Compilers and Formal Languages

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Slides & Progs: KEATS

Pollev: https://pollev.com/cfltutoratki576

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2 Regular Expressions, Derivatives	7 Compilation, JVM
3 Automata, Regular Languages	8 Compiling Functional Languages
4 Lexing, Tokenising	9 Optimisations
5 Grammars, Parsing	10 LLVM

While Tokens

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

The Goal of this Course

Write a compiler

Today a lexer.

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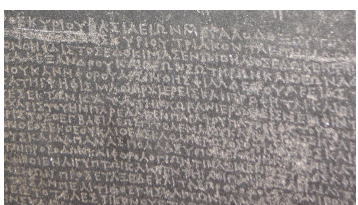

lexing $\Rightarrow$ recognising words (Stone of Rosetta)

Regular Expressions

In programming languages they are often used to recognise:

- operands, digits
- identifiers
- numbers (non-leading zeros)
- keywords
- comments

`http://www.regexper.com`

Lexing: Test Case

```
write "Fib";
read n;
minus1 := 0;
minus2 := 1;
while n > 0 do {
       temp := minus2;
       minus2 := minus1 + minus2;
       minus1 := temp;
       n := n - 1
};
write "Result";
write minus2
```

"if true then then 42 else +"

KEYWORD:

  if, then, else,

WHITESPACE:

  " ", \n,

IDENTIFIER:

  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*.

Or, keywords are `if` etc and identifiers are letters followed by "letters + numbers + _"*

```
if      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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http://www.haskell.org/haskellwiki/Regex_Posix

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traditional lexers are fast, but hairy

Sulzmann & Lu Matcher

We want to match the string abc using r_1:

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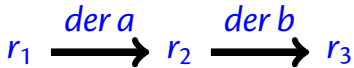

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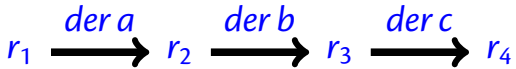

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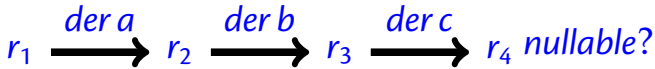

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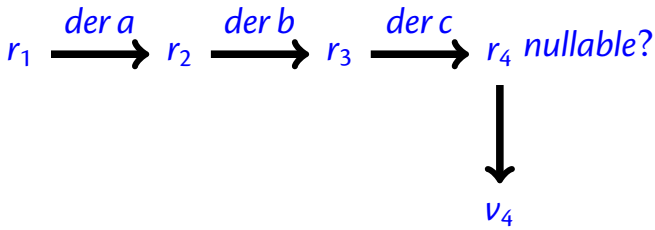

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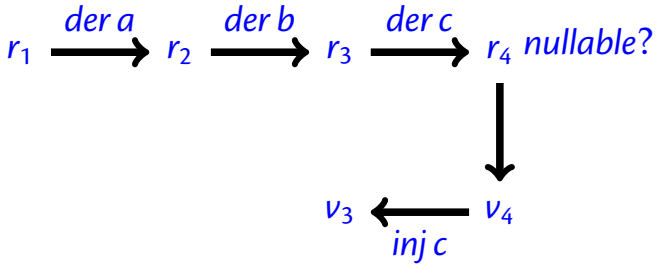

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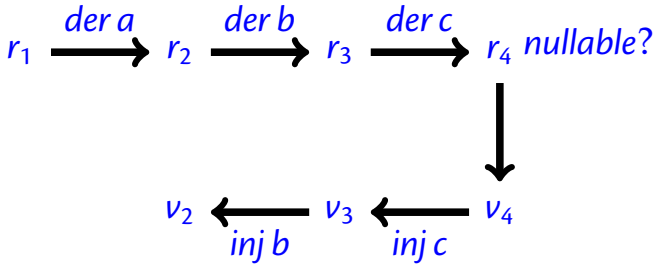

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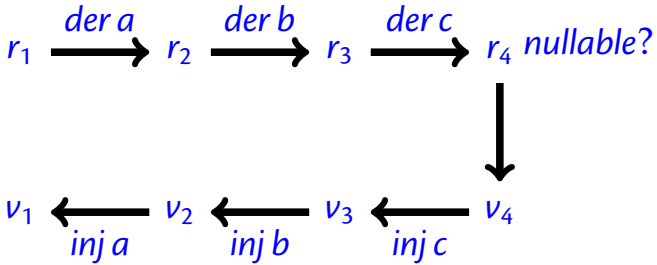

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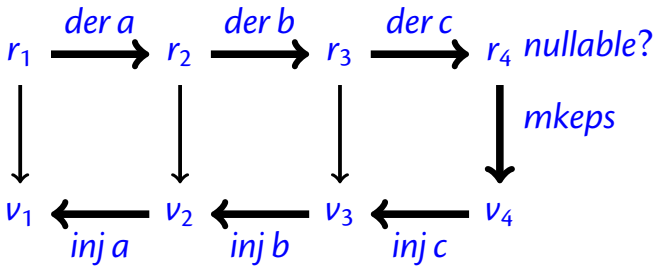


Regexes and Values

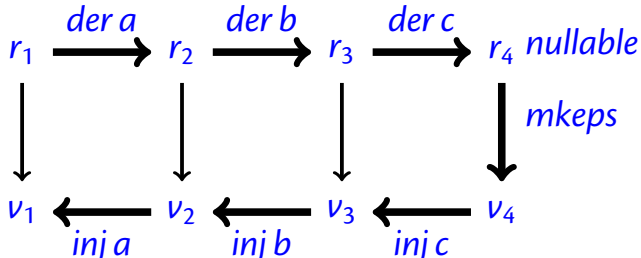
Regular expressions and their corresponding values:

$$
\begin{array}{rcl}
r & ::= & \mathbf{0} \\
 & | & \mathbf{1} \\
 & | & c \\
 & | & r_1 \cdot r_2 \\
 & | & r_1 + r_2 \\
 & | & r^* \\
 & | & (r)
\end{array}
\qquad
\begin{array}{rcl}
v & ::= & \\
 & & \mathit{Empty} \\
 & | & \mathit{Char}(c) \\
 & | & \mathit{Seq}(v_1, v_2) \\
 & | & \mathit{Left}(v) \\
 & | & \mathit{Right}(v) \\
 & | & \mathit{Stars}\,[] \\
 & | & \mathit{Stars}\,[v_1, \ldots v_n]
\end{array}
$$

```
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 Sequ(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
```

r_1: $a \cdot (b \cdot c)$
r_2: $\mathbf{1} \cdot (b \cdot c)$
r_3: $(\mathbf{0} \cdot (b \cdot c)) + (\mathbf{1} \cdot c)$
r_4: $(\mathbf{0} \cdot (b \cdot c)) + ((\mathbf{0} \cdot c) + \mathbf{1})$



r_1: $a \cdot (b \cdot c)$
r_2: $\mathbf{1} \cdot (b \cdot c)$
r_3: $(\mathbf{0} \cdot (b \cdot c)) + (\mathbf{1} \cdot c)$
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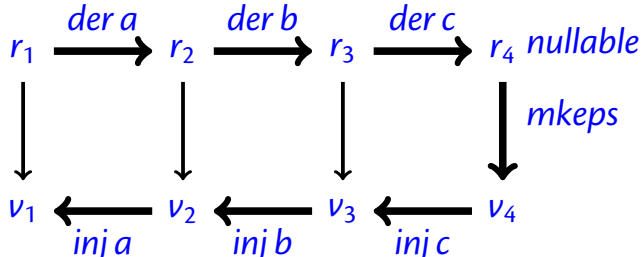


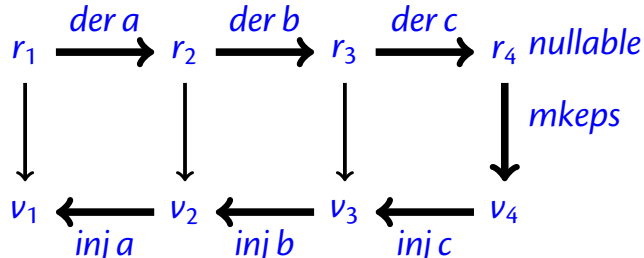
v_1: $Seq(Char(a), Seq(Char(b), Char(c)))$
v_2: $Seq(Empty, Seq(Char(b), Char(c)))$
v_3: $Right(Seq(Empty, Char(c)))$
v_4: $Right(Right(Empty))$

Flatten

Obtaining the string underlying a value:

$$
\begin{array}{lcl}
|Empty| & \stackrel{\text{def}}{=} & [] \\
|Char(c)| & \stackrel{\text{def}}{=} & [c] \\
|Left(v)| & \stackrel{\text{def}}{=} & |v| \\
|Right(v)| & \stackrel{\text{def}}{=} & |v| \\
|Seq(v_1, v_2)| & \stackrel{\text{def}}{=} & |v_1| \mathbin{@} |v_2| \\
|Stars\,[v_1, \ldots, v_n]| & \stackrel{\text{def}}{=} & |v_1| \mathbin{@} \ldots \mathbin{@} |v_n|
\end{array}
$$

r_1: $a \cdot (b \cdot c)$
r_2: $\mathbf{1} \cdot (b \cdot c)$
r_3: $(\mathbf{0} \cdot (b \cdot c)) + (\mathbf{1} \cdot c)$
r_4: $(\mathbf{0} \cdot (b \cdot c)) + ((\mathbf{0} \cdot c) + \mathbf{1})$



v_1: $Seq(Char(a), Seq(Char(b), Char(c)))$
v_2: $Seq(Empty, Seq(Char(b), Char(c)))$
v_3: $Right(Seq(Empty, Char(c)))$
v_4: $Right(Right(Empty))$

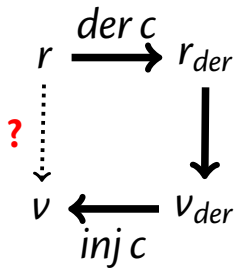
$|v_1|$: abc
$|v_2|$: bc
$|v_3|$: c
$|v_4|$: $[]$

Mkeps

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

$$
\begin{array}{lcl}
mkeps\,(\mathbf{1}) & \stackrel{\text{def}}{=} & Empty \\
mkeps\,(r_1 + r_2) & \stackrel{\text{def}}{=} & \text{if } nullable(r_1) \\
 & & \text{then } Left(mkeps(r_1)) \\
 & & \text{else } Right(mkeps(r_2)) \\
mkeps\,(r_1 \cdot r_2) & \stackrel{\text{def}}{=} & Seq(mkeps(r_1), mkeps(r_2)) \\
mkeps\,(r^*) & \stackrel{\text{def}}{=} & Stars\,[]
\end{array}
$$

Inject



Inject

Injecting ("Adding") a character to a value

$$
\begin{array}{ll}
inj\ (c)\ c\ (Empty) & \stackrel{\text{def}}{=} Char\ c \\
inj\ (r_1 + r_2)\ c\ (Left(v)) & \stackrel{\text{def}}{=} Left(inj\ r_1\ c\ v) \\
inj\ (r_1 + r_2)\ c\ (Right(v)) & \stackrel{\text{def}}{=} Right(inj\ r_2\ c\ v) \\
inj\ (r_1 \cdot r_2)\ c\ (Seq(v_1, v_2)) & \stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2) \\
inj\ (r_1 \cdot r_2)\ c\ (Left(Seq(v_1, v_2))) & \stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2) \\
inj\ (r_1 \cdot r_2)\ c\ (Right(v)) & \stackrel{\text{def}}{=} Seq(mkeps(r_1), inj\ r_2\ c\ v) \\
inj\ (r^*)\ c\ (Seq(v, Stars\ vs)) & \stackrel{\text{def}}{=} Stars\ (inj\ r\ c\ v\ ::\ vs)
\end{array}
$$

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

$$inj\,(c)\,c\,(Empty) \stackrel{\text{def}}{=} Char\,c$$

$$inj\ (r_1 + r_2)\ c\ (Left(v)) \stackrel{\text{def}}{=} Left(inj\ r_1\ c\ v)$$
$$inj\ (r_1 + r_2)\ c\ (Right(v)) \stackrel{\text{def}}{=} Right(inj\ r_2\ c\ v)$$

$$
\begin{array}{ll}
inj\ (r_1 \cdot r_2)\ c\ (Seq(v_1, v_2)) & \stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2) \\
inj\ (r_1 \cdot r_2)\ c\ (Left(Seq(v_1, v_2))) & \stackrel{\text{def}}{=} Seq(inj\ r_1\ c\ v_1, v_2) \\
inj\ (r_1 \cdot r_2)\ c\ (Right(v)) & \stackrel{\text{def}}{=} Seq(mkeps(r_1), inj\ r_2\ c\ v)
\end{array}
$$

$$
der\ c\ (r_1 \cdot r_2) \stackrel{\text{def}}{=} \textbf{if}\ nullable(r_1)\ \textbf{then}\ (der\ c\ r_1) \cdot r_2 + der\ c\ r_2\ \textbf{else}\ (der\ c\ r_1) \cdot r_2
$$

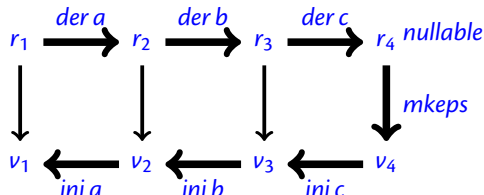
$$inj\,(r^*)\,c\,(Seq(v, Stars\,vs)) \stackrel{\text{def}}{=} Stars\,(inj\,r\,c\,v\ ::\ vs)$$

Lexing

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

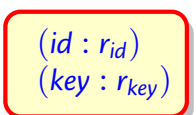
$$lex\ r\ a :: s \stackrel{\text{def}}{=} inj\ r\ a\ lex(der(a, r), s)$$

lex: returns a value



Records

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



Records

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

$(id : r_{id})$
$(key : r_{key})$

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 $(z : ((x : ab) + (y : ba))$

$(id : r_{id})$
$(key : r_{key})$

- A regular expression for email addresses

$$\begin{array}{l}(\text{name: } [a\text{-}z0\text{-}9\_\,.-]^+)\cdot@\cdot\\ \quad(\text{domain: } [a\text{-}z0\text{-}9\,-]^+)\cdot.\cdot\\ \quad\quad(\text{top\_level: } [a\text{-}z\,.]^{\{2,6\}})\end{array}$$

`christian.urban@kcl.ac.uk`

- the result environment:

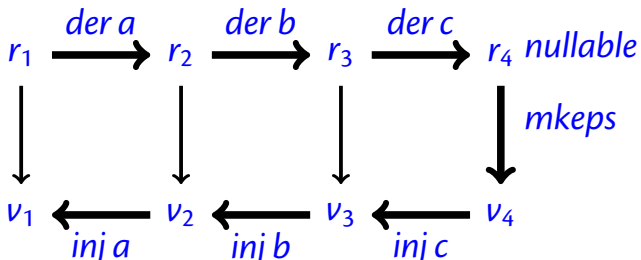
$$[(\mathit{name} : \texttt{christian.urban}),\ (\mathit{domain} : \texttt{kcl}),\ (\mathit{top\_level} : \texttt{ac.uk})]$$

While Tokens

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

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.



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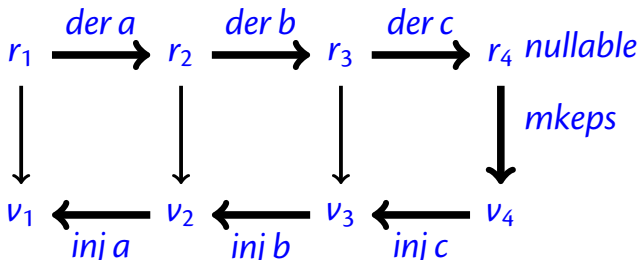


$$(\mathbf{0} \cdot (b \cdot c)) + ((\mathbf{0} \cdot c) + \mathbf{1}) \mapsto \mathbf{1}$$

Normally we would have

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

and answer how this regular expression matches the empty string with the value

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

But now we simplify this to $\mathbf{1}$ and would produce Empty (see *mkeps*).

Rectification

rectification functions:

$$
\begin{array}{lcll}
r \cdot \mathbf{0} & \mapsto & \mathbf{0} & \\
\mathbf{0} \cdot r & \mapsto & \mathbf{0} & \\
r \cdot \mathbf{1} & \mapsto & r & \lambda f_1\, f_2\, v.\, Seq(f_1\, v, f_2\, Empty) \\
\mathbf{1} \cdot r & \mapsto & r & \lambda f_1\, f_2\, v.\, Seq(f_1\, Empty, f_2\, v) \\
r + \mathbf{0} & \mapsto & r & \lambda f_1\, f_2\, v.\, Left(f_1\, v) \\
\mathbf{0} + r & \mapsto & r & \lambda f_1\, f_2\, v.\, Right(f_2\, v) \\
r + r & \mapsto & r & \lambda f_1\, f_2\, v.\, Left(f_1\, v)
\end{array}
$$

Rectification

			rectification functions:
$r \cdot \mathbf{0}$	$\mapsto$	$\mathbf{0}$	
$\mathbf{0} \cdot r$	$\mapsto$	$\mathbf{0}$	
$r \cdot \mathbf{1}$	$\mapsto$	r	$\lambda f_1\, f_2\, v.\, Seq(f_1\, v, f_2\, Empty)$
$\mathbf{1} \cdot r$	$\mapsto$	r	$\lambda f_1\, f_2\, v.\, Seq(f_1\, Empty, f_2\, v)$
$r + \mathbf{0}$	$\mapsto$	r	$\lambda f_1\, f_2\, v.\, Left(f_1\, v)$
$\mathbf{0} + r$	$\mapsto$	r	$\lambda f_1\, f_2\, v.\, Right(f_2\, v)$
$r + r$	$\mapsto$	r	$\lambda f_1\, f_2\, v.\, Left(f_1\, v)$

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

Rectification $\_ + \_$

$simp(r)$:

case $r = r_1 + r_2$

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

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

case $r_{1s} = \mathbf{0}$: return $(r_{2s}, \lambda v.\, Right(f_{2s}(v)))$

case $r_{2s} = \mathbf{0}$: return $(r_{1s}, \lambda v.\, Left(f_{1s}(v)))$

case $r_{1s} = r_{2s}$: return $(r_{1s}, \lambda v.\, Left(f_{1s}(v)))$

otherwise: return $(r_{1s} + r_{2s}, f_{alt}(f_{1s}, f_{2s}))$

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

$\lambda v.$ case $v = Left(v')$: return $Left(f_1(v'))$

case $v = Right(v')$: return $Right(f_2(v'))$

```
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 (ZERO, _) => (r2s, F_RIGHT(f2s))
      case (_, ZERO) => (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 $\_ \cdot \_$

$simp(r)$:...

case $r = r_1 \cdot r_2$

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

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

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

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

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

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

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

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

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

```
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 (ZERO, _) => (ZERO, F_ERROR)
      case (_, ZERO) => (ZERO, F_ERROR)
      case (ONE, _) => (r2s, F_SEQ_Empty1(f1s, f2s))
      case (_, ONE) => (r1s, F_SEQ_Empty2(f1s, f2s))
      case _ => (SEQ(r1s,r2s), F_SEQ(f1s, f2s))
    }
  }
  ...}
def F_SEQ_Empty1(f1: Val => Val, f2: Val => Val) =
  (v:Val) => Sequ(f1(Empty), f2(v))
def F_SEQ_Empty2(f1: Val => Val, f2: Val => Val) =
  (v:Val) => Sequ(f1(v), f2(Empty))
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

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

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

Rectification Example

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

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

$$f_{alt}(f_{s1}, f_{s2}) \stackrel{\text{def}}{=}$$
$$\lambda v.\ \text{case } v = Left(v'): \quad \text{return } Left(f_{s1}(v'))$$
$$\text{case } v = Right(v'): \text{return } Right(f_{s2}(v'))$$

Rectification Example

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

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

$$\begin{array}{ll} \lambda v. & \text{case } v = Left(v'): \quad \text{return } Left(v') \\ & \text{case } v = Right(v'): \text{return } Right(Right(v')) \end{array}$$

Rectification Example

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

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

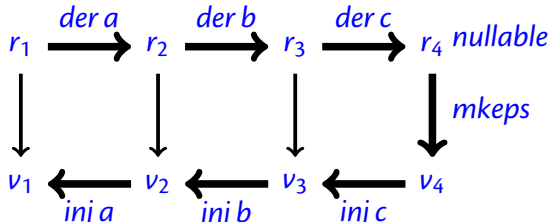
$$\begin{array}{ll} \lambda v. & \text{case } v = Left(v'): \quad \text{return } Left(v') \\ & \text{case } v = Right(v'): \text{return } Right(Right(v')) \end{array}$$

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

Lexing with Simplification

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

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



Environments

Obtaining the "recorded" parts of a value:

$$
\begin{array}{lcl}
env(Empty) & \stackrel{\text{def}}{=} & [] \\
env(Char(c)) & \stackrel{\text{def}}{=} & [] \\
env(Left(v)) & \stackrel{\text{def}}{=} & env(v) \\
env(Right(v)) & \stackrel{\text{def}}{=} & env(v) \\
env(Seq(v_1, v_2)) & \stackrel{\text{def}}{=} & env(v_1) \mathbin{@} env(v_2) \\
env(Stars\,[v_1, \ldots, v_n]) & \stackrel{\text{def}}{=} & env(v_1) \mathbin{@} \ldots \mathbin{@} env(v_n) \\
env(Rec(x : v)) & \stackrel{\text{def}}{=} & (x : |v|) :: env(v)
\end{array}
$$

While Tokens

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

```
"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(+)
```

Lexer: 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.

Environments

Obtaining the "recorded" parts of a value:

$$
\begin{array}{lcl}
env(Empty) & \stackrel{\text{def}}{=} & [] \\
env(Char(c)) & \stackrel{\text{def}}{=} & [] \\
env(Left(v)) & \stackrel{\text{def}}{=} & env(v) \\
env(Right(v)) & \stackrel{\text{def}}{=} & env(v) \\
env(Seq(v_1, v_2)) & \stackrel{\text{def}}{=} & env(v_1) \mathbin{@} env(v_2) \\
env(Stars[v_1, \ldots, v_n]) & \stackrel{\text{def}}{=} & env(v_1) \mathbin{@} \ldots \mathbin{@} env(v_n) \\
env(Rec(x : v)) & \stackrel{\text{def}}{=} & (x : |v|) :: env(v)
\end{array}
$$

While Tokens

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

```
"if true then then 42 else +"
```

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

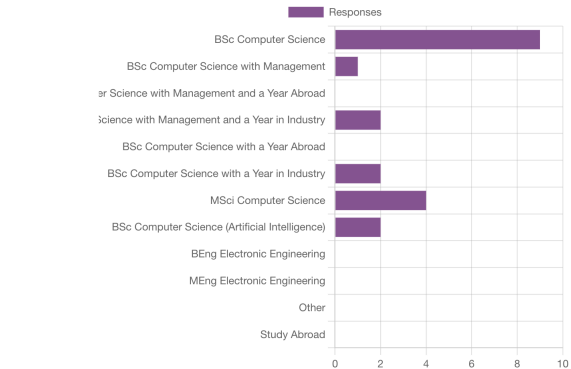
```
"if true then then 42 else +"
```

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

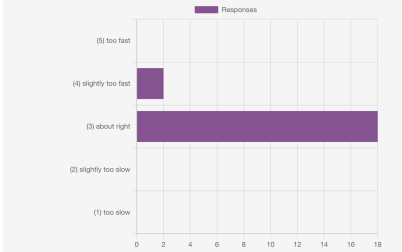
Week 3 Feedback

Submitted answers: 20
Questions: 12

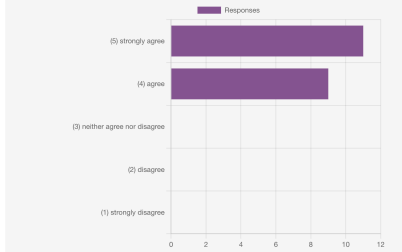
(Programme) Which degree programme are you studying?



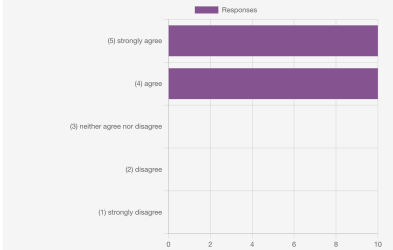
(AppropriatePace) ...teaches at a pace that is:



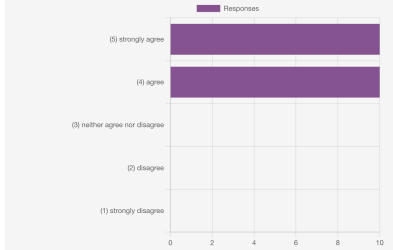
(ExplainsMaterialClearly) ...explains the material clearly



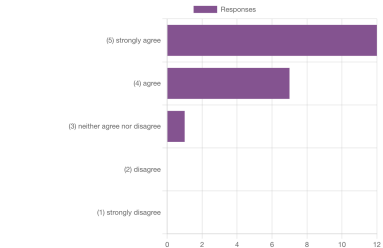
(contemporary) ..makes clear the contemporary relevance of the subject



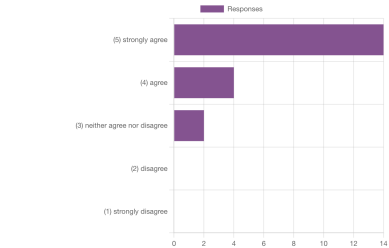
(keats) ...provides useful information on KEATS



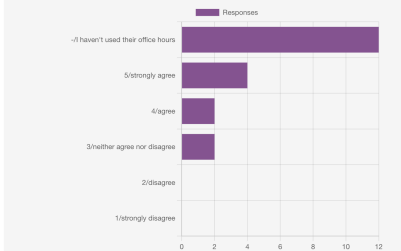
(objectives) ...has (have) made the module objectives clear



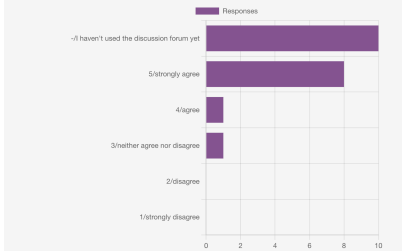
(amethods) ...has (have) made the assessment methods clear



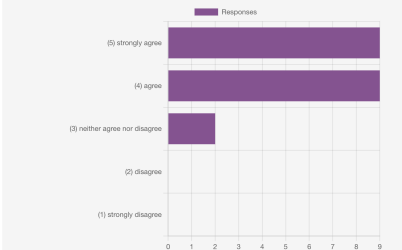
(ohours) ...is available to answer questions in office hours:



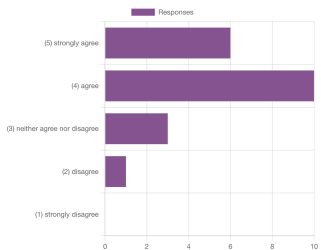
(forum) ...is available to answer questions on the discussion forum:



(Audible) The video lectures and other content on KEATS are helpful



(facilities) The live teaching sessions are helpful



- Great lecturer. Looking forward to the next lecture!
- Would it be possible for you to post the answer of the homework to KEATS after sgts each week? It will be very helpful for us to prepare for the exam. Thank you.
- A lot of the parts of the LGT are going through what was covered in the videos. While this is helpful to refresh students' minds, I think it would be better if the Pollev questions were checked more regularly to focus on what students want support with

$\Rightarrow$ Reluctant, but I am prepared for selected questions to make the answers public.
$\Rightarrow$ The content viewing numbers are a bit worrying. Therefore the reflex on my side is to lecture the content again. I also receive quite a large number of basic questions about CW2.

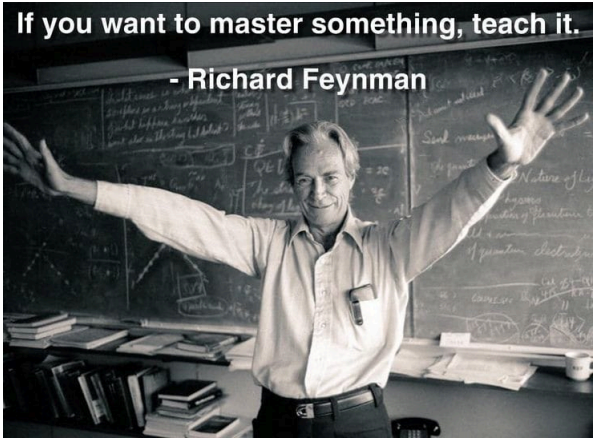
- Regarding module content, the content is not only interesting but relevant, up-to-date, and applicable to the real world. The practical, real-world application of the module is made abundantly clear through the coursework-focused delivery of the module. The content of the module progresses fast, but that is due to the nature of the content and the aims of the module. The learning aims and assessment are clearly explained.

  Regarding teaching, Dr. Urban is incredibly helpful both inside (and even outside) contact hours. I can tell the lecturer is very passionate about teaching the module. TAs are on hand to help with all aspects of the module, with the lecturer having taken care to have dedicated TAs for resolving technical issues. Discussions both on the forum and in lessons are encouraged, and the module is structured so that high engagement with the content and live lessons will make it easier for students to do the module (which is, of course, a good thing).

  Only 3 weeks in I would very highly recommend the module. It is a difficult subject, but a pleasure to study at the same time.

- Professor Christian is incredibly patient. He always stays longer after live session lectures to answer additional questions, even though he doesn't need to. He made me feel that no questions are stupid. Thanks so much!
- I am enjoying your module at the moment, I think you clearly explain every point and answer all questions during the live tutorial.
- It would be helpful to be given the full set of coursework templates on GitHub so that there is less ambiguity regarding future courseworks.
- Maybe some additional exercises in the LGT would be useful
- This module handout are the most useful thing I have ever seen in this uni.
- This module is structured very well and is very interesting. Thank you

$\Rightarrow$ In case of CW3 the starting files are comb1.sc and comb2.sc uploaded to KEATS. The CW3 & 4 files are now on Github.


If you want to master something, teach it.
- Richard Feynman