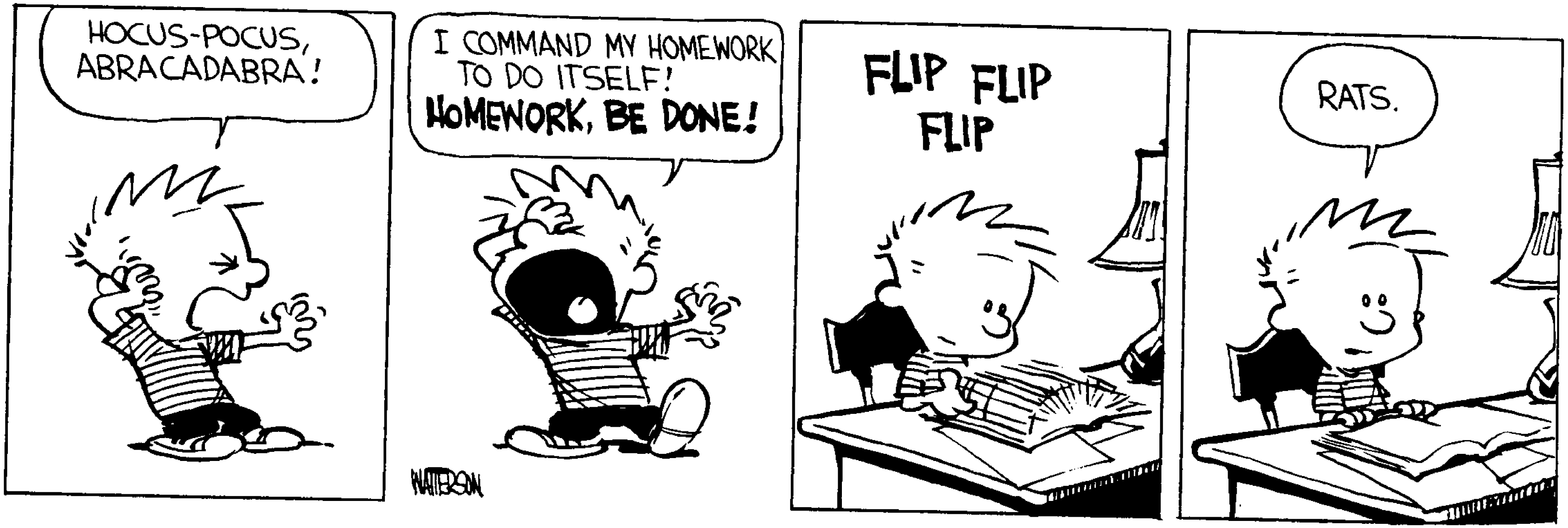
Lexical Analysis

Finite Automata

(Part 1 of 2)


HOCUS-POCUS, ABRACADABRA!
I COMMAND MY HOMEWORK TO DO ITSELF! HOMEWORK, BE DONE!
FLIP FLIP FLIP
RATS.
WATTERSON

Cunning Plan

- Informal Sketch of Lexical Analysis
  - LA identifies tokens from input string
  - lexer : (char list) → (token list)
- Issues in Lexical Analysis
  - Lookahead
  - Ambiguity
- Specifying Lexers
  - Regular Expressions
  - Examples

One-Slide Summary

- **Lexical analysis** turns a stream of characters into a stream of tokens.
- **Regular expressions** are a way to specify sets of strings. We use them to describe tokens.

Fold Batter Lightly …

- fold_left f a [1;…;n] == f (… (f (f a 1) 2)) n

```
fold_left (fun a e -> e :: a) [] [1;2;3]      = [3;2;1]
fold_left (fun a e -> a @ [e]) [] [1;2;3]     = [1;2;3]
```

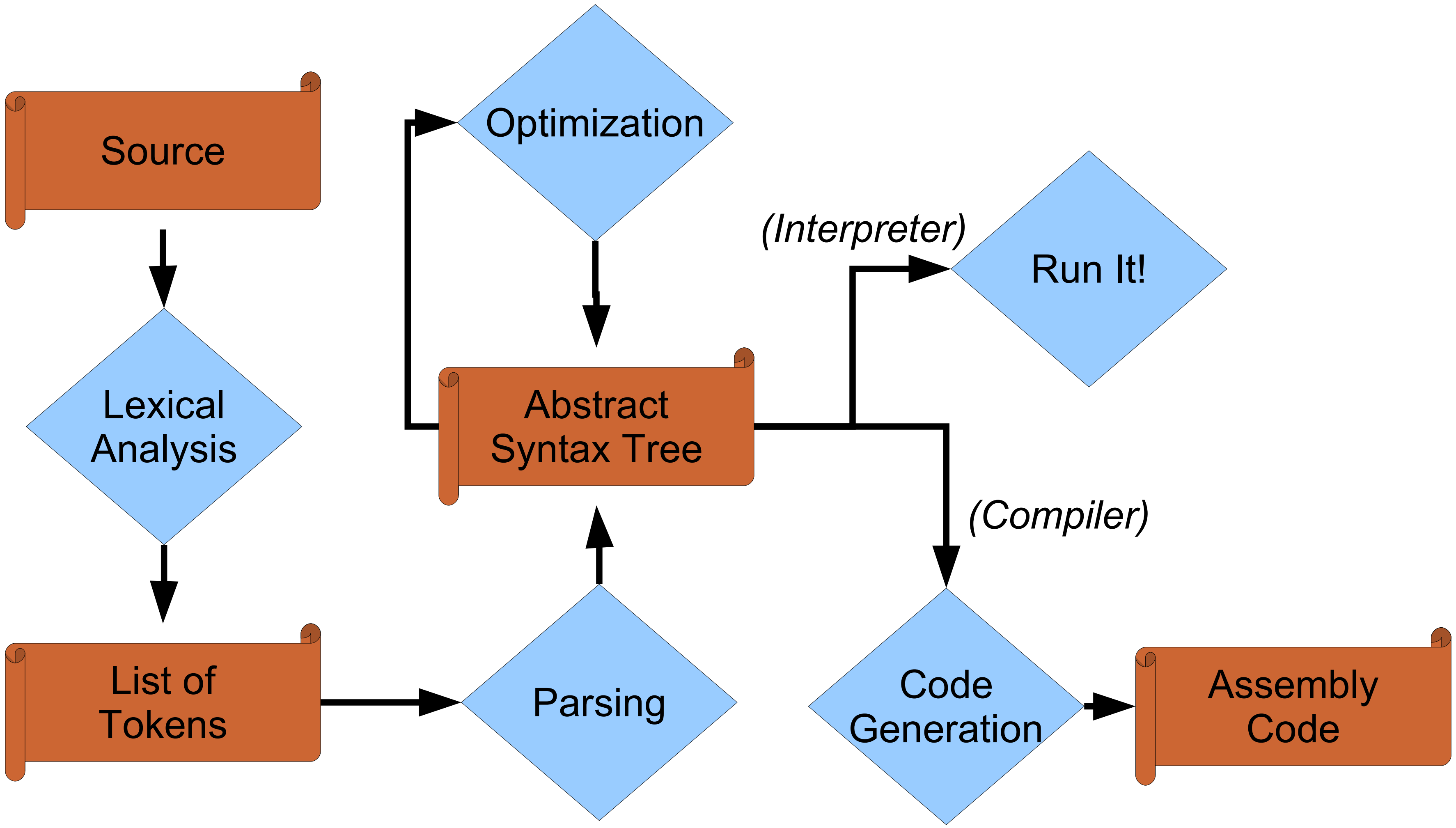
- fold_right f [1;…;n] b == f 1 (f 2 (… (f n b)))

```
fold_right (fun a e -> e :: a) [1;2;3] []     = [1;2;3]
fold_right (fun e a -> a @ [e]) [1;2;3] []    = [3;2;1]
```

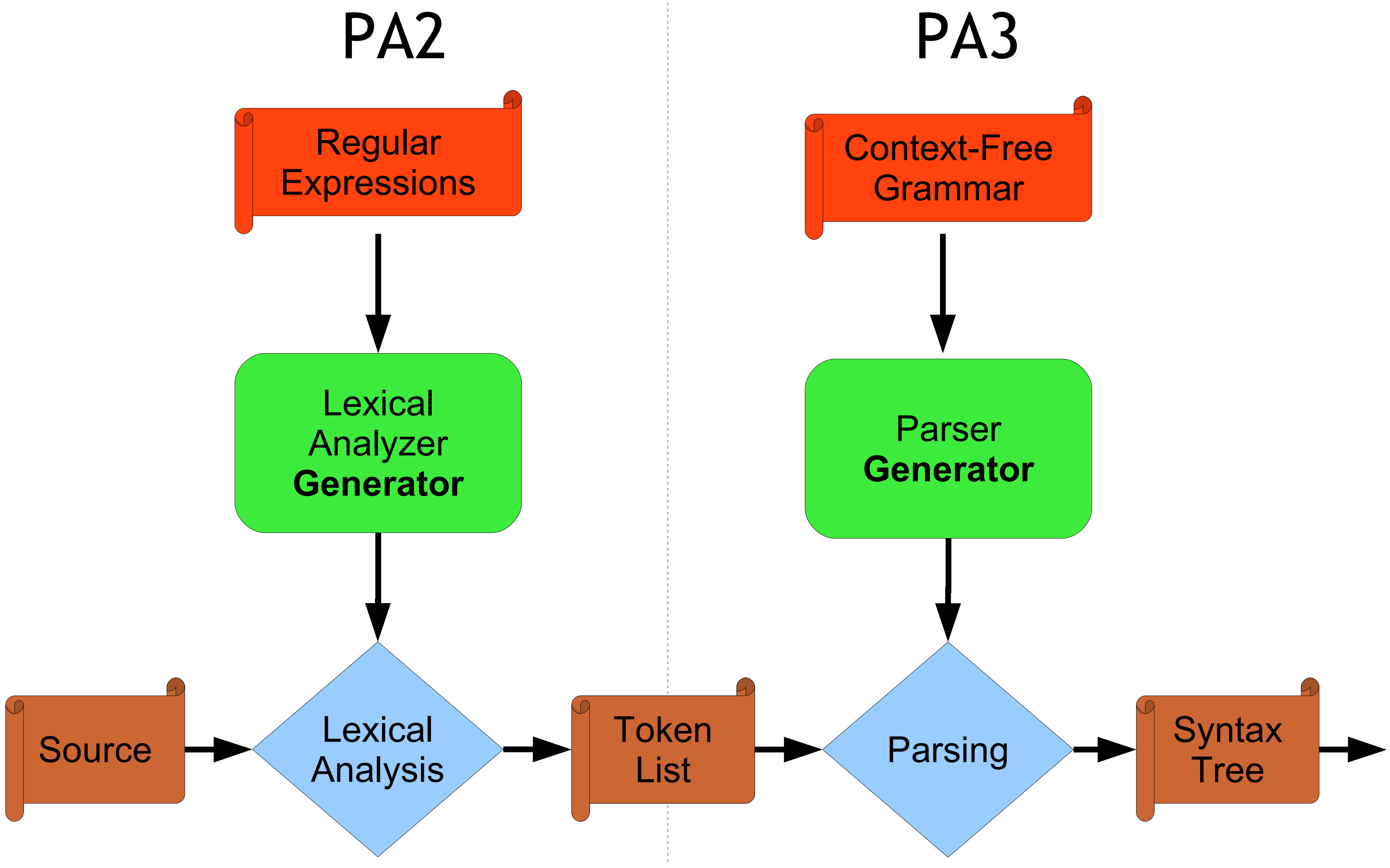
Internet Explorer
Question of the day: Which technological invention do you think has impacted our lives more - the telephone or the internet?
about a minute ago · Like · Comment

Billy [redacted] You know you can post Polls on facebook now, right? IE, Always a little behind the times.
2 seconds ago · Like

Interpreter and Compiler Structure



Detail: Modern Reality



Lexical Analysis

- What do we want to do? Example:

```
if (i == j)
  z = 0;
else
  z = 1;
```

- The input is just a sequence of characters:

```
if (i == j)\n\tz = 0;\nelse\n\tz = 1;
```

- Goal: partition input strings into substrings
  - And classify them according to their role

What's a Token?

- Output of lexical analysis is a list of tokens
- A **token** is a syntactic category
  - In English:
    - noun, verb, adjective, …
  - In a programming language:
    - Identifier, Integer, Keyword, Whitespace, …
- Parser relies on token distinctions:
  - e.g., identifiers are treated differently than keywords

Tokens

- Tokens correspond to **sets of strings**.

- **Identifier**: strings of letters or digits, starting with a letter
- **Integer**: a non-empty string of digits
- **Keyword**: “else” or “if” or “begin” or …
- **Whitespace**: a non-empty sequence of blanks, newlines, and/or tabs
- **OpenPar**: a left-parenthesis

Lexical Analyzer: Build It!

- An implementation must do two things:
- Recognize substrings corresponding to tokens
- Return the value or lexeme of the token
  - The lexeme is the substring

[redacted]
What have I done... :/
9 minutes ago via Mobile · Like · Comment

[redacted] made a facebook status
6 minutes ago · Like · 2 people

[redacted] Honestly shut up!
5 minutes ago · Like · 1 person

Example

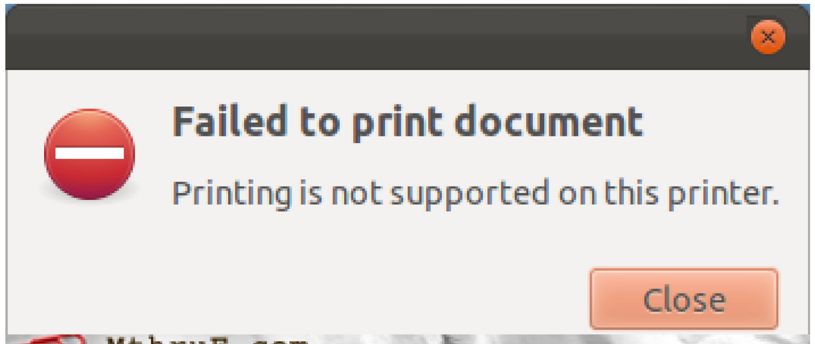
- Recall:

```
if (i == j)\n\tz = 0;\nelse\n\tz = 1;
```

- Token-lexeme pairs returned by the lexer:
  - <Keyword, “if”>
  - <Whitespace, “ ”>
  - <OpenPar, “(”>
  - <Identifier, “i”>
  - <Whitespace, “ ”>
  - <Relation, “==”>
  - <Whitespace, “ ”>
  - …

Lexical Analyzer: Implementation

- The lexer usually *discards* “uninteresting” tokens that don't contribute to parsing.
- Examples: Whitespace, Comments
  - Exception: which language cares about whitespace?
- Question: What happens if we remove all whitespace and comments *prior* to lexing?



Failed to print document

Printing is not supported on this printer.

Lookahead

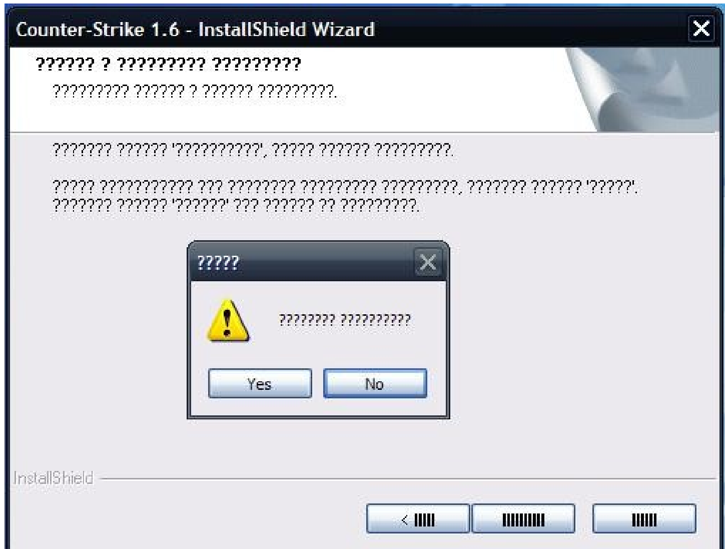
- The goal is to partition the string. That is implemented by reading left-to-right, recognizing one token at a time.
- **Lookahead** may be required to decide where one token ends and the next token begins
  - Even our simple example has lookahead issues
  - **i** vs. **if**
  - **=** vs. **==**

Still Needed

- A way to describe the lexemes of each token
  - Recall: lexeme = "the substring corresponding to the token"
- A way to resolve ambiguities
  - Is **if** two variables **i** and **f**?
  - Is **==** two equal signs **= =**?

Languages

- **Definition.** Let Σ be a set of characters. A language over Σ is a set of strings of characters drawn from Σ. Σ is called the alphabet.


Counter-Strike 1.6 - InstallShield Wizard

?????? ? ????????? ?????????

????????? ?????? ? ?????? ?????????.

??????? ?????? '??????????', ????? ?????? ?????????.

????? ??????????? ??? ???????? ????????? ?????????, ??????? ?????? '?????'. ??????? ?????? '??????' ??? ?????? ?? ?????????.

?????

???????? ?????????

Examples of Languages

- Alphabet = English Characters
- Language = English Sentences
  - Note: *Not* every string of English characters is an English sentence.
  - Example: xayenb sbe'
- Alphabet = ASCII characters
- Language = C Programs
  - Note: ASCII character set is different from English character set.

Notation

- **Languages** are sets of strings
- We need some notation for specifying which sets we want
  - that is, which strings are in the set
- For lexical analysis we care about *regular languages*, which can be described using *regular expressions*.

Regular Expressions

- Each **regular expression** is a notation for a regular language (a set of words)
  - You'll see the exact notation in minute!

- If **A** is a regular expression then we write **L(A)** to refer to the language denoted by **A**

Error Retrieving values in VB App.
Either you didn't enter the data properly, or the developer for this screwed up royally. I'm leaning towards 'A'.

Base Regular Expression

- Single character: 'c'
  - L('c') = { “c” }   (for any $c \in \Sigma$)
- Concatenation: AB
  - A and B are other regular expressions
  - L(AB) = { ab | a ∈ L(A) and b ∈ L(B) }
- Example: L('i' 'f') = { “if” }
  - We abbreviate 'i' 'f' as 'if'

Compound Regular Expressions

- Union
  - L(A | B) = { s | s ∈ L(A) or s ∈ L(B) }

- Examples:
  - L('if' | 'then' | 'else') = { "if", "then", "else" }
  - L('0'|'1'|'2'|'3'|'4'|'5'|'6'|'7'|'8'|'9') = *what?*
- Fun Example:
  - L(('0'|'1') ('0'|'1')) = {"00","01","10","11"}

Starz!

- So far we have only finite languages
- Iteration: A*
  - L(A*) = {“”} ∪ L(A) ∪ L(AA) ∪ L(AAA) …
- Examples:
  - L('0'*) = {“”, “0”, “00”, “000”, “0000”, … }
  - L('1''0'*) = {“1”, “10”, “100”, “1000”, …}
- Empty: ε
  - L(ε) = { “” }

Microsoft
Search Microsoft.com for:
Go
Help and Support
Help and Support Home | Select a Product | Advanced Search

Error Message: Your Password Must Be at Least 18770 Characters and Cannot Repeat Any of Your Previous 30689 Passwords

Q: Advertising (810 / 842)

- The United States Forest Service's ursine mascot first appeared in 1944. Give his catch-phrase safety message.

Natural Languages

- These languages, of which there are about 250, are often mutually intelligible and constitute a major branch of the Niger-Congo languages. They are spoken largely in central, east and southern Africa. Popular examples include Swahili, with 80 million speakers, Shona, with 11 million, and Zulu, with 10 million. They commonly use words such as *muntu* or *mutu* for “person”. Words such as bongos, chimpanzee, gumbo, jumbo, mambo, rumba and safari come from these languages.

Q: Music (150 / 842)

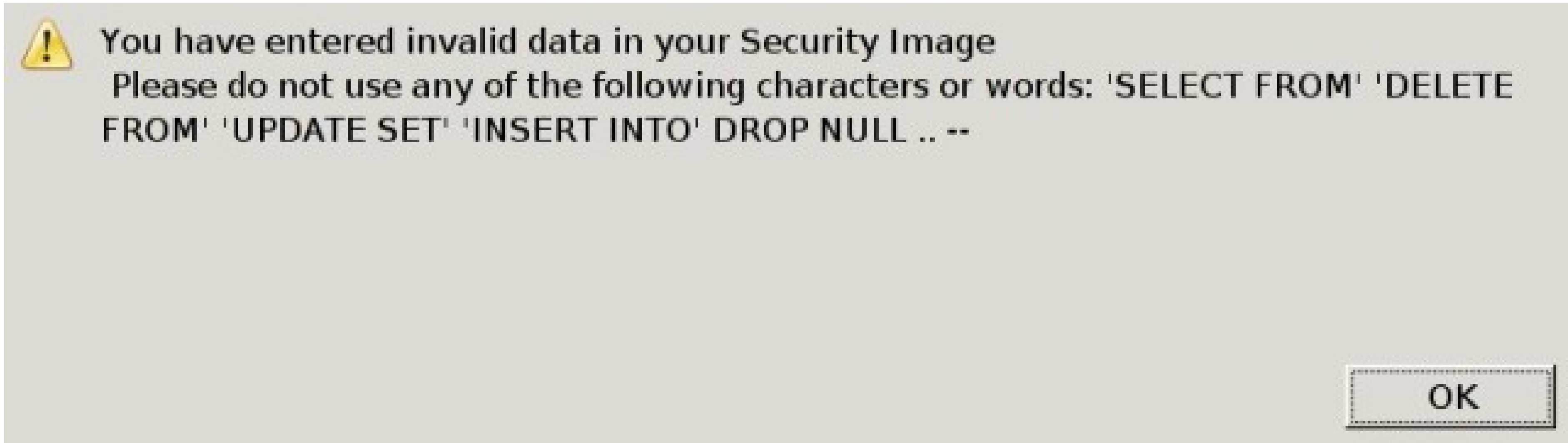
- In this 1958 Sheb Wooley song the pigeon-toed title character wears short shorts and wants to get a job in a rock'n'roll band playing the horn, but is perhaps best known for his skin tone and non-standard diet.

Example: Keyword

- Keyword: “else” or “if” or “begin” or …

'else' | 'if' | 'begin' | …

(Recall: 'else' abbreviates 'e' 'l' 's' 'e')



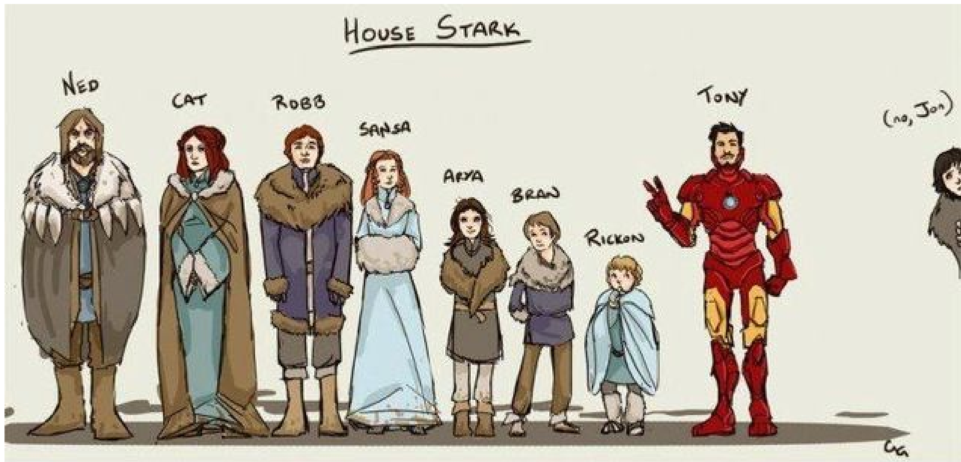
You have entered invalid data in your Security Image
Please do not use any of the following characters or words: 'SELECT FROM' 'DELETE FROM' 'UPDATE SET' 'INSERT INTO' DROP NULL .. --

Example: Integers

- Integer: a non-empty string of digits

```
digit = '0' | '1' | '2' | '3' | '4'
        | '5' | '6' | '7' | '8' | '9'
number = digit digit*
```

Abbreviation: A+ = A A*



Example: Identifier

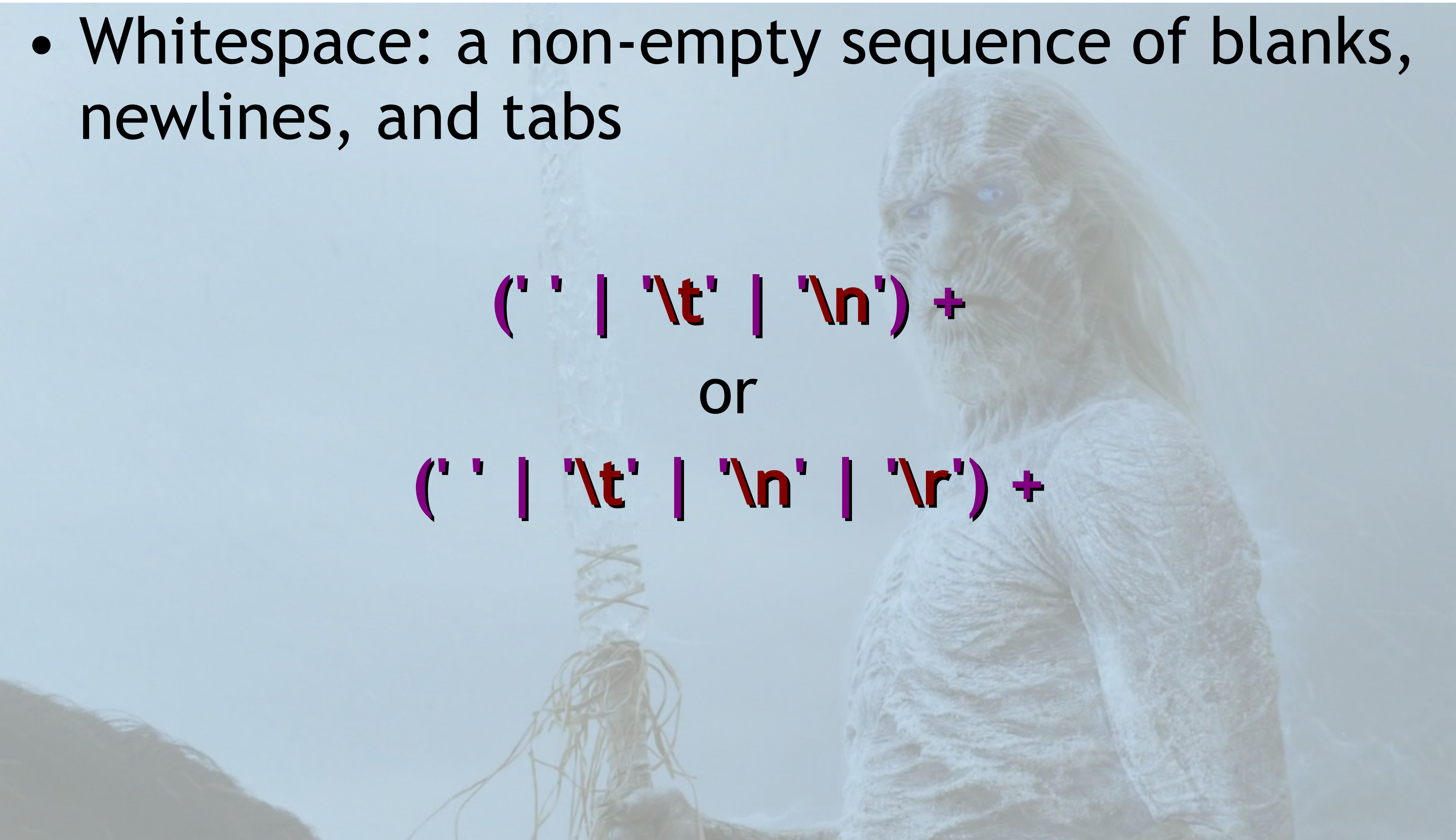
- Identifier: string of letters or digits, starting with a letter

letter = 'A' | ... | 'Z' | 'a' | ... | 'z'

ident = letter (letter | digit)*

Is (letter* | digit*) the same?

Example: Whitespace



- Whitespace: a non-empty sequence of blanks, newlines, and tabs

```
(' ' | '\t' | '\n') +
```

or

```
(' ' | '\t' | '\n' | '\r') +
```

Example: Phone Numbers

- Regexps are everywhere!
- Consider: (434) 924-1021

Σ	= {0, 1, 2, 3, …, 9, (,), -}
area	= digit digit digit
exch	= digit digit digit
phone	= digit digit digit digit
number	= '(' area ')' exch '-' phone

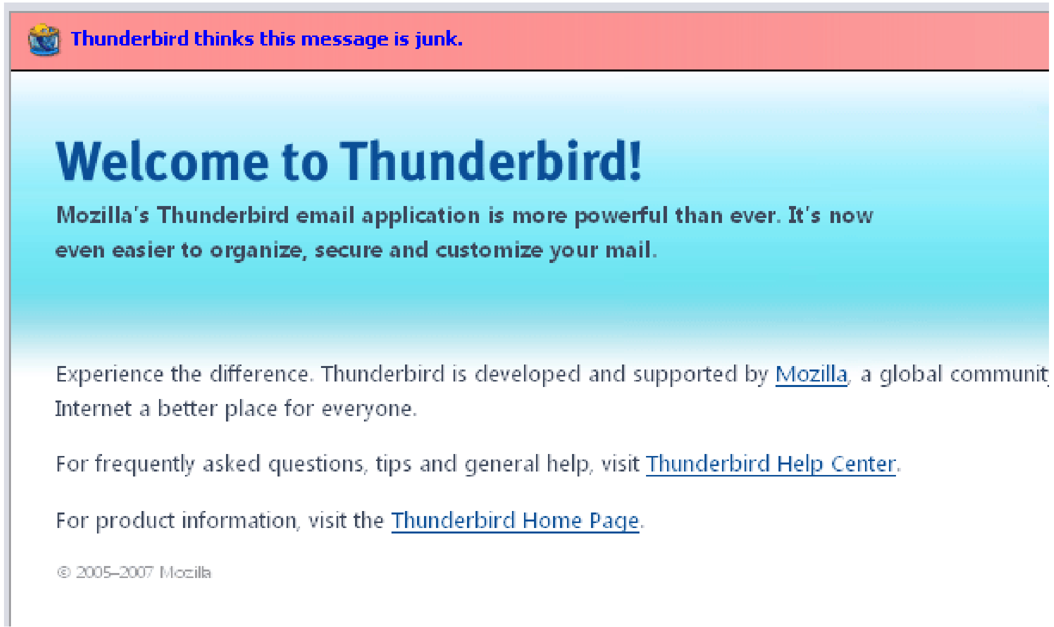
Example: Email Addresses

- Consider weimer@cs.virginia.edu

Σ = {a, b, …, z, ., @}

name = letter+

address = name '@' name ('.' name)*



Thunderbird thinks this message is junk.

Welcome to Thunderbird!

Mozilla's Thunderbird email application is more powerful than ever. It's now even easier to organize, secure and customize your mail.

Experience the difference. Thunderbird is developed and supported by Mozilla, a global communit
Internet a better place for everyone.

For frequently asked questions, tips and general help, visit Thunderbird Help Center.

For product information, visit the Thunderbird Home Page.

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Regexp Summary

- Regular expressions describe many useful languages
- Next: Given a string s and a regexp R, is

$$s \in L(R)$$

- But a yes/no answer is not enough!
- Instead: partition the input into lexemes
- We will adapt regular expression to this goal

Subsequent Outline

- Specifying lexical structure using regexps
- Finite Automata
  - Deterministic Finite Automata (DFAs)
  - Non-deterministic Finite Automata (NFAs)
- Implementation of Regular Expressions
  - Regexp -> NFA -> DFA -> Tables
  - The tables are the heart of the lexer, which is just a while loop that takes in the current input character and looks up the new state in the transition table.

Lexical Specification (1)

- Select a set of tokens
  - Number, Keyword, Identifier, ...
- Write a regexp for the lexemes of each token
  - Number = digit+
  - Keyword = 'if' | 'else' | ...
  - Identifier = letter (letter | digit) *
  - OpenPar = '('
  - ...

Lexical Specification (2)

- Construct R, matching all lexemes for all tokens:

  R = Keyword | Identifier | Number | ...

  R = R1 | R2 | R3 | ...

- Fact: if s ∈ L(R) then s is a lexeme
  - Furthermore, s ∈ L(Rj) for some j
  - This j determines the token that is reported

Lexical Specification (3)

- Let the input be $x_1 \dots x_n$
  - Each x_i is in the alphabet Σ
- For $1 \le i \le n$, check
  - $x_1 \dots x_i \in L(R)$
- If so, it must be that
  - $x_1 \dots x_i \in L(Rj)$ for some j
- Remove $x_1 \dots x_i$ from the input and restart

Lexing Example

- R = Whitespace | Integer | Identifer | Plus
- Parse "f +3 +g"
  - "f" matches R, more precisely Identifier
  - " " matches R, more precisely Whitespace
  - "+" matches R, more precisely Plus
  - ...
  - The token-lexeme pairs are
  - <Identifier, "f">
  - <Whitespace, " ">
  - <Plus, "+"> ...

In the future, we'll just drop whitespace.

Ambiguities

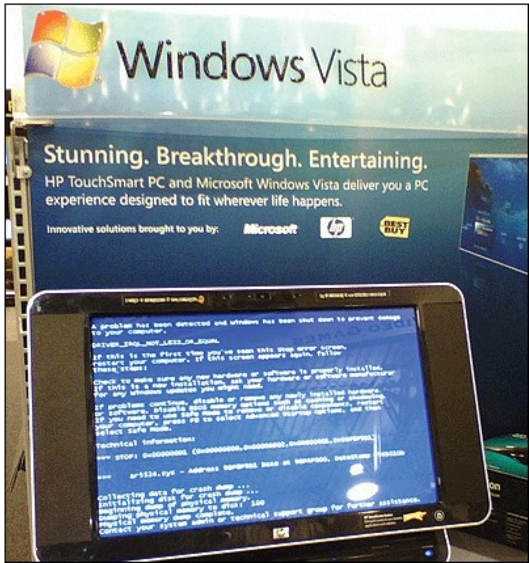
- Our algorithm is ambiguous!
- Example:
  - R = Whitespace | Integer | Identifier | Plus
- Parse “foo+3”
  - “f” matches R, more precisely Identifier
  - But also “fo” matches R, and “foo”, but not “foo+”
- How much input is used?
  - Maximal Munch rule: Pick the longest possible substring that matches R

Ambiguities (2)

- R = Whitespace | 'new' | Integer | Identifier
- Parse “new foo”
  - “new” matches R, more precisely 'new'
  - but also Identifier – which one do we pick?
- In general, use the rule listed **first**.
  - No, really.
- So we must list 'new' (and other keywords) before Identifier.

Error Handling

- R = Whitespace | Integer | Identifier | '+'
- Parse "=56"
  - No prefix matches R: not "=", nor "=5", nor "=56"
- Problem: we can't just get stuck and die
- Solution:
  - New rule matches all "bad" strings
  - Put it last
- Lexer tools allow the writing of:
  - R = R1 | R2 | ... | Rn | Error


Windows Vista
Stunning. Breakthrough. Entertaining.
HP TouchSmart PC and Microsoft Windows Vista deliver you a PC experience designed to fit wherever life happens.
Innovative solutions brought to you by:
Microsoft

Summary

Cool Demo?

- Regular expressions provide a concise notation for string patterns
- Their use in lexical analysis requires small extensions
  - To resolve ambiguities
  - To handle errors
- Good algorithms known (next)
  - Requiring only a single pass over the input
  - And few operations per character (table lookup)