

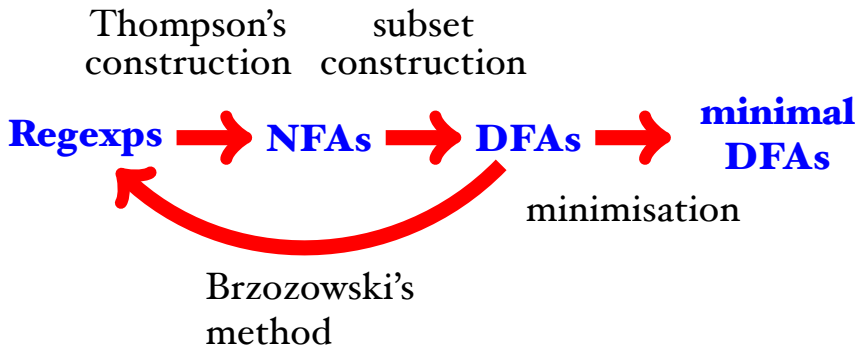
# Compilers and Formal Languages (4)

Email: christian.urban at kcl.ac.uk

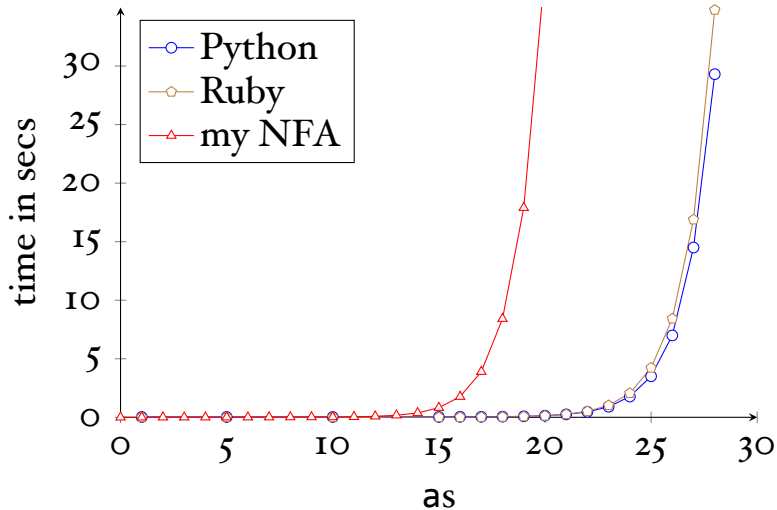
Office: SI.27 (1st floor Strand Building)

Slides: KEATS (also home work is there)

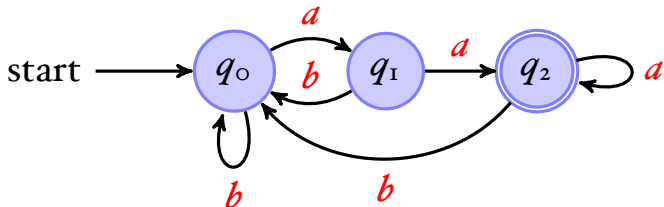
# Regexps and Automata



$$a^? \{n\} \cdot a \{n\}$$



# DFA to Rexp



$$q_0 = \mathbf{I} + q_0 b + q_1 b + q_2 b \quad (\text{start state})$$

$$q_1 = q_0 a$$

$$q_2 = q_1 a + q_2 a$$

Arden's Lemma:

$$\text{If } q = qr + s \text{ then } q = sr^*$$

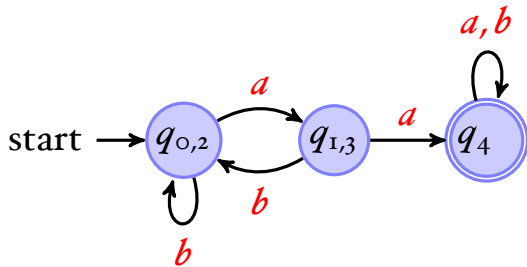
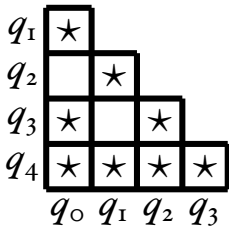
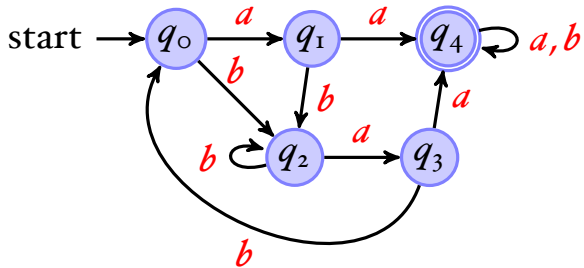
# DFA Minimisation

- 1 Take all pairs  $(q, p)$  with  $q \neq p$
- 2 Mark all pairs that accepting and non-accepting states
- 3 For all unmarked pairs  $(q, p)$  and all characters  $c$  test whether

$$(\delta(q, c), \delta(p, c))$$

are marked. If yes, then also mark  $(q, p)$ .

- 4 Repeat last step until no change.
- 5 All unmarked pairs can be merged.



minimal automaton

# Regular Languages

Two equivalent definitions:

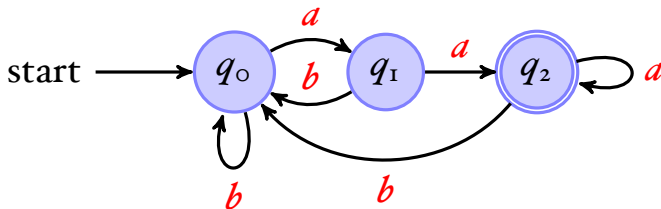
A language is **regular** iff there exists a regular expression that recognises all its strings.

A language is **regular** iff there exists an automaton that recognises all its strings.

for example  $a^n b^n$  is not regular

# Negation

Regular languages are closed under negation:

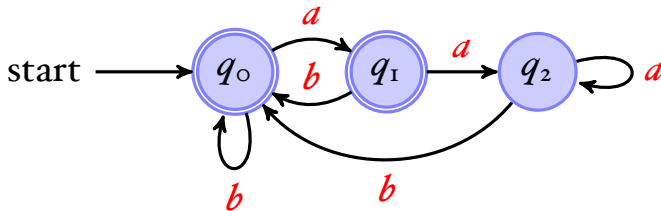


But requires that the automaton is **completed!**



# Negation

Regular languages are closed under negation:



But requires that the automaton is **completed!**

# The Goal of this Course

## Write A Compiler



Today a lexer.

# Survey: Thanks!

- **My Voice** “lecturer speaks in a low voice and is hard to hear him” “please use mic” “please use mic & lecture recording”
- **Pace** “faster pace” “a bit quick for me personally”
- **Recording** “please use recording class”
- **Module Name** “misleading”
- **Examples** “more examples”
- **Assessment** “really appreciate extension of first coursework”

# Lexing

```
1 write "Fib";
2 read n;
3 minus1 := 0;
4 minus2 := 1;
5 while n > 0 do {
6     temp := minus2;
7     minus2 := minus1 + minus2;
8     minus1 := temp;
9     n := n - 1
10 };
11 write "Result";
12 write minus2
```



```
1 write "Input a number ";
2 read n;
3 while n > 1 do {
4     if n % 2 == 0
5     then n := n/2
6     else n := 3*n+1;
7 };
8 write "Yes";
```

”if true then then 42 else +”

KEYWORD:

if, then, else,

WHITESPACE:

” ”, \n,

IDENT:

LETTER · (LETTER + DIGIT + \_)\*

NUM:

(NONZERODIGIT · DIGIT\*) + 0

OP:

+

COMMENT:

/\* · ~ (ALL\* · (\* / ) · ALL\*) · \*/

”if true then then 42 else +”

```
KEYWORD(if),  
WHITESPACE,  
IDENT(true),  
WHITESPACE,  
KEYWORD(then),  
WHITESPACE,  
KEYWORD(then),  
WHITESPACE,  
NUM(42),  
WHITESPACE,  
KEYWORD(else),  
WHITESPACE,  
OP(+)
```

”if true then then 42 else +”

KEYWORD(if),  
IDENT(true),  
KEYWORD(then),  
KEYWORD(then),  
NUM(42),  
KEYWORD(else),  
OP(+)



There is one small problem with the tokenizer.  
How should we tokenize:

”x-3”

ID: ...

OP:

”+”, ”-”

NUM:

(NONZERODIGIT · DIGIT\*) + ”0”

NUMBER:

NUM + (”-” · NUM)

The same problem with

$$(ab + a) \cdot (c + bc)$$

and the string *abc*.

The same problem with

$$(ab + a) \cdot (c + bc)$$

and the string *abc*.

The same problem with

$$(ab + a) \cdot (c + bc)$$

and the string *abc*.

Or, keywords are `if` and identifiers are letters followed by “letters + numbers + `_`”\*

*iffoo*

# POSIX: Two Rules

- Longest match rule (“maximal munch rule”): The longest initial substring matched by any regular expression is taken as the next token.
- Rule priority: For a particular longest initial substring, the first regular expression that can match determines the token.

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traditional lexers are fast, but hairy

# Sulzmann Matcher

We want to match the string *abc* using  $r_1$ :

$$r_1 \xrightarrow{\text{der } a} r_2$$



# Sulzmann Matcher

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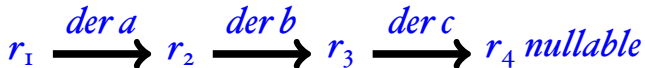
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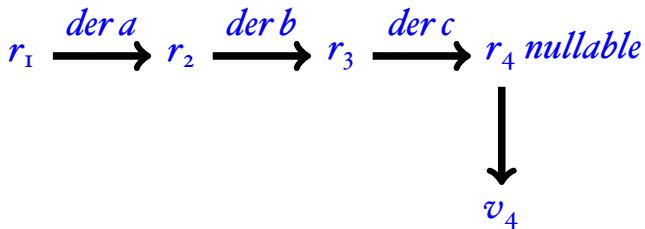
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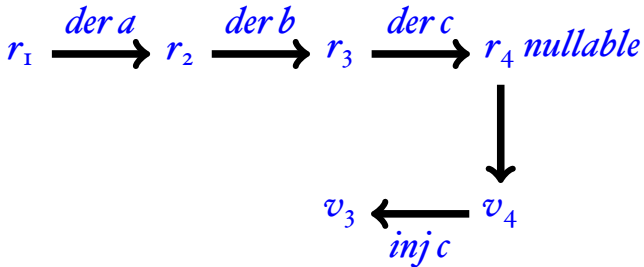
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We want to match the string *abc* using  $r_1$ :



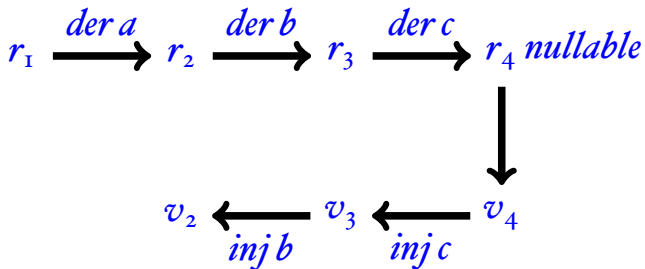
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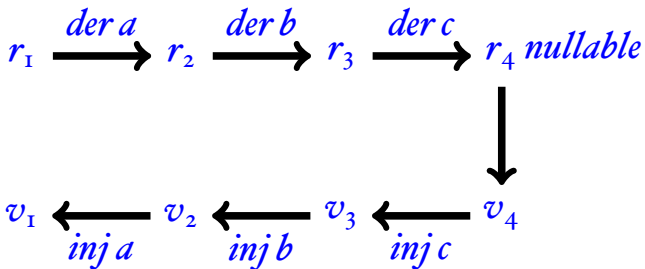
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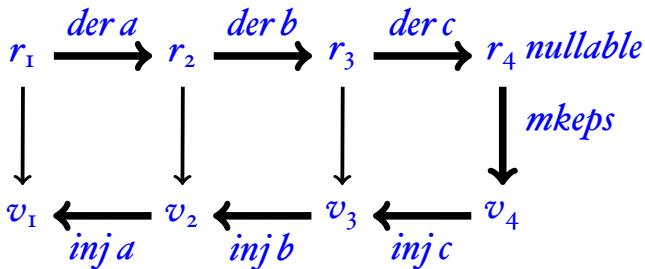
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# Sulzmann Matcher

We want to match the string *abc* using  $r_1$ :





# Regexes and Values

Regular expressions and their corresponding values:

$r ::=$	<b>O</b>	$v ::=$	<i>Empty</i>
	<b>I</b>		<i>Char</i> ( $c$ )
	$c$		<i>Seq</i> ( $v_1, v_2$ )
	$r_1 \cdot r_2$		<i>Left</i> ( $v$ )
	$r_1 + r_2$		<i>Right</i> ( $v$ )
	$r^*$		$\square$
			$[v_1, \dots, v_n]$

```
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
```

```
abstract class Val
case object Empty extends Val
case class Chr(c: Char) extends Val
case class Seq(v1: Val, v2: Val) extends Val
case class Left(v: Val) extends Val
case class Right(v: Val) extends Val
case class Stars(vs: List[Val]) extends Val
```

# Mkeps

Finding a (posix) value for recognising the empty string:

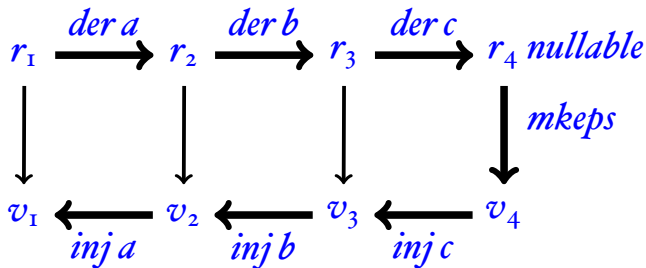
$$\begin{aligned} \mathit{mkeps} \mathbf{I} &\stackrel{\text{def}}{=} \mathit{Empty} \\ \mathit{mkeps} r_1 + r_2 &\stackrel{\text{def}}{=} \text{if } \mathit{nullable}(r_1) \\ &\quad \text{then } \mathit{Left}(\mathit{mkeps}(r_1)) \\ &\quad \text{else } \mathit{Right}(\mathit{mkeps}(r_2)) \\ \mathit{mkeps} r_1 \cdot r_2 &\stackrel{\text{def}}{=} \mathit{Seq}(\mathit{mkeps}(r_1), \mathit{mkeps}(r_2)) \\ \mathit{mkeps} r^* &\stackrel{\text{def}}{=} \square \end{aligned}$$

# Inject

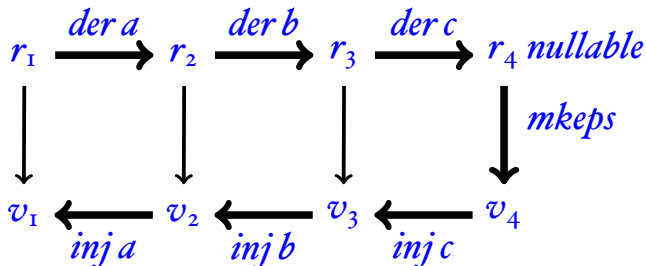
Injecting (“Adding”) a character to a value

$$\begin{aligned} inj(c) c Empty & \stackrel{\text{def}}{=} Char\ c \\ inj(r_I + r_2) c Left(v) & \stackrel{\text{def}}{=} Left(inj\ r_I\ c\ v) \\ inj(r_I + r_2) c Right(v) & \stackrel{\text{def}}{=} Right(inj\ r_2\ c\ v) \\ inj(r_I \cdot r_2) c Seq(v_I, v_2) & \stackrel{\text{def}}{=} Seq(inj\ r_I\ c\ v_I, v_2) \\ inj(r_I \cdot r_2) c Left(Seq(v_I, v_2)) & \stackrel{\text{def}}{=} Seq(inj\ r_I\ c\ v_I, v_2) \\ inj(r_I \cdot r_2) c Right(v) & \stackrel{\text{def}}{=} Seq(mkeps(r_I), inj\ r_2\ c\ v) \\ inj(r^*) c Seq(v, vs) & \stackrel{\text{def}}{=} inj\ r\ c\ v :: vs \end{aligned}$$

*inj*: 1st arg  $\mapsto$  a rexp; 2nd arg  $\mapsto$  a character; 3rd arg  $\mapsto$  a value



$$\begin{aligned}
 r_1: & a \cdot (b \cdot c) \\
 r_2: & \mathbf{I} \cdot (b \cdot c) \\
 r_3: & (\mathbf{O} \cdot (b \cdot c)) + (\mathbf{I} \cdot c) \\
 r_4: & (\mathbf{O} \cdot (b \cdot c)) + ((\mathbf{O} \cdot c) + \mathbf{I})
 \end{aligned}$$

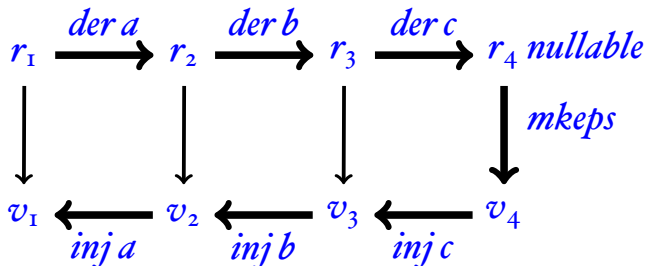


$$\begin{aligned}
 v_1: & \text{Seq}(\text{Char}(a), \text{Seq}(\text{Char}(b), \text{Char}(c))) \\
 v_2: & \text{Seq}(\text{Empty}, \text{Seq}(\text{Char}(b), \text{Char}(c))) \\
 v_3: & \text{Right}(\text{Seq}(\text{Empty}, \text{Char}(c))) \\
 v_4: & \text{Right}(\text{Right}(\text{Empty}))
 \end{aligned}$$

# Flatten

Obtaining the string underlying a value:

$ Empty $	$\stackrel{\text{def}}{=} []$
$ Char(c) $	$\stackrel{\text{def}}{=} [c]$
$ Left(v) $	$\stackrel{\text{def}}{=}  v $
$ Right(v) $	$\stackrel{\text{def}}{=}  v $
$ Seq(v_1, v_2) $	$\stackrel{\text{def}}{=}  v_1  @  v_2 $
$ [v_1, \dots, v_n] $	$\stackrel{\text{def}}{=}  v_1  @ \dots @  v_n $

$$\begin{aligned}
 r_1: & a \cdot (b \cdot c) \\
 r_2: & \mathbf{I} \cdot (b \cdot c) \\
 r_3: & (\mathbf{O} \cdot (b \cdot c)) + (\mathbf{I} \cdot c) \\
 r_4: & (\mathbf{O} \cdot (b \cdot c)) + ((\mathbf{O} \cdot c) + \mathbf{I})
 \end{aligned}$$


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 v_1: & \text{Seq}(\text{Char}(a), \text{Seq}(\text{Char}(b), \text{Char}(c))) \\
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 v_3: & \text{Right}(\text{Seq}(\text{Empty}, \text{Char}(c))) \\
 v_4: & \text{Right}(\text{Right}(\text{Empty}))
 \end{aligned}$$

$$\begin{aligned}
 |v_1|: & abc \\
 |v_2|: & bc \\
 |v_3|: & c \\
 |v_4|: & []
 \end{aligned}$$

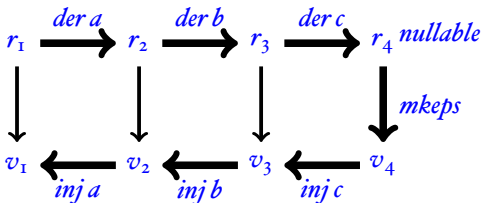


# Lexing

$lex\ r\ [] \stackrel{\text{def}}{=} \text{if } nullable(r) \text{ then } mkeps(r) \text{ else } error$

$lex\ r\ c :: s \stackrel{\text{def}}{=} inj\ r\ c\ lex(\text{der}(c, r), s)$

*lex*: returns a value



# Records

- new regex:  $(x : r)$     new value:  $Rec(x, v)$

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- $nullable(x : r) \stackrel{\text{def}}{=} nullable(r)$
- $der\ c(x : r) \stackrel{\text{def}}{=} (x : der\ c\ r)$
- $mkeps(x : r) \stackrel{\text{def}}{=} Rec(x, mkeps(r))$
- $inj(x : r)\ c\ v \stackrel{\text{def}}{=} Rec(x, inj\ r\ c\ v)$

# Records

- new regex:  $(x : r)$     new value:  $Rec(x, v)$
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- $inj(x : r)\ c\ v \stackrel{\text{def}}{=} Rec(x, inj\ r\ c\ v)$

for extracting subpatterns  $(z : ((x : ab) + (y : ba)))$

- A regular expression for email addresses

(name:  $[a-z0-9_.-]^+$ ).@.  
(domain:  $[a-z0-9.-]^+$ ) ..  
(top\_level:  $[a-z.]{2,6}$ )

christian.urban@kcl.ac.uk

- the result environment:

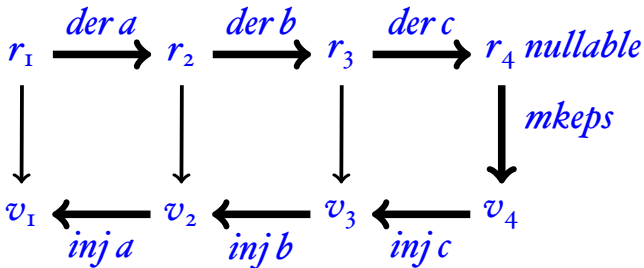
$[(name : christian.urban),$   
 $(domain : kcl),$   
 $(top\_level : ac.uk)]$

# While Tokens

WHILE\_REGS  $\stackrel{\text{def}}{=}$  ((**"k"** : KEYWORD) +  
(**"i"** : ID) +  
(**"o"** : OP) +  
(**"n"** : NUM) +  
(**"s"** : SEMI) +  
(**"p"** : (LPAREN + RPAREN)) +  
(**"b"** : (BEGIN + END)) +  
(**"w"** : WHITESPACE))\*

# Simplification

- If we simplify after the derivative, then we are building the value for the simplified regular expression, but *not* for the original regular expression.



$$(\mathbf{0} \cdot (b \cdot c)) + ((\mathbf{0} \cdot c) + \mathbf{1}) \mapsto \mathbf{1}$$

Normally we would have

$$(\mathbf{0} \cdot (b \cdot c)) + ((\mathbf{0} \cdot c) + \mathbf{1})$$

and answer

$$\mathit{Right}(\mathit{Right}(\mathit{Empty}))$$

But now we simplify to  $\mathbf{1}$  and produce *Empty*.



# Rectification

rectification  
functions:

$$r \cdot \mathbf{0} \mapsto \mathbf{0}$$

$$\mathbf{0} \cdot r \mapsto \mathbf{0}$$

$$r \cdot \mathbf{I} \mapsto r \quad \lambda f_1 f_2 v. \text{Seq}(f_1 v, f_2 \text{Empty})$$

$$\mathbf{I} \cdot r \mapsto r \quad \lambda f_1 f_2 v. \text{Seq}(f_1 \text{Empty}, f_2 v)$$

$$r + \mathbf{0} \mapsto r \quad \lambda f_1 f_2 v. \text{Left}(f_1 v)$$

$$\mathbf{0} + r \mapsto r \quad \lambda f_1 f_2 v. \text{Right}(f_2 v)$$

$$r + r \mapsto r \quad \lambda f_1 f_2 v. \text{Left}(f_1 v)$$

# Rectification

rectification  
functions:

$$r \cdot \mathbf{0} \mapsto \mathbf{0}$$

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$$\mathbf{I} \cdot r \mapsto r \quad \lambda f_1 f_2 v. \text{Seq}(f_1 \text{Empty}, f_2 v)$$

$$r + \mathbf{0} \mapsto r \quad \lambda f_1 f_2 v. \text{Left}(f_1 v)$$

$$\mathbf{0} + r \mapsto r \quad \lambda f_1 f_2 v. \text{Right}(f_2 v)$$

$$r + r \mapsto r \quad \lambda f_1 f_2 v. \text{Left}(f_1 v)$$

old *simp* returns a rexp;

new *simp* returns a rexp and a rectification function.

# Rectification

$\mathit{simp}(r)$ :

case  $r = r_I + r_2$

let  $(r_{I_S}, f_{I_S}) = \mathit{simp}(r_I)$

$(r_{2_S}, f_{2_S}) = \mathit{simp}(r_2)$

case  $r_{I_S} = \mathbf{0}$ : return  $(r_{2_S}, \lambda v. \mathit{Right}(f_{2_S}(v)))$

case  $r_{2_S} = \mathbf{0}$ : return  $(r_{I_S}, \lambda v. \mathit{Left}(f_{I_S}(v)))$

case  $r_{I_S} = r_{2_S}$ : return  $(r_{I_S}, \lambda v. \mathit{Left}(f_{I_S}(v)))$

otherwise: return  $(r_{I_S} + r_{2_S}, f_{\mathit{alt}}(f_{I_S}, f_{2_S}))$

$f_{\mathit{alt}}(f_1, f_2) \stackrel{\text{def}}{=}$

$\lambda v. \text{case } v = \mathit{Left}(v') : \text{return } \mathit{Left}(f_1(v'))$

$\text{case } v = \mathit{Right}(v') : \text{return } \mathit{Right}(f_2(v'))$

```

def simp(r: Rexp): (Rexp, Val => Val) = r match {
  case ALT(r1, r2) => {
    val (r1s, f1s) = simp(r1)
    val (r2s, f2s) = simp(r2)
    (r1s, r2s) match {
      case (NULL, _) => (r2s, F_RIGHT(f2s))
      case (_, NULL) => (r1s, F_LEFT(f1s))
      case _ =>
        if (r1s == r2s) (r1s, F_LEFT(f1s))
        else (ALT (r1s, r2s), F_ALT(f1s, f2s))
    }
  }
  ...
}

```

```

def F_RIGHT(f: Val => Val) = (v:Val) => Right(f(v))
def F_LEFT(f: Val => Val) = (v:Val) => Left(f(v))
def F_ALT(f1: Val => Val, f2: Val => Val) =
  (v:Val) => v match {
    case Right(v) => Right(f2(v))
    case Left(v) => Left(f1(v)) }

```

# Rectification

*simp*(*r*):...

case  $r = r_1 \cdot r_2$

let  $(r_{1s}, f_{1s}) = \text{simp}(r_1)$

$(r_{2s}, f_{2s}) = \text{simp}(r_2)$

case  $r_{1s} = \mathbf{0}$ : return  $(\mathbf{0}, f_{\text{error}})$

case  $r_{2s} = \mathbf{0}$ : return  $(\mathbf{0}, f_{\text{error}})$

case  $r_{1s} = \mathbf{I}$ : return  $(r_{2s}, \lambda v. \text{Seq}(f_{1s}(\text{Empty}), f_{2s}(v)))$

case  $r_{2s} = \mathbf{I}$ : return  $(r_{1s}, \lambda v. \text{Seq}(f_{1s}(v), f_{2s}(\text{Empty})))$

otherwise: return  $(r_{1s} \cdot r_{2s}, f_{\text{seq}}(f_{1s}, f_{2s}))$

$f_{\text{seq}}(f_1, f_2) \stackrel{\text{def}}{=}$

$\lambda v. \text{case } v = \text{Seq}(v_1, v_2): \text{return } \text{Seq}(f_1(v_1), f_2(v_2))$

```

def simp(r: Rexp): (Rexp, Val => Val) = r match {
  case SEQ(r1, r2) => {
    val (r1s, f1s) = simp(r1)
    val (r2s, f2s) = simp(r2)
    (r1s, r2s) match {
      case (NULL, _) => (NULL, F_ERROR)
      case (_, NULL) => (NULL, F_ERROR)
      case (EMPTY, _) => (r2s, F_SEQ_Void1(f1s, f2s))
      case (_, EMPTY) => (r1s, F_SEQ_Void2(f1s, f2s))
      case _ => (SEQ(r1s, r2s), F_SEQ(f1s, f2s))
    }
  }
}
...

```

```

def F_SEQ_Void1(f1: Val => Val, f2: Val => Val) =
  (v:Val) => Sequ(f1(Void), f2(v))

```

```

def F_SEQ_Void2(f1: Val => Val, f2: Val => Val) =
  (v:Val) => Sequ(f1(v), f2(Void))

```

```

def F_SEQ(f1: Val => Val, f2: Val => Val) =
  (v:Val) => v match {
    case Sequ(v1, v2) => Sequ(f1(v1), f2(v2)) }

```

# Rectification Example

$$(b \cdot c) + (\mathbf{0} + \mathbf{1}) \mapsto (b \cdot c) + \mathbf{1}$$

# Rectification Example

$$(\underline{b \cdot c}) + (\underline{\mathbf{0} + \mathbf{1}}) \mapsto (b \cdot c) + \mathbf{1}$$



# Rectification Example

$$(\underline{b \cdot c}) + (\underline{\mathbf{0} + \mathbf{I}}) \mapsto (b \cdot c) + \mathbf{I}$$

$$\begin{aligned} f_{s1} &= \lambda v.v \\ f_{s2} &= \lambda v.Right(v) \end{aligned}$$

# Rectification Example

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{1})} \mapsto (b \cdot c) + \mathbf{1}$$

$$\begin{aligned} f_{s_1} &= \lambda v. v \\ f_{s_2} &= \lambda v. \mathit{Right}(v) \end{aligned}$$

$$\begin{aligned} f_{alt}(f_{s_1}, f_{s_2}) &\stackrel{\text{def}}{=} \\ &\lambda v. \text{case } v = \mathit{Left}(v') : \text{return } \mathit{Left}(f_{s_1}(v')) \\ &\quad \text{case } v = \mathit{Right}(v') : \text{return } \mathit{Right}(f_{s_2}(v')) \end{aligned}$$

# Rectification Example

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{1})} \mapsto (b \cdot c) + \mathbf{1}$$

$$\begin{aligned} f_{s1} &= \lambda v.v \\ f_{s2} &= \lambda v.Right(v) \end{aligned}$$

$\lambda v.$  case  $v = Left(v')$ : return  $Left(v')$   
case  $v = Right(v')$ : return  $Right(Right(v'))$

# Rectification Example

$$\underline{(b \cdot c) + (\mathbf{0} + \mathbf{1})} \mapsto (b \cdot c) + \mathbf{1}$$

$$f_{s1} = \lambda v.v$$

$$f_{s2} = \lambda v.Right(v)$$

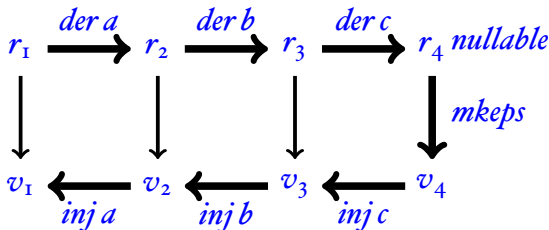
$\lambda v.$  case  $v = Left(v')$ : return  $Left(v')$   
case  $v = Right(v')$ : return  $Right(Right(v'))$

*mkeps* simplified case:  $Right(Empty)$   
rectified case:  $Right(Right(Empty))$

# Lexing with Simplification

$\text{lex } r \ [] \stackrel{\text{def}}{=} \text{if } \text{nullable}(r) \text{ then } \text{mkeps}(r) \text{ else } \text{error}$

$\text{lex } r \ c \ :: \ s \stackrel{\text{def}}{=} \text{let } (r', \text{frect}) = \text{simp}(\text{der}(c, r))$   
 $\text{inj } r \ c \ (\text{frect}(\text{lex}(r', s)))$



# Environments

Obtaining the “recorded” parts of a value:

$env(Empty)$	$\stackrel{\text{def}}{=} []$
$env(Char(c))$	$\stackrel{\text{def}}{=} []$
$env(Left(v))$	$\stackrel{\text{def}}{=} env(v)$
$env(Right(v))$	$\stackrel{\text{def}}{=} env(v)$
$env(Seq(v_1, v_2))$	$\stackrel{\text{def}}{=} env(v_1) @ env(v_2)$
$env([v_1, \dots, v_n])$	$\stackrel{\text{def}}{=} env(v_1) @ \dots @ env(v_n)$
$env(Rec(x : v))$	$\stackrel{\text{def}}{=} (x :  v ) :: env(v)$

# While Tokens

WHILE\_REGS  $\stackrel{\text{def}}{=} ((\text{"k"} : \text{KEYWORD}) +$   
     $(\text{"i"} : \text{ID}) +$   
     $(\text{"o"} : \text{OP}) +$   
     $(\text{"n"} : \text{NUM}) +$   
     $(\text{"s"} : \text{SEMI}) +$   
     $(\text{"p"} : (\text{LPAREN} + \text{RPAREN})) +$   
     $(\text{"b"} : (\text{BEGIN} + \text{END})) +$   
     $(\text{"w"} : \text{WHITESPACE}))^*$

”if true then then 42 else +”

```
KEYWORD(if),  
WHITESPACE,  
IDENT(true),  
WHITESPACE,  
KEYWORD(then),  
WHITESPACE,  
KEYWORD(then),  
WHITESPACE,  
NUM(42),  
WHITESPACE,  
KEYWORD(else),  
WHITESPACE,  
OP(+)
```



”if true then then 42 else +”

KEYWORD(if),  
IDENT(true),  
KEYWORD(then),  
KEYWORD(then),  
NUM(42),  
KEYWORD(else),  
OP(+)

# Two Rules

- Longest match rule (“maximal munch rule”): The longest initial substring matched by any regular expression is taken as next token.
- Rule priority: For a particular longest initial substring, the first regular expression that can match determines the token.

$$\text{zeroable}(\emptyset) \stackrel{\text{def}}{=} \text{true}$$

$$\text{zeroable}(\epsilon) \stackrel{\text{def}}{=} \text{false}$$

$$\text{zeroable}(c) \stackrel{\text{def}}{=} \text{false}$$

$$\text{zeroable}(r_1 + r_2) \stackrel{\text{def}}{=} \text{zeroable}(r_1) \wedge \text{zeroable}(r_2)$$

$$\text{zeroable}(r_1 \cdot r_2) \stackrel{\text{def}}{=} \text{zeroable}(r_1) \vee \text{zeroable}(r_2)$$

$$\text{zeroable}(r^*) \stackrel{\text{def}}{=} \text{false}$$

$\text{zeroable}(r)$  if and only if  $L(r) = \{\}$