML

Several grammar interpreters to rely the burden of writing FSM code

- › FSF's GNU Bison – Included in GCC
- › YACC – Yet Another Compiler-Compiler



GNU Bison



Converts a context-free grammar into a deterministic LR parser
(but not only) in C

- › Recognizes correct sentences from a grammar
- › <https://www.gnu.org/software/bison/>



Input format: Bison grammar files

```
%{  
    Prologue  
%}  
  
Bison declarations  
  
%%  
Grammar rules  
%%  
  
Epilogue
```



Bison prologue



C-style code that will be appended at the beginning of the generated file

- › Useful for defining macros, includes, headers..
- › `ptypes.h` contains Bison internal data structures: trees, tokens...

```
%{  
    #define _GNU_SOURCE  
    #include <stdio.h>  
    #include "ptypes.h"  
%}  
  
%union {  
    long n;  
    tree t; /* tree is defined in ptypes.h. */  
}  
  
%{  
    static void print_token (yytoken_kind_t token, YYSTYPE val);  
%}
```




Grammar rules



- › Like-BNF syntax
- › Can also include (C) language-specific rules

```
// results => non-terminal;  
// components => any  
result: components...;
```

```
// C statement  
{C statements}
```

```
// Multiple rules  
result:  
    rule1-components...  
| rule2-components...  
...  
;
```

```
// recursive rule  
expseq1:  
    exp  
| expseq1 ',' exp  
;
```



Example - Reverse-polish notation calculator

rpcalc.y

```
input:      /* empty */
           | input line
;

line:       '\n'
           | exp '\n' { printf ("\t%.10g\n", $1); }
;

exp:        NUM          { $$ = $1;          }
           | exp exp '+'  { $$ = $1 + $2;    }
           | exp exp '-'  { $$ = $1 - $2;    }
           | exp exp '*'  { $$ = $1 * $2;    }
           | exp exp '/'  { $$ = $1 / $2;    }
           /* Exponentiation */
           | exp exp '^'  { $$ = pow ($1, $2); }
           /* Unary minus */
           | exp 'n'      { $$ = -$1;        }
;
%%
```



Example - Reverse-polish notation calculator

"A complete input is either an empty string, or a complete input followed by an input line"

rpcalc.y

```
input:      /* empty */
           | input line
;

line:       '\n'
           | exp '\n' { printf ("\t%.10g\n", $1); }
;

exp:        NUM                { $$ = $1; }
           | exp exp '+'       { $$ = $1 + $2; }
           | exp exp '-'       { $$ = $1 - $2; }
           | exp exp '*'       { $$ = $1 * $2; }
           | exp exp '/'       { $$ = $1 / $2; }
           /* Exponentiation */
           | exp exp '^'       { $$ = pow ($1, $2); }
           /* Unary minus */
           | exp 'n'           { $$ = -$1; }
;

%%
```



Example - Reverse-polish notation calculator

rpcalc.y

```
input:      /* empty */
           | input line
;

line:       '\n'
           | exp '\n' { printf ("\t%.10g\n", $1); }
;

exp:        NUM { $1 }
           | exp exp '+' { $1+$2 }
           | exp exp '-' { $1-$2 }
           | exp exp '*' { $1*$2 }
           | exp exp '/' { $1/$2 }
           /* Exponentiation */
           | exp exp '^' { $1^$2 }
           /* Unary minus */
           | exp 'n' { -$1 }
;

%%
```

"Can be either a newline, or an expression followed by a newline"

Also, specifies an **action** that prints this value (exp, indicated by *\$1*)

Note: we use language-specific features and libraries, such as `printf` (in prologue, I included `stdio.h`)



Example - Reverse-polish notation calculator

rpcalc.y

Multi-rules expression ("pure" numbers + six arithm operators)

Actions specify how to translate it in C

- \$\$ => result
- \$1, \$2 => operators
- (remember to `#include math.h` ☺)

```
; }  
  
;  
  
exp:      NUM                { $$ = $1;          }  
      | exp exp '+'          { $$ = $1 + $2;    }  
      | exp exp '-'          { $$ = $1 - $2;    }  
      | exp exp '*'          { $$ = $1 * $2;    }  
      | exp exp '/'          { $$ = $1 / $2;    }  
      /* Exponentiation */  
      | exp exp '^'          { $$ = pow ($1, $2); }  
      /* Unary minus */  
      | exp 'n'              { $$ = -$1;        }  
  
;  
%%
```




Exercise (optional)


Let's
code!

Write a parser for the following grammar using Bison

```
P = {  
  <frase> ::= <soggetto> <verbo> <compl-ogg>  
  <soggetto> ::= <articolo><nome>  
  <articolo> ::= il  
  <nome> ::= gatto | topo | sasso  
  <verbo> ::= mangia | beve  
  <compl-ogg> ::= <articolo> <nome>  
}
```



Event driven Systems





Event driven systems

A system that reacts from external stimula

- › Instantly?
- › Aka: Cyber-Physical Systems (CPS)

Can be

- › Synchronous
- › Asynchronous



Synchronous (Active polling)

- › Infinite loop

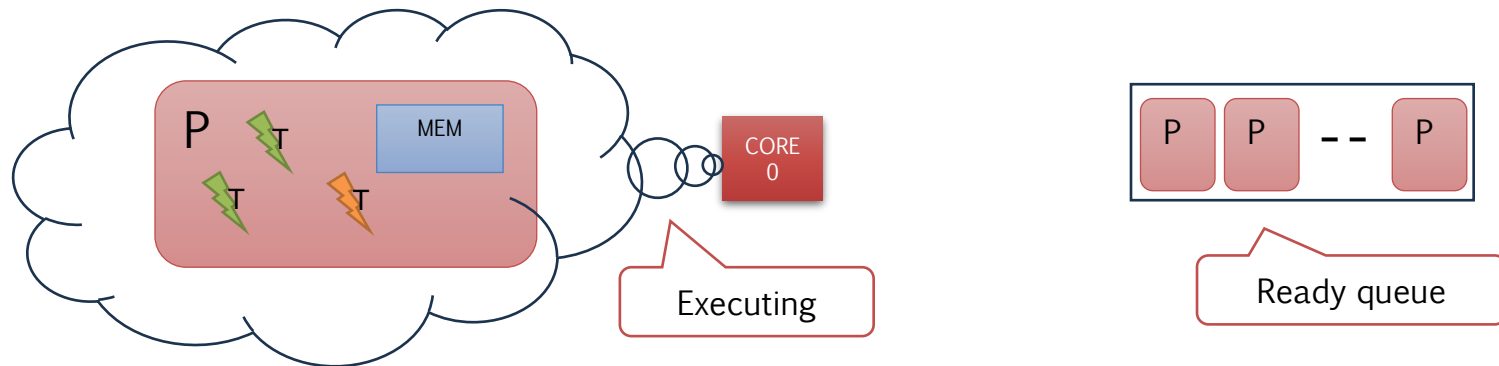
```
char c;  
while (c != EXIT_VALUE)  
    c = readC();  
  
// We can go, now
```

- › **Pros:** extremely fast and reactive
- › **Cons:** waste of resources as one core is busy
 - Possible workaround: insert a sleep

OS scheduling in a nutshell

Modern Operating Systems (OSses) allocate processes to cores

- › Aka: threads, tasks...there is a bit of confusion (we'll clarify this later on)
- › Scheduling theory – Real-Time systems (not covered in this course)
- › So, when a process is running, that core is busy and cannot be used by other cores



...but when is the core released?

- › Can be enforced (whatchdogs, timers...) – **PRO:** prevents starvation | **CON:** drastic event
- › Can be done by the process itself – **PRO:** done exactly when programmers want | **CON:** explicit in code



Yield/sleep: explicit releasing control

Typically, two primitives exposed at the application level. Example in C on GNU/Linux

- › Yield ()
- › sleep (long ms)

```
char c;
while (c != EXIT_VALUE) {
    sleep(3000L); // Deschedule thread/process,
                 // and put it in the READY Q
                 // after 3000 ms

    c = readC();
}
```

```
char c;
while (c != EXIT_VALUE) {
    yield(); // Deschedule thread/process,
            // and put it in the READY Q

    c = readC();
}
```

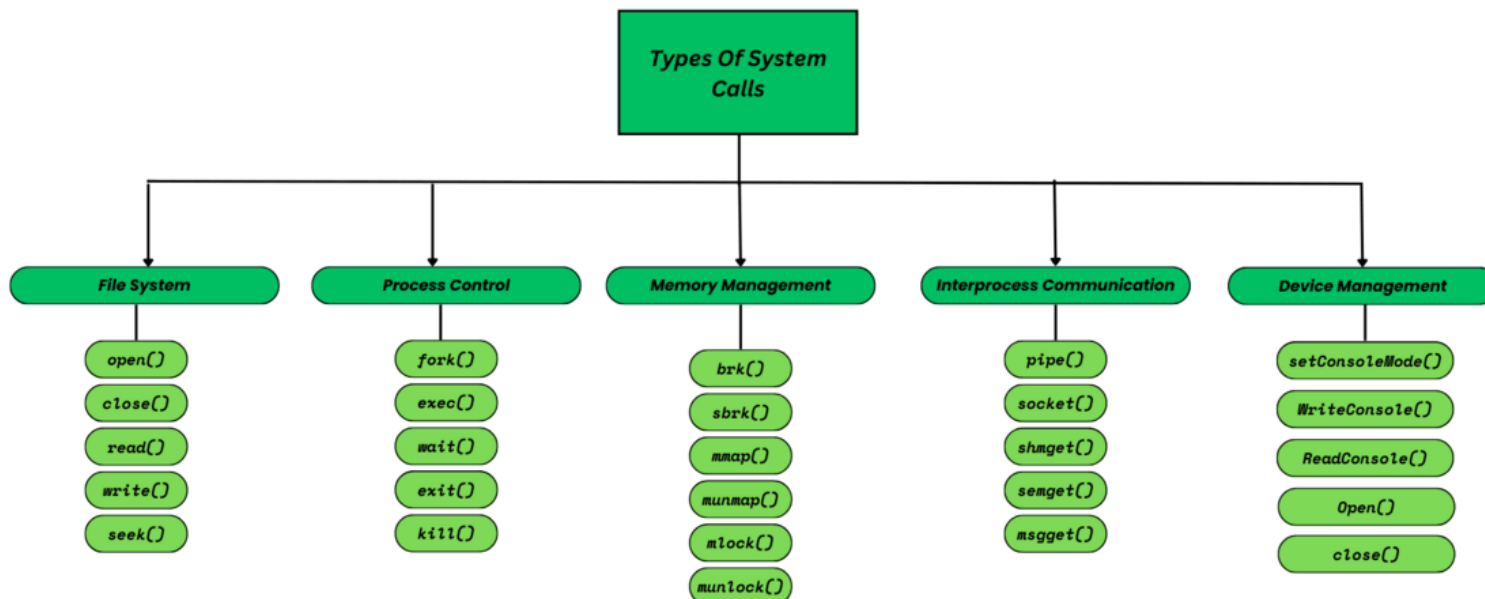


syscalls: “explicitly” releasing control

System calls – Requesting services / help from the OS

- › They are **not** library calls!
- › They might require time / blocking
- › They typically include yield/async waiting

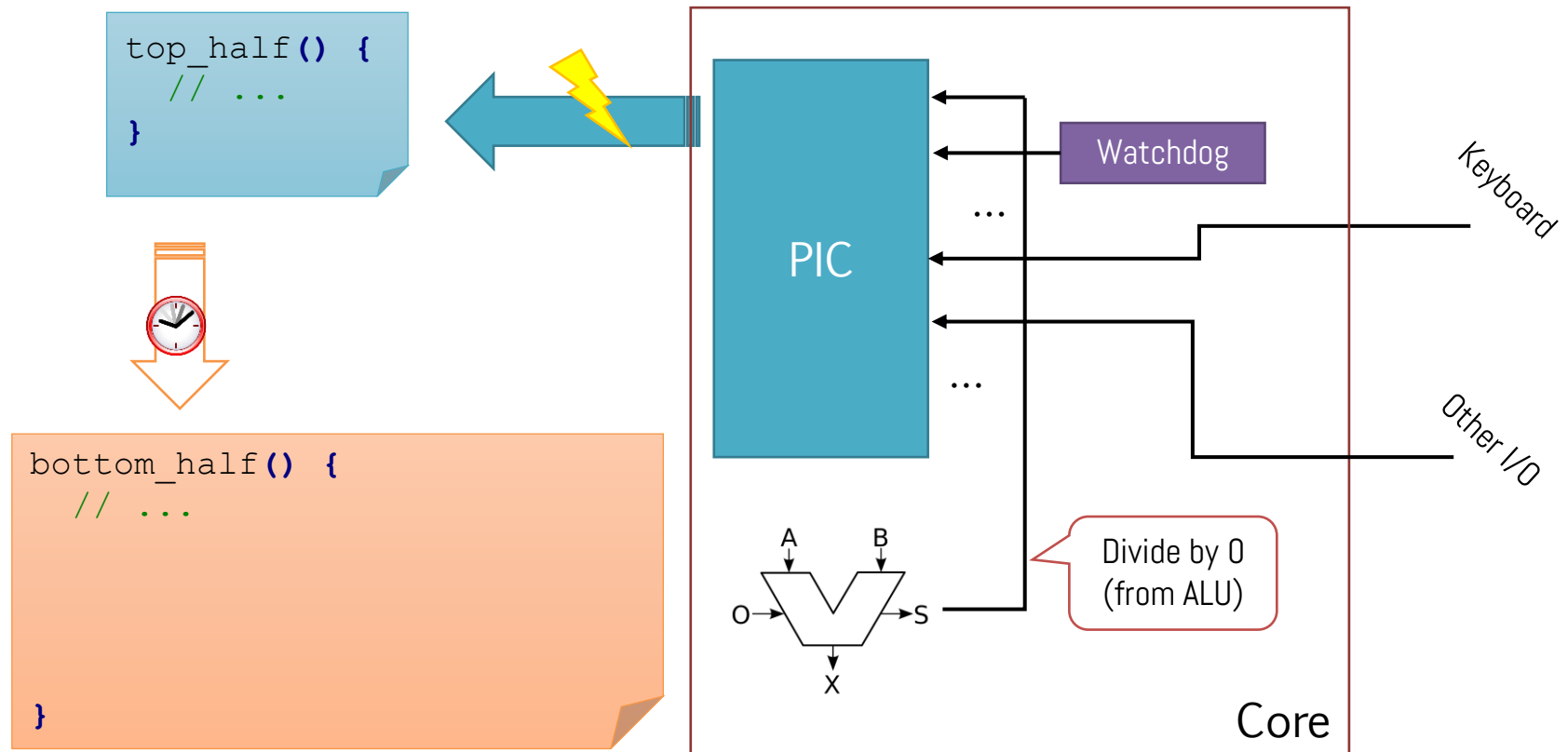
```
FILE *f; // Declare handler (pointer) for file  
  
f = fopen ("fileopen","mode"); // Open file  
  
read (f,"%d", &num); // Read an integer  
  
write (f, 'p'); // Write 'p' on file  
  
fclose (f); // Close file
```





Asynchronous (Interrupt Service Routine)

- › Programmable interrupt controller (hierarchy)



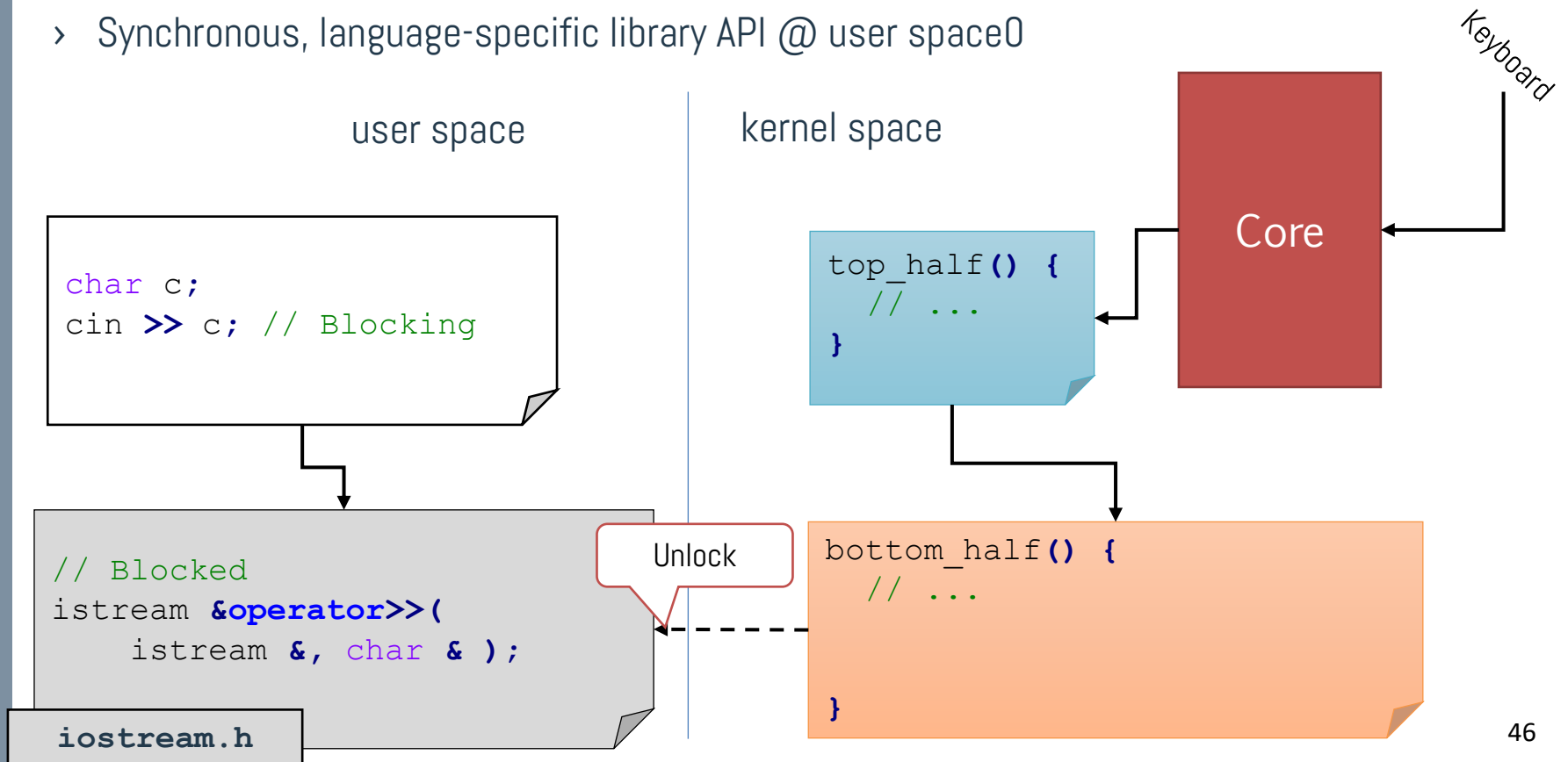
- › **Pros:** "pay-as-you-go"
- › **Cons:** takes more time to issue a ISP



...a mix of the two

Keyboard management in a General-Purpose system

- › GNU/Linux
- › ISP with bottom-half and top-half @ kernel space
- › Synchronous, language-specific library API @ user space0





How to run the examples

Let's
code!

- › Find them in Code/ folder from the course website

For C++: compile

- › `$ gcc code.cpp -o code -Wall -lstdc++`

Run (Unix/Linux)

`$./code`

Run (Win/Cygwin)

`$./code.exe`

References



Course website

- › http://hipert.unimore.it/people/paolob/pub/Industrial_Informatics/index.html

My contacts

- › paolo.burgio@unimore.it
- › <http://hipert.mat.unimore.it/people/paolob/>

Resources

- › Alessandro Fantechi, «Informatica Industriale», Città Studi Edizioni
- › For interrupts
 - Robert Love, «Linux kernel development», Pearson
- › For GNU Bison
 - http://dinosaur.compilertools.net/bison/bison_5.html
- › A "small blog"
 - <http://www.google.com>