Compilers and Formal Languages

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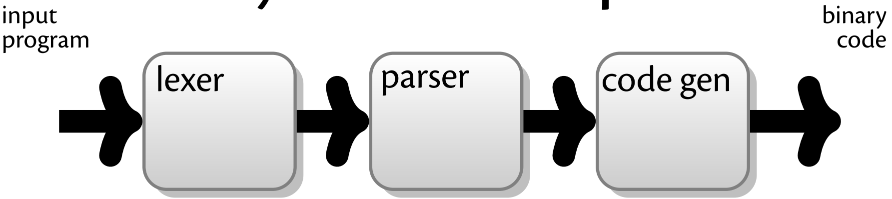
Slides & Progs:	KEATS
Pollev:	https://pollev.com/cfltutoratki576

The Goal of this Module...

... you write a compiler



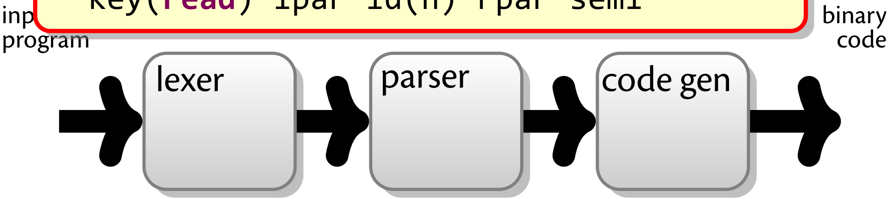
The Goal of this Module...

lexer input: a string

```
"read(n);"
```

lexer output: a sequence of tokens

```
key(read) lpar id(n) rpar semi
```



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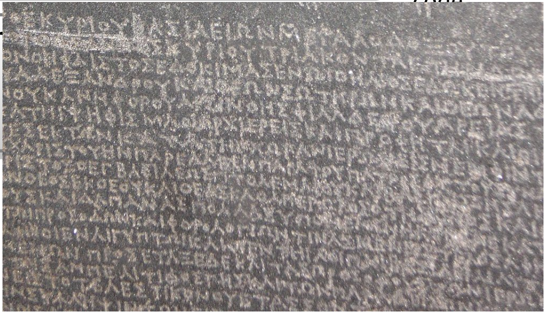
inp
program

lexer

par

binary
code



lexing ⇒ recognising words (Stone of Rosetta)

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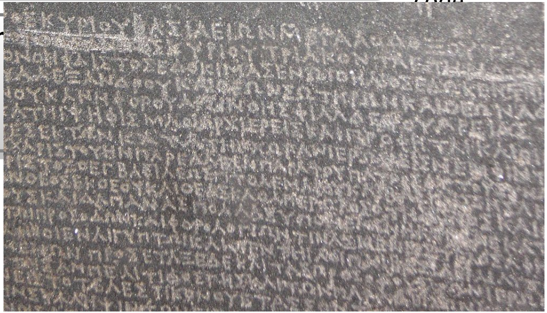
`key(read) lpar id(n) rpar semi`

`if` ⇒ keyword
`iffoo` ⇒ identifier



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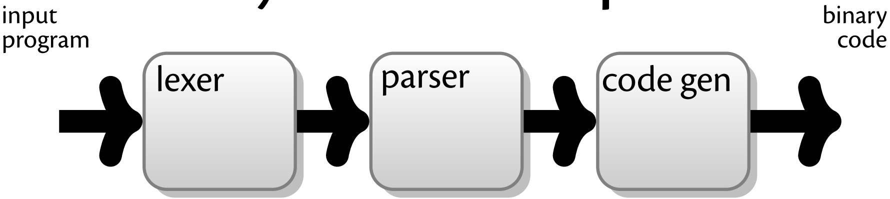
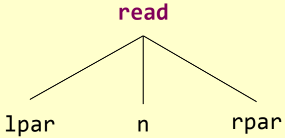


The Goal of this Module...

parser input: a sequence of tokens

```
key(read) lpar id(n) rpar semi
```

parser output: an abstract syntax tree



binary
code

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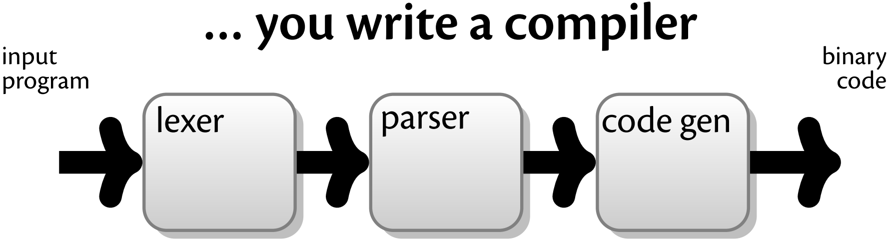
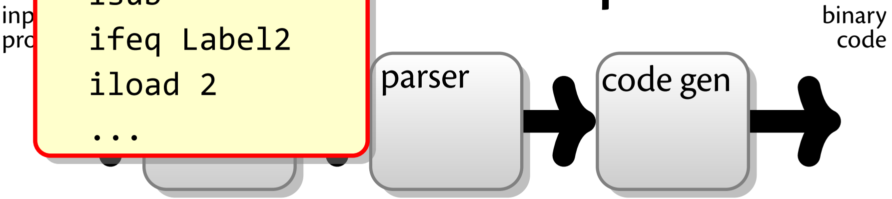


The Goal of this Module...

code generation:

```
istore 2
iload 2
ldc 10
isub
ifeq Label2
iload 2
...
```

rite a compiler



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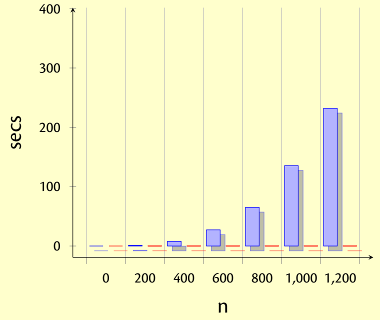
inp
pro

parser



The Goal of this Module...

Compiler explorers, e.g.: `https://gcc.godbolt.org`

inp
pro

```
// Type your code here, or load an example.
int square(int num) {
    if (num % 2 == 0)
      { return num + num; }
    else
      { return num * num; }
}
```

```
square(int):
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], edi
        mov     eax, DWORD PTR [rbp-4]
        and     eax, 1
        test    eax, eax
        jne     .L2
        mov     eax, DWORD PTR [rbp-4]
        add     eax, eax
        jmp     .L3
.L2:
        mov     eax, DWORD PTR [rbp-4]
        imul    eax, eax
.L3:
        pop     rbp
        ret
```

source ⟶ binary

The Goal of this Module...

inp
pro

Compiler explorer for Java: `https://javap.yawk.at`

```java
import java.util.*;
import lombok.*;

public class Main {
    public Main() {
        int i = 0;
        i++;
    }
}
```

```
      Code:
        stack=1, locals=2, args_size=1
          start local 0 // Main this
           0: aload_0
           1: invokespecial #1
           4: iconst_0
           5: istore_1
          start local 1 // int i
           6: iinc          1, 1
           9: return
          end local 1 // int i
          end local 0 // Main this
```

source ⟶ byte code

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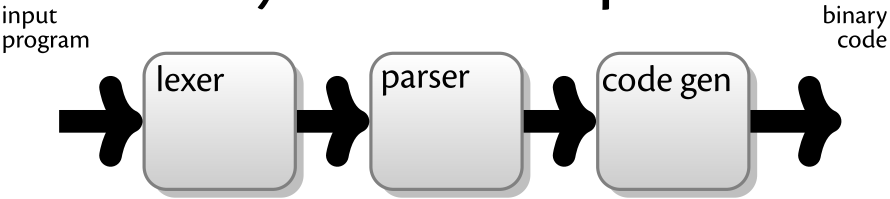

Why Study Compilers?

John Regehr (Univ. Utah, LLVM compiler hacker) ☞

"...It's effectively a perpetual employment act for solid compiler hackers."

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"...It's effectively a perpetual employment act for solid compiler hackers."

- **Hardware is getting weirder rather than getting clocked faster.**

  "Almost all processors are multicores nowadays and it looks like there is increasing asymmetry in resources across cores. Processors come with vector units, crypto accelerators etc. We have DSPs, GPUs, ARM big.little, and Xeon Phi. This is only scratching the surface."

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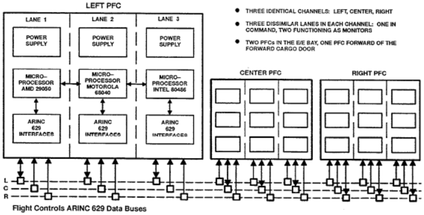
"…It's effectively a perpetual employment act for solid compiler hackers."

- **We're getting tired of low-level languages and their associated security disasters.**

  "We want to write new code, to whatever extent possible, in safer, higher-level languages. Compilers are caught right in the middle of these opposing trends: one of their main jobs is to help bridge the large and growing gap between increasingly high-level languages and increasingly wacky platforms."

Why Bother with Compilers?

Boeing 777's: First flight in 1994. They want to achieve triple redundancy for potential hardware faults. ☞



They compile 1 Ada program to

- Intel 80486
- Motorola 68040 (old Macintosh's)
- AMD 29050 (RISC chips used often in laser printers)

using 3 independent compilers.

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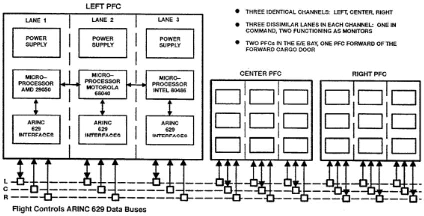

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using 3 independent compilers.

Airbus uses C and static analysers. Recently started using CompCert.

What Do Compilers Do?

Remember BF*** from PEP?

`>`	$\Rightarrow$	move one cell right
`<`	$\Rightarrow$	move one cell left
`+`	$\Rightarrow$	increase cell by one
`-`	$\Rightarrow$	decrease cell by one
`.`	$\Rightarrow$	print current cell
`,`	$\Rightarrow$	input current cell
`[`	$\Rightarrow$	loop begin
`]`	$\Rightarrow$	loop end
	$\Rightarrow$	everything else is a comment

A “Compiler” for BF*** to C

`>`	$\Rightarrow$	`ptr++`
`<`	$\Rightarrow$	`ptr--`
`+`	$\Rightarrow$	`(*ptr)++`
`-`	$\Rightarrow$	`(*ptr)--`
`.`	$\Rightarrow$	`putchar(*ptr)`
`,`	$\Rightarrow$	`*ptr = getchar()`
`[`	$\Rightarrow$	`while(*ptr){`
`]`	$\Rightarrow$	`}`
	$\Rightarrow$	ignore everything else

```
char field[30000]
char *ptr = &field[15000]
```

Another "Compiler" for BF to C

`>...>`	$\Rightarrow$	`ptr += n`
`<...<`	$\Rightarrow$	`ptr -= n`
`+...+`	$\Rightarrow$	`(*ptr) += n`
`-...-`	$\Rightarrow$	`(*ptr) -= n`
`.`	$\Rightarrow$	`putchar(*ptr)`
`,`	$\Rightarrow$	`*ptr = getchar()`
`[`	$\Rightarrow$	`while(*ptr){`
`]`	$\Rightarrow$	`}`
	$\Rightarrow$	ignore everything else

```
char field[30000]
char *ptr = &field[15000]
```

A Brief Compiler History

- Turing Machines, 1936 (a tape as memory)
- Regular Expressions, 1956
- The first compiler for COBOL, 1957 (Grace Hopper)
- But surprisingly research papers are still published nowadays
- "Parsing: The Solved Problem That Isn't" ☞

Grace Hopper

(she made it to David Letterman's Tonight Show ☞)

Some Housekeeping

Exam will be computer-based, invigilated in some big examination hall:

- final exam in January (35%)
- five CWs (65%)

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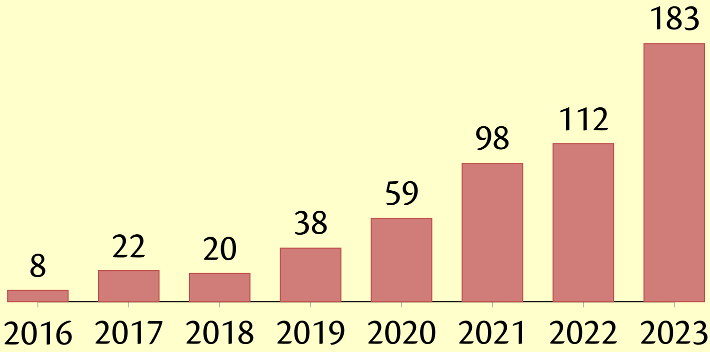
- final exam in January (35%)
- five CWs (65%)

Weekly Homework (optional):

- uploaded on KEATS, send answers via email, (try to!) respond individually
- all questions in the exam will be from the HWs!!

Students in CFL



Student numbers since the start of the compiler module.

Homework

Until 2 years ago: I did not give out solutions; students sent emails to me and I responded to them individually.

Since last year: We will review the homework mainly during the SGTs.

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I will still choose the questions from the HW for the exam, but there might be some larger amount of deviation.

Some Housekeeping

Coursework (5 accounting for 65%):

- matcher (5%)
- lexer (10%)
- parser / interpreter (10%)
- JVM compiler (15%)
- LLVM compiler (25%)

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(Haskell, Rust, Swift)

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you can use any programming language you like (Haskell, Rust, Swift)
you can use any code I show you and is uploaded to KEATS...**BUT NOTHING ELSE!**

Ammonite & Scala 3

I will show you all my code in Amm / Scala 3

```
$ amm
Loading...
Welcome to the Ammonite Repl 2.5.9 (Scala 3.2.2 Java 17.0.7)
scala> 1 + 2
res0: Int = 3
```

Ammonite & Scala 3

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$ amm
Loading...
Welcome to the Ammonite Repl 2.5.9 (Scala 3.2.2 Java 17.0.7)
scala> 1 + 2
res0: Int = 3
```

Do not use Amm + Scala 2!

```
$ amm2
Loading...
Welcome to the Ammonite Repl 2.5.9 (Scala 2.13.11 Java 17.0.7)
scala>
```

For problems

- Harry Dilnot
- Meilai

Lectures 1 - 5

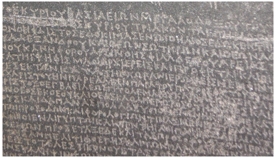
transforming strings into structured data

Lexing based on regular expressions

(recognising "words")

Parsing

(recognising "sentences")



Stone of Rosetta

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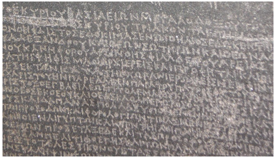


Stone of Rosetta

Lectures 5 - 10

code generation for a small imperative and a small functional language

Interpreters

(directly runs a program)

Compilers

(generate JVM code and LLVM-IR code)

Familiar Regular Expresssions

```
[a-z0-9_\.-]+ @ [a-z0-9\.-]+ . [a-z\.]{2,6}
```

`re*`	matches 0 or more times
`re+`	matches 1 or more times
`re?`	matches 0 or 1 times
`re{n}`	matches exactly `n` number of times
`re{n,m}`	matches at least `n` and at most `m` times
`[...]`	matches any single character inside the brackets
`[^...]`	matches any single character not inside the brackets
`a-z A-Z`	character ranges
`\d`	matches digits; equivalent to `[0-9]`
`.`	matches every character except newline
`(re)`	groups regular expressions and remembers the matched text

Notation for REs

Some “innocent” examples

Let’s try two examples

`(a*)*b`   `[a?]{n}[a]{n}`

Some "innocent" examples

Let's try two examples

`(a*)*b` `[a?]{n}[a]{n}`

and match them with strings of the form

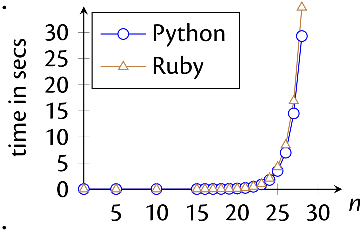
$\texttt{a}, \texttt{aa}, \texttt{aaa}, \texttt{aaaa}, \texttt{aaaaa}, \underbrace{\texttt{a...a}}_{n}$

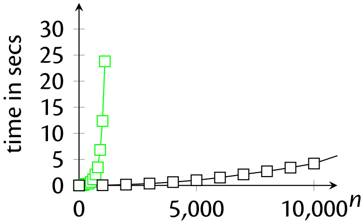
Why Bother with Regexes?

Ruby, Python, Java 8

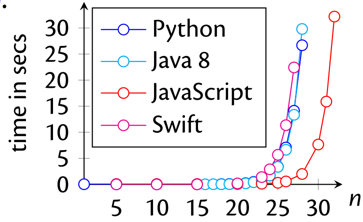
Us (after next lecture)

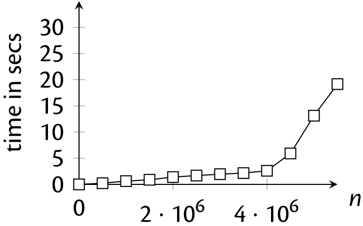
`[a?]{n}[a]{n}`:





`(a*)*b`:





matching with strings $\underbrace{a\ldots a}_{n}$

Incidents

- a global outage on 2 July 2019 at **Cloudflare** (first one for six years)

```
(?:(?:\"|'|\]|\}|\\|\d|(?:nan|infinity|true|false|
null|undefined|symbol|math)|\`|\-|\+)+[)]*;?((?:\s
|-|~|!|{}|\|\||\+)*.*(?:.*=.*)))
```

It serves more web traffic than Twitter, Amazon, Apple, Instagram, Bing & Wikipedia combined. ☞

- on 20 July 2016 the **Stack Exchange** webpage went down because of an evil regular expression ☞

Evil Regular Expressions

- Regular expression Denial of Service (ReDoS)
- Some evil regular expressions:
  - `[a?]{n} [a]{n}`
  - `(a*)* b`
  - `([a-z]+)*`
  - `(a + aa)*`
  - `(a + a?)*`
- sometimes also called catastrophic backtracking
- this is a problem for Network Intrusion Detection systems, Cloudflare, StackExchange, Atom editor
- https://vimeo.com/112065252

Rust vs. Scala (from PEP)

Re: Another question of purely academic interest about regex implementation in cw3

This conversation is interesting to me, and I've researched it a little bit [...] I also disagree with Dr. Urban on the cost/benefit of non-GC languages [...]

But regardless, Scala is a lot slower than, say, C or Rust. To say it's not is basically wrong (imo). Perhaps one could argue that some of the guarantees Scala has makes it easier to write multi-threaded programs that utilise more of the CPU... but, in my opinion, this is also a bit misleading. Most CPUs have something like 4 to 12 cores nowadays. It's very possible that a given Scala program runs 4-12x slower than its Rust equivalent. Would you rather have your program run quickly and use a single core, or have it run equally quickly... and... hog your entire CPU for its duration?...

– Oliver Iliffe, discussion from PEP

Regex Lib in Rust

regex v1.9.5

An implementation of regular expressions for Rust. This implementation uses finite automata and guarantees linear time matching on all inputs.

Readme | 150 Versions | Dependencies | Dependents

regex

This crate provides routines for searching strings for matches of a regular expression (aka "regex"). The regex syntax supported by this crate is similar to other regex engines, but it lacks several features that are not known how to implement efficiently. This includes, but is not limited to, look-around and backreferences. In exchange, all regex searches in this crate have worst case `O(m * n)` time complexity, where `m` is proportional to the size of the regex and `n` is proportional to the size of the string being searched.

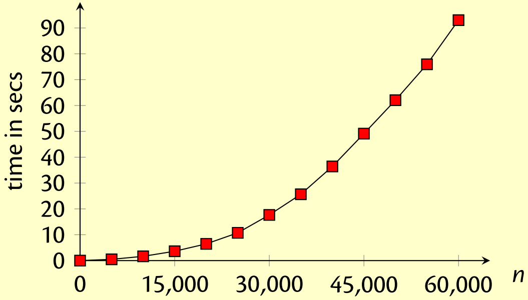
Metadata

- 25 days ago
- v1.60.0
- MIT OR Apache-2.0
- 254 kB

Install

Run the following Cargo command in your project directory:

re: $(abc)^{\{n\}}$ str: $\underbrace{abc\ldots abc}_{n}$




```
extern crate regex;

use regex::Regex;
use std::time::Instant;

// bounded regular expression example

fn main() {
    for bound in (0..=60000).step_by(5000) {

        let re = Regex::new(&format!("(abc){{{}}}", bound)).unwrap();
        let text = "abc".repeat(bound);

        let start_time = Instant::now();
        let is_match = re.is_match(&text);
        let elapsed_time = start_time.elapsed().as_secs_f64();

        println!("Bound: {}, Match: {}, Time: {} seconds", bound, is_ma
    }
}
```

(Basic) Regular Expressions

Their inductive definition:

r	$::=$	$\mathbf{0}$	nothing
	$\mid$	$\mathbf{1}$	empty string / " " / []
	$\mid$	c	character
	$\mid$	$r_1 + r_2$	alternative / choice
	$\mid$	$r_1 \cdot r_2$	sequence
	$\mid$	r^*	star (zero or more)

(B

Their

```scala
abstract class Rexp
case object ZERO extends Rexp
case object ONE extends Rexp
case class CHAR(c: Char) extends Rexp
case class ALT(r1: Rexp, r2: Rexp) extends Rexp
case class SEQ(r1: Rexp, r2: Rexp) extends Rexp
case class STAR(r: Rexp) extends Rexp
```

r	$::=$	$\mathbf{0}$	nothing
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	$\mid$	r^*	star (zero or more)

Strings

...are lists of characters. For example `"hello"`

$$[h, e, l, l, o] \text{ or just } hello$$

the empty string: $[]$ or `""`

the concatenation of two strings:

$$s_1 @ s_2$$

$foo @ bar = foobar$
$baz @ [] = baz$

Languages, Strings

- **Strings** are lists of characters, for example

  $[], abc$ (Pattern match: $c :: s$)

- A **language** is a set of strings, for example

  $$\{[], hello, foobar, a, abc\}$$

- **Concatenation** of strings and languages

  $$foo\ @\ bar = foobar$$

  $$A\ @\ B \stackrel{\text{def}}{=} \{s_1\ @\ s_2 \mid s_1 \in A \wedge s_2 \in B\}$$

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Let
$A = \{foo, bar\}$
$B = \{a, b\}$

$A\ @\ B = \{fooa, foob, bara, barb\}$

Two Corner Cases

$$A \,@\, \{[]\} = ?$$

Two Corner Cases

$$A\,@\,\{[]\} = ?$$

$$A\,@\,\{\} = ?$$

The Meaning of a Regex

...all the strings a regular expression can match.

$$
\begin{array}{rcl}
L(\mathbf{0}) & \stackrel{\text{def}}{=} & \{\} \\
L(\mathbf{1}) & \stackrel{\text{def}}{=} & \{[]\} \\
L(c) & \stackrel{\text{def}}{=} & \{[c]\} \\
L(r_1 + r_2) & \stackrel{\text{def}}{=} & L(r_1) \cup L(r_2) \\
L(r_1 \cdot r_2) & \stackrel{\text{def}}{=} & L(r_1) \,@\, L(r_2) \\
L(r^*) & \stackrel{\text{def}}{=} &
\end{array}
$$

L is a function from regular expressions to sets of strings (languages):

$L : \text{Rexp} \Rightarrow \text{Set}[\text{String}]$

The Power Operation

- The ***nth* Power** of a language:

$$\begin{array}{lcl} A^0 & \stackrel{\text{def}}{=} & \{[]\} \\ A^{n+1} & \stackrel{\text{def}}{=} & A @ A^n \end{array}$$

For example

$$\begin{array}{lcll} A^4 & = & A @ A @ A @ A & (@ \{[]\}) \\ A^1 & = & A & (@ \{[]\}) \\ A^0 & = & \{[]\} & \end{array}$$

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L(r^*) & \stackrel{\text{def}}{=} & \bigcup_{0 \le n} L(r)^n
\end{array}
$$

The Star Operation

- The **Kleene Star** of a language:

$$A\star \stackrel{\text{def}}{=} \bigcup_{0\leq n} A^n$$

This expands to

$$A^0 \cup A^1 \cup A^2 \cup A^3 \cup A^4 \cup \ldots$$

or

$$\{[]\} \;\cup\; A \;\cup\; A@A \;\cup\; A@A@A \;\cup\; A@A@A@A \cup \ldots$$

The Meaning of a Regex

$$
\begin{array}{rcl}
L(\mathbf{0}) & \stackrel{\text{def}}{=} & \{\} \\
L(\mathbf{1}) & \stackrel{\text{def}}{=} & \{[]\} \\
L(c) & \stackrel{\text{def}}{=} & \{[c]\} \\
L(r_1 + r_2) & \stackrel{\text{def}}{=} & L(r_1) \cup L(r_2) \\
L(r_1 \cdot r_2) & \stackrel{\text{def}}{=} & \{s_1 @ s_2 \mid s_1 \in L(r_1) \wedge s_2 \in L(r_2)\} \\
L(r^*) & \stackrel{\text{def}}{=} & (L(r))\star
\end{array}
$$

The Meaning of Matching

A regular expression r matches a string s provided

$$s \in L(r)$$

...and the point of the next lecture is to decide this problem as fast as possible (unlike Python, Ruby, Java)

Questions

- Say $A = \{[a], [b], [c], [d]\}$.

  How many strings are in A^4 ?

Questions

- Say $A = \{[a], [b], [c], [d]\}$.

  How many strings are in A^4 ?

  What if $A = \{[a], [b], [c], []\}$;
  how many strings are then in A^4 ?

Questions

- Assume a set A contains 4 strings and a set B contains 7 strings. None of the strings is the empty string.
- How many strings are in $A \mathbin{@} B$?

CH

Assume a language A contains 7 strings, and B contains 4 strings. How many strings are in the concatenation of these two languages?

If you want to find the number of strings in the concatenation of two languages A and B, you need to multiply the number of strings in each language. So, if A contains 7 strings and B contains 4 strings, the number of strings in the concatenation of A and B is:

Number of strings in A concatenated with B = |A| * |B| = 7 * 4 = 28

There are 28 strings in the concatenation of these two languages.

...for amusement

CH No this is incorrect. Think again.

I apologize for the incorrect response earlier. You are right; my previous answer was incorrect.

When concatenating two languages A and B, you need to consider all possible combinations of strings from A and B. For each string in A, you can concatenate it with every string in B, resulting in a new string. To find the total number of strings in the concatenation, you multiply the number of strings in A by the number of strings in B.

So, if A contains 7 strings and B contains 4 strings, the number of strings in the concatenation of A and B is:

Number of strings in A concatenated with B = |A| * |B| = 7 * 4 = 28

There are indeed 28 different strings in the concatenation of these two languages.

Questions?

SGT TAs:	Flavio Melinte Citea	(was a KURF last summer)
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Coursework

Do we need to provide instructions on running the coursework files if we're using languages other than Scala? Thanks

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Zip-File for Coursework

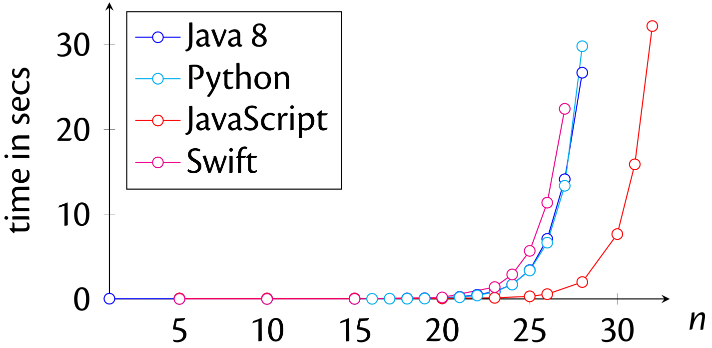
Please, please submit a zipfile that generates a subdirectory

`NameFamilyName`

What is the trick?

What was the trick to improve the evil regular expressions matcher to have such good results compared to other programming languages? Is it working better on casual regular expressions (the ones that Python and Java handle pretty well), too? Or was it just optimised for these evil ones?

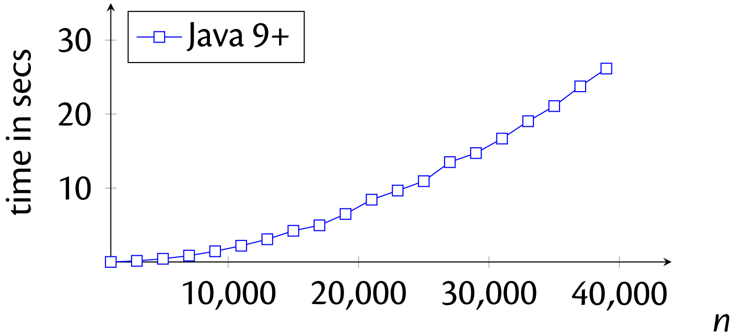
Thanks to Martin Mikusovic



Regex: $(a^*)^* \cdot b$

Strings of the form $\underbrace{a \ldots a}_{n}$

Same Example in Java 9+



Regex: $(a^*)^* \cdot b$

Strings of the form $\underbrace{a \ldots a}_{n}$