The Halting Problems of Network Stack Insecurity

Original paper[1] by Len Sassaman, Meredith L. Patterson, Sergey Bratus and Anna Shubina

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University of Birmingham - School of Computer Science
Tom Chothia's Internet Security Seminar module

15 March 2013

[1] ;login: The USENIX Magazine, vol. 36, no. 6, December 2011 https://www.usenix.org/publications/login/december-2011-volume-36-number-6/halting-problems-network-stack-insecurity

Before we start

These slides can be downloaded at the following address:

http://r.rogdham.net/17

The full description of the images (including authors and license) is available at the end of this presentation. Indeed, in most of the cases, putting the description next to the image would be given the answer to the questions I may ask during the presentation.

Agenda

1. Language theory in a nutshell
2. Model of the network stack... getting weird
3. Principles of secure design
4. Conclusion

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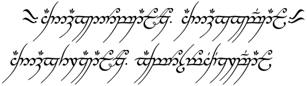
What is a language?

Natural languages

- English
- Sign languages

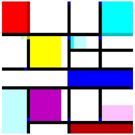
Constructed languages

- Esperanto
- Tolkien's Elvish languages



Programming languages

- C, Python, Java, Haskell, Piet



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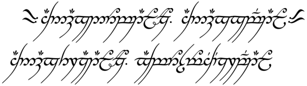

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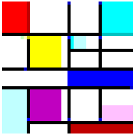

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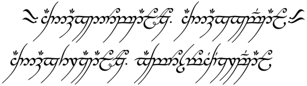

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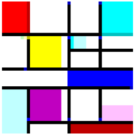

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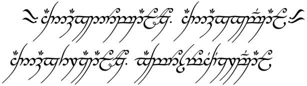

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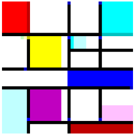

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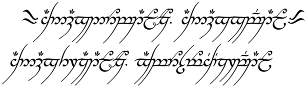

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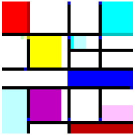

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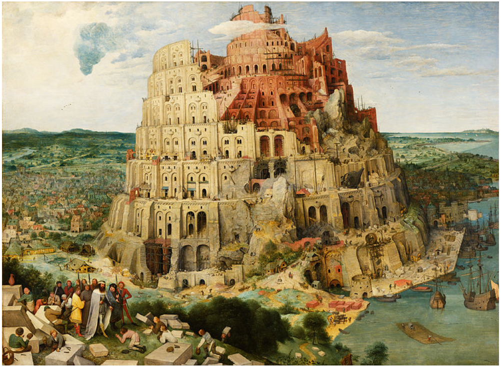

Dialects

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- ANSI C: C89. . . C11

Ambiguities

- “not bad”
- “ice cream” / “I scream”

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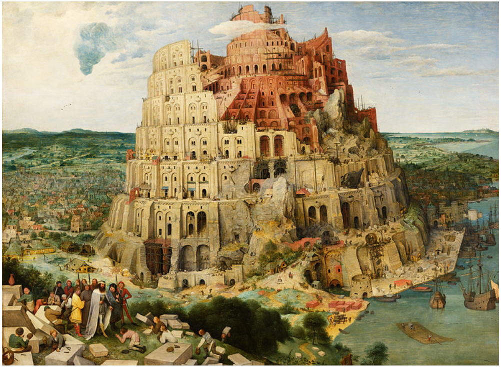

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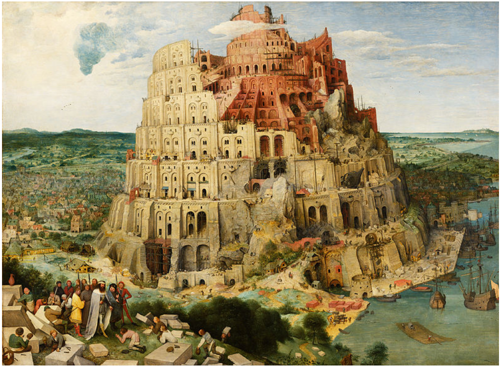

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Moving to language theory

We need a formal description of a language (read “mathematics”).

And then tools to work on languages:

- recogniser
  - does a word belong to a language?
  - this is an equivalent way to describe a language
- parsers
  - analysing a word of the language, extracting some meaning
  - usually easy once you have the recogniser

Any example of recogniser or parser?

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Any example of recogniser or parser?

Recognizer and parser example: email addresses

Recogniser: REGEX

```
if(preg_match(
        '/^[a-z0-9_.-]+@[a-z0-9.-]+\.[a-z0-9-]{2,4}$/',
        $email)) {
    echo 'Valid email address.';
}
```

Parser: just add capturing groups!

```
m = re.match(
    r'^(?P<user>[a-z0-9_.-]+)@'
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if m and m.group('domain') == 'bham.ac.uk':
    print 'Hello, %s!' % m.group('user')
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Note: over-simplified REGEX here, do not use it in real life!

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Some formalism

Definition (Alphabet)

An *alphabet* is a finite set Σ of symbols.

Definition (Word)

A *word* is a finite sequence α of symbols over an alphabet Σ ($\alpha \in \Sigma^*$).

A word can contain spaces!
Notation for the empty word: ϵ.

Definition (Language)

A *language* is a set L of words over an alphabet Σ (i.e. $L \subseteq \Sigma^*$).

A language can contain an infinite number of words (e.g. Σ^*).

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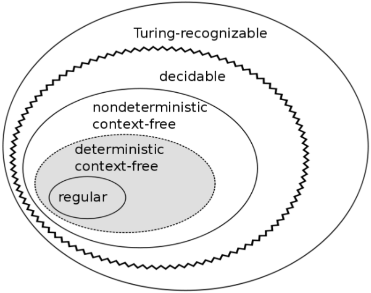

Chomsky hierarchy

Classes of languages

- Regular to recursively enumerable
- How easy it is to recognise a word
- How expressive you can be
- This paper: how secure your application would be

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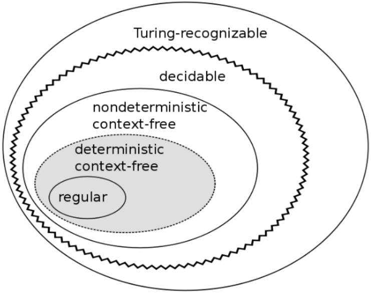

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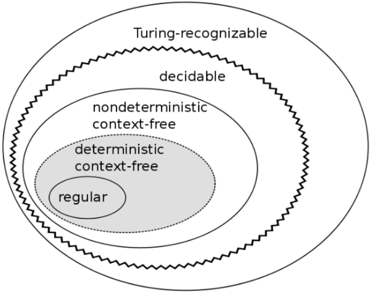

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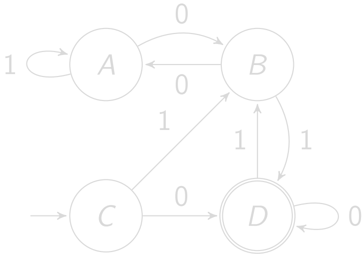
Regular

Summary:

- REGEX
- (Deterministic) finite state automaton

Example:

- multiples of 3 written in binary
- REGEX: `/^(0|(1(01*0)*1))+$/`
- DFSA:



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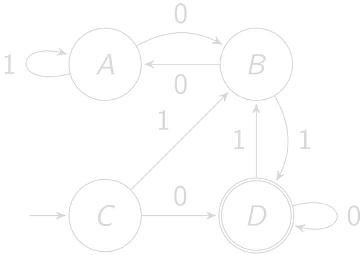

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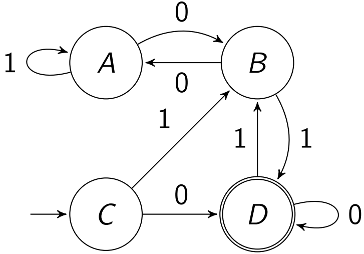
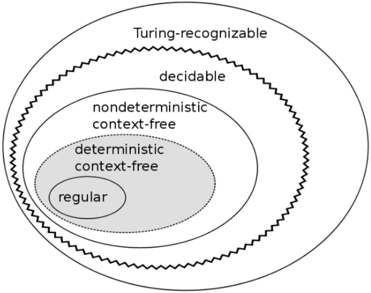


Limit of regular languages



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Many languages are not regular

- $L = \{\alpha^n\beta^n | n \in \mathbb{N}\}$
- *Do you think HTML is regular?*

We have other categories of languages!

- need more *context*

I will go directly to recursively enumerable languages.

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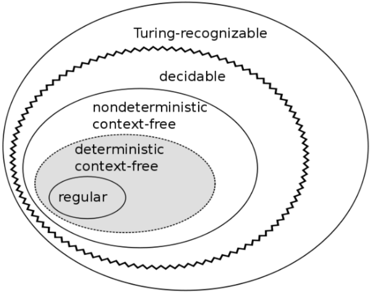

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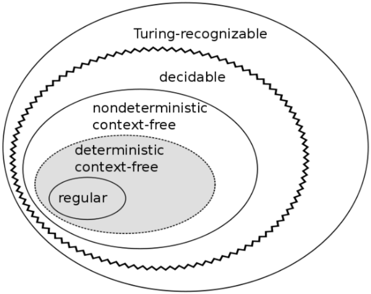

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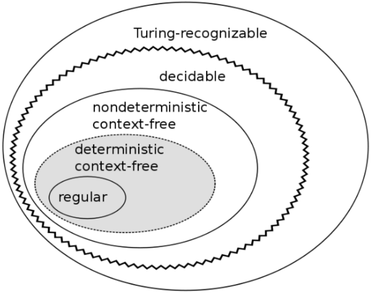

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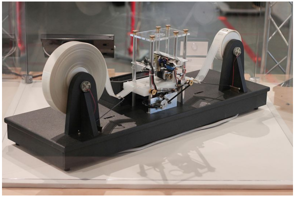
Recursively enumerable languages

Turing machine

- very simple computer; but infinite storage
- tape, head, state register, action table



Recursively enumerable languages

- there exists a Turing machine, which, given a word, will
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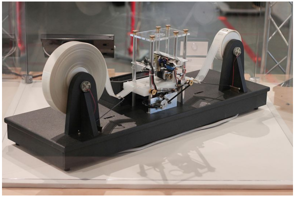

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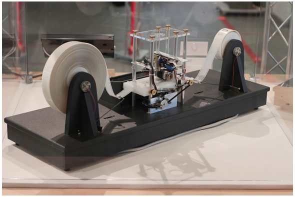

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Halting problem

YOU ARE NOW INSIDE A MATHEMATICAL SINGULARITY WHERE INFINITY ENDS.
WOW. REALLY?
HERE, THE KOCH SNOWFLAKE IS EVERYWHERE DIFFERENTIABLE, THERE IS NO HALTING PROBLEM, AND AMERICANS HAVE ADOPTED THE METRIC SYSTEM.
YOU'RE KIDDING!
THIS PLACE IS AMAZING.

Given a Turing machine and an input, tell if the machine will eventually halt if run with that input

- undecidable
- basically, you have no choice but to run the machine
  - wait some time
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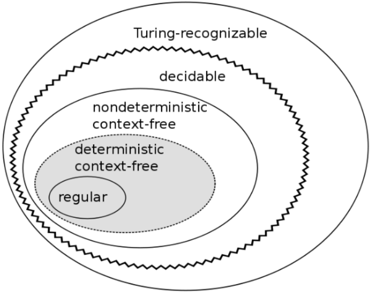


Chomsky hierarchy

Each class of language is included in the next one

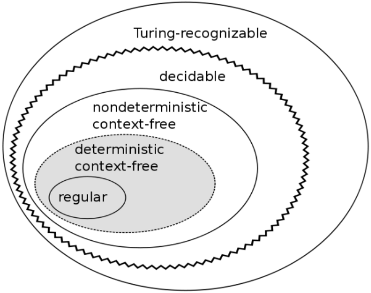
- can handle new languages
- needs more computational power

Grey region: equivalence between two machines is decidable

For each class of language there is a machine which required just the computational power needed

Which one would be more useful to an attacker?

Chomsky hierarchy again



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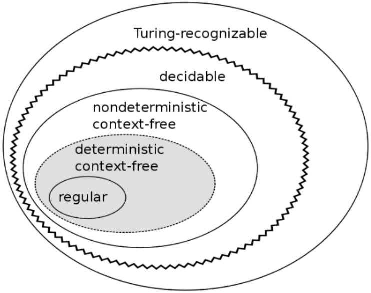

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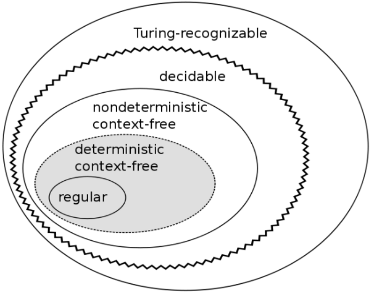

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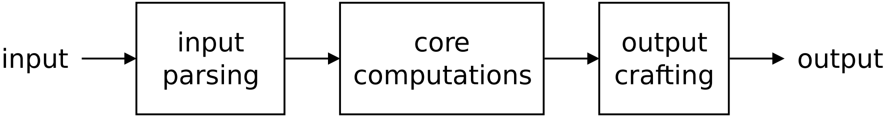
Model of a program



What does a program do?

- take some input
- parse it
- do some computation
- create the output
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This model includes:

- application inputs
- network stack inputs
- mono-block applications
- multi-blocks applications

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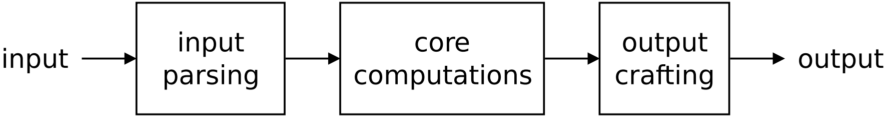

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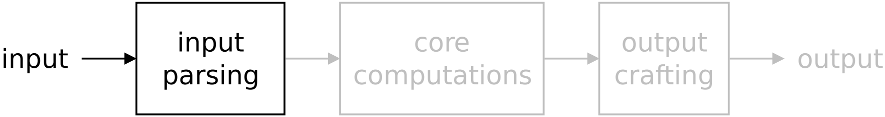
Input parsing matters



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- does not covers all security problems
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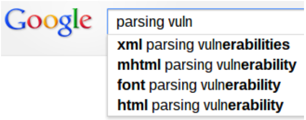

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xml parsing vuln**erabilities**
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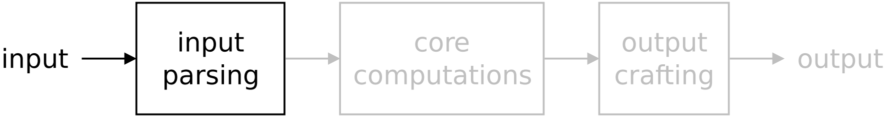

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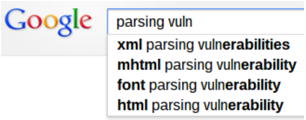
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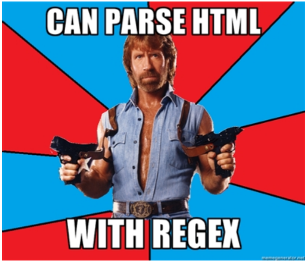
In the real world

How input parsing is done in the real world?



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- handwritten recognisers
  - faulty
- usually REGEX
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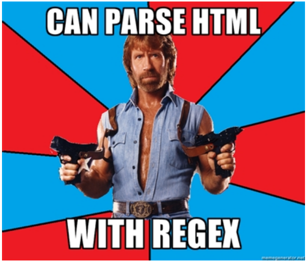
Are open standards helping?

In the real world



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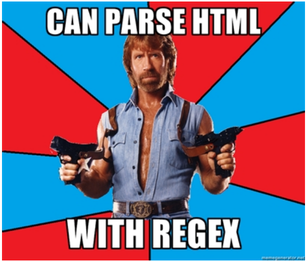

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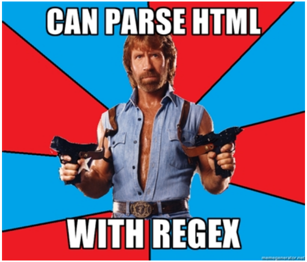

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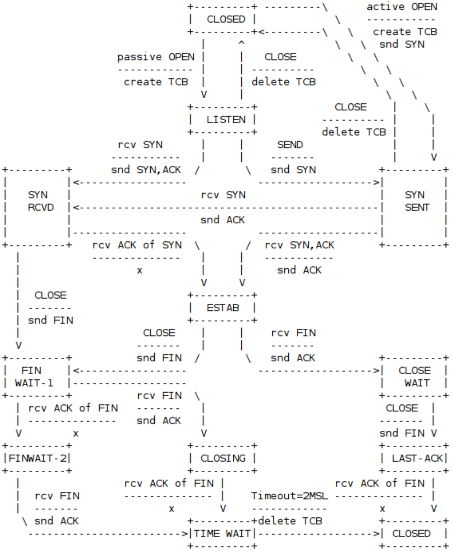
RFC 793: TCP



```
                              +---------+ ---------\      active OPEN
                              |  CLOSED |            \    -----------
                              +---------+<---------\   \   create TCB
                                |     ^              \   \  snd SYN
                   passive OPEN |     |   CLOSE        \   \
                   ------------ |     | ----------       \   \
                    create TCB  |     | delete TCB         \   \
                                V     |                      \   \
                              +---------+            CLOSE    |    \
                              |  LISTEN |          ---------- |     |
                              +---------+          delete TCB |     |
                   rcv SYN      |     |     SEND              |     |
                  -----------   |     |    -------            |     V
 +---------+      snd SYN,ACK  /       \   snd SYN          +---------+
 |         |<-----------------           ------------------>|         |
 |   SYN   |                    rcv SYN                     |   SYN   |
 |   RCVD  |<-----------------------------------------------|   SENT  |
 |         |                    snd ACK                     |         |
 |         |------------------           -------------------|         |
 +---------+   rcv ACK of SYN  \       /  rcv SYN,ACK       +---------+
   |           --------------   |     |   -----------
   |                  x         |     |     snd ACK
   |                            V     V
   |  CLOSE                   +---------+
   | -------                  |  ESTAB  |
   | snd FIN                  +---------+
   |                   CLOSE    |     |    rcv FIN
   V                  -------   |     |    -------
 +---------+          snd FIN  /       \   snd ACK          +---------+
 |  FIN    |<-----------------           ------------------>|  CLOSE  |
 | WAIT-1  |------------------                              |   WAIT  |
 +---------+          rcv FIN  \                            +---------+
   | rcv ACK of FIN   -------   |                            CLOSE  |
   | --------------   snd ACK   |                           ------- |
   V        x                   V                           snd FIN V
 +---------+                  +---------+                   +---------+
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 +---------+                  +---------+                   +---------+
   |                rcv ACK of FIN |                 rcv ACK of FIN |
   |  rcv FIN       -------------- |    Timeout=2MSL -------------- |
   |  -------              x       V    ------------        x       V
    \ snd ACK                 +---------+delete TCB         +---------+
     ------------------------>|TIME WAIT|------------------>| CLOSED  |
                              +---------+                   +---------+
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TCP Connection State Diagram

"NOTE BENE: this diagram is only a summary and must not be taken as the total specification."

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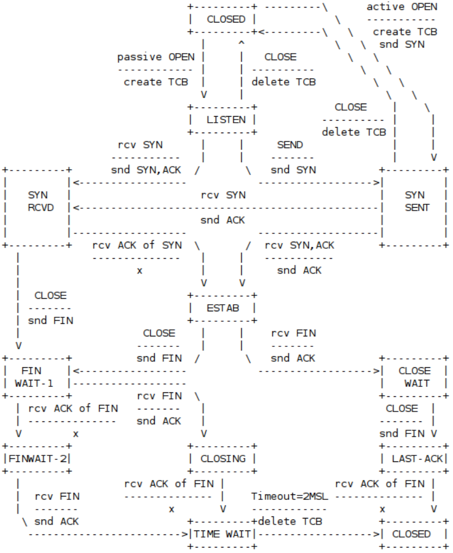

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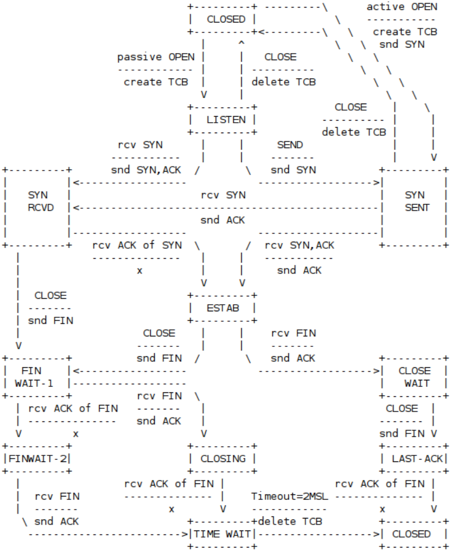

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What if... we don't use them?

$ man 7 tcp

Linux uses the BSD compatible interpretation of the urgent pointer field by default. **This violates RFC 1122**, but is required for interoperability with other stacks. It can be changed via /proc/sys/net/ipv4/tcp_stdurg.

So what do we have?

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- detect differences in implementations (dialects)
- xprobe, nmap...

Real exploits

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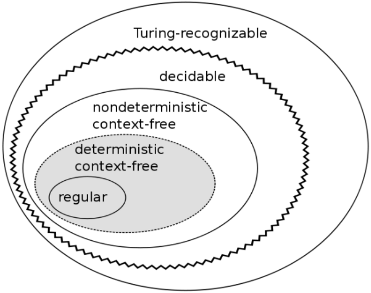

Chomsky hierarchy

Pick different parsers of the same protocol

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Outside the grey area, automaton equivalence is undecidable

- but we can still find differences!

Result

- they found *clusters* of 0 days
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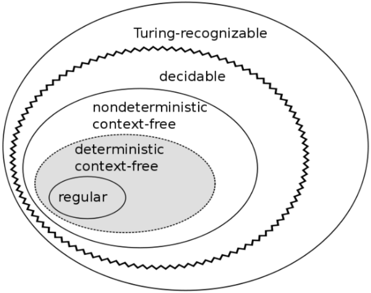

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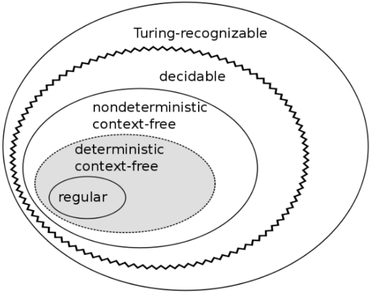

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Example: exploit on X.509 parsing (2009)

Craft a certificate with

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CN=www.mywebsite.com/CN=www.bank.com/CN=*
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OpenSSL parser was only considering `www.mywebsite.com`

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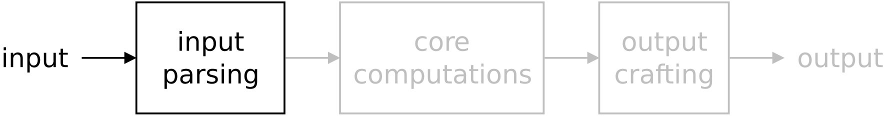

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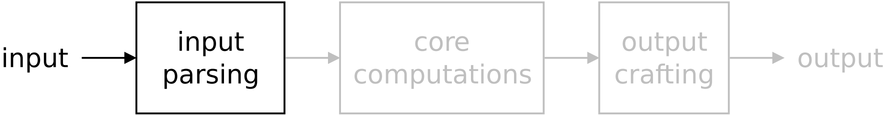

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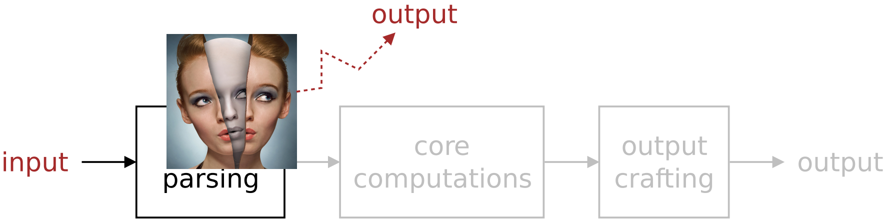

output

input

parsing

core computations

output crafting

output

Formalising:

- using an unexpected language having side-effects
- exploiting the *weird machine*

You have already done that. . . Particularly true for the following:

- (blind) SQL injection
- ROP!!!

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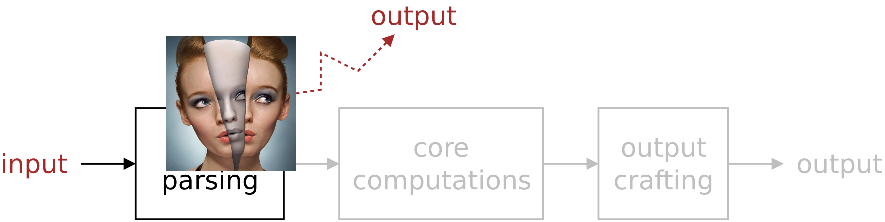

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Don't give to the parser more computational power than needed

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Obviously, only works if the parser does not need to be Turing-complete...

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Agenda

1. Language theory in a nutshell
2. Model of the network stack. . . getting weird
3. Principles of secure design
4. Conclusion

Principles of secure design

Definition (Principle 1)

Request and grant minimal computational power

Definition (Principle 2)

Secure composition requires parser computational equivalence

Ok, what does that mean?

What are you supposed to do:

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- create the parser automatically from the BNF of the protocol (if any)
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How much power does your protocol really needs?

- do you really needs those length fields?
  - would make your protocol at least context-sensitive
  - could you use S-expressions instead? (context-free)

Avoid the halting problem of network stack insecurity

- don't create recursively enumerable protocols
- otherwise parsing is undecidable

It's easy to give too much computational power

- PDFs have build-in JS support
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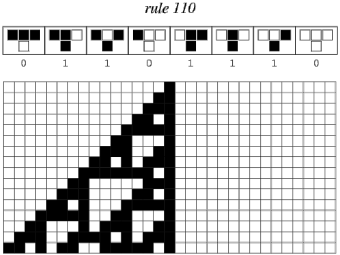

What is Rule 110?

- you have a infinite array filled with 0s and 1s
- at each iteration, change each cell n depending on the values of cells $(n-1,\ n,\ n+1)$ of the previous iteration
- is Turing-complete

Implementation of Rule 110 in HTML + CSS3

- needs some basic interaction from the user
- is obviously not working on infinite arrays
- so HTML + CSS3 is almost Turing-complete
- https://github.com/elitheeli/stupid-machines/blob/master/rule110/rule110-full.html

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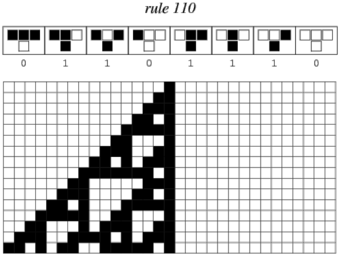


What is Rule 110?

- you have a infinite array filled with 0s and 1s
- at each iteration, change each cell *n* depending on the values of cells $(n-1,\ n,\ n+1)$ of the previous iteration
- is Turing-complete

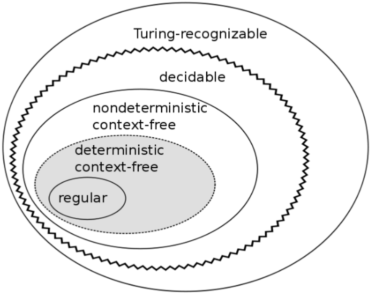
Implementation of Rule 110 in HTML + CSS3

- needs some basic interaction from the user
- is obviously not working on infinite arrays
- so HTML + CSS3 is almost Turing-complete
- https://github.com/elitheeli/stupid-machines/blob/master/rule110/rule110-full.html

Principle 2 of secure design for protocol design

Definition (Principle 2)

Secure composition requires parser computational equivalence



Chomsky hierarchy

Parser equivalence is only possible to check for the grey categories

- see principle 1

Create BNF of your protocol

- so that implementations can use them
- and checking computational equivalence is easier

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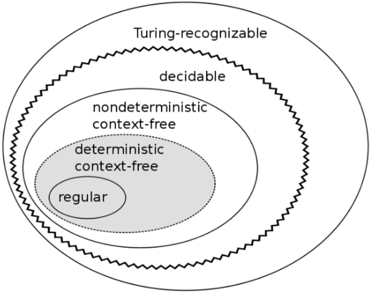

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About Postel's law

Definition (Postel's law (or robustness principle), from RFC 793)

Be conservative in what you do, be liberal in what you accept from others.

- Trade security for laziness
- Goes against principle 2 (no equivalence between parsers)
- It's even easier to use a very strict input parser, if we have the corresponding BNF

Was from 1981... maybe it's time to patch it?

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The Postel's law patch

```
--- ietf/postels-principle
+++ ietf/postels-principle
- Be liberal about what you accept.
+ Be definite about what you accept.(*)
+
+ Treat inputs as a language, accept it with a matching computational
+ power, generate its recognizer from its grammar.
+
+ Treat input-handling computational power as privilege, and reduce it
+ whenever possible.
+
+
+ (*) For the sake of your users, be definite about what you accept.
+ Being liberal worked best for simpler protocols and languages,
+ and is in fact limited to such languages; be sure to keep your
+ language regular or at most context free (no length fields).
+ Being more liberal did not work so well for early IPv4 stacks:
+ they were initially vulnerable to weak packet parser attacks, and
+ ended up eliminating many options and features from normal use.
+ Furthermore, presence of these options in traffic came to be regarded
+ as a sign of suspicious or malicious activities, to be mitigated by
+ traffic normalization or outright rejection. At current protocol
+ complexities, being liberal actually means exposing the users of your
+ software to intractable or malicious computations.
```

http://www.cs.dartmouth.edu/∼sergey/langsec/postel-principle-patch.txt

Agenda

1 Language theory in a nutshell

2 Model of the network stack… getting weird

3 Principles of secure design

4 Conclusion

What have we done so far

Formalise network stack

- (partial) explanation of fingerprinting
- method to find 0 days (parse tree differential analysis)

Principles of secure design

- for protocol designs
- for parser implementations
- let's just walk through them again

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Principles of secure design

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- for parser implementations

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Principle 0: full recognition before processing

Principle 1: minimal computational power

Principle 2: parser computational equivalence

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Q&A time!