CS 591 S2—Formal Language Theory: Integrating Experimentation and Proof—Fall 2019

Problem Set 3

Model Answers

Problem 1

To begin with, we put the following declarations in the file `ps3-p1.sml`:

```
val zero = Sym.fromString "0";
val one  = Sym.fromString "1";

fun diff (nil : str) = 0
  | diff (b :: bs)   =
      if Sym.equal(b, zero)
      then ~1 + diff bs
      else 1 + diff bs;

fun equal n =
      Set.filter
      (fn x => diff x = 0)
      (StrSet.power(StrSet.fromString "0, 1", n));

fun upto 0 = equal 0
  | upto n = StrSet.union(equal n, upto(n - 1));

fun locSimp n = Reg.locallySimplify(SOME n, Reg.obviousSubset);

fun assess reg =
      let val cc = Reg.ccToList(Reg.cc reg)
      in (cc, length cc, Reg.size reg, Reg.numConcats reg,
          Reg.numSyms reg, Reg.standardized reg)
      end;
```

We then load this file into Forlan:

```
- use "ps3-p1.sml";
[opening ps3-p1.sml]
val zero = - : sym
val one = - : sym
val diff = fn : str -> int
val equal = fn : int -> str set
val upto = fn : int -> str set
val locSimp = fn : int -> reg -> bool * reg
val assess = fn : reg -> int list * int * int * int * int * bool
val it = () : unit
```

Given a natural number n:

- `equal` returns $\{\, w \in \{0,1\}^* \mid |w| = n \text{ and } \mathbf{diff}\ w = 0 \,\}$; and
- `upto` returns $\{\, w \in \{0,1\}^* \mid |w| \leq n \text{ and } \mathbf{diff}\ w = 0 \,\}$.

The function `locSimp` locally simplifies a regular expression using `Reg.obviousSubset` as the approximation to subset testing, and considering up to n structural reorganizations at each recursive call. And the function `assess` assesses the complexity of a regular expression.

Thus `upto 6` returns X, and we bind `xs` to X:

```
- val xs = upto 6;
val xs = - : str set
- Set.size xs;
val it = 29 : int
- StrSet.output("", xs);
%, 01, 10, 0011, 0101, 0110, 1001, 1010, 1100, 000111, 001011, 001101, 001110,
010011, 010101, 010110, 011001, 011010, 011100, 100011, 100101, 100110, 101001,
101010, 101100, 110001, 110010, 110100, 111000
val it = () : unit
```

To begin our first attempt at finding a simple regular expression generating X, we create a regular expression, `reg`, consisting of the union of all the elements of X:

```
- val reg = Reg.fromStrSet xs;
val reg = - : reg
- Reg.output("", reg);
% + 01 + 10 + 0011 + 0101 + 0110 + 1001 + 1010 + 1100 + 000111 + 001011 +
001101 + 001110 + 010011 + 010101 + 010110 + 011001 + 011010 + 011100 + 100011 +
100101 + 100110 + 101001 + 101010 + 101100 + 110001 + 110010 + 110100 + 111000
val it = () : unit
```

Then, we can try locally simplifying `reg` with increasing values of n: 10, 1000, 1500:

```
- val (b, reg10) = locSimp 10 reg;
val b = false : bool
val reg10 = - : reg
- assess reg10;
val it =
  ([0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0],97,193,68,96,true)
  : int list * int * int * int * int * bool
- Reg.output("", reg10);
% +
0
(1 + 0(0111 + 1(1 + 011 + 1(01 + 10))) +
 1(01 + 0(011 + 1(01 + 10)) + 1(0 + 0(01 + 10) + 100))) +
1
(0 + 001 + 00011 + 00101 + 00110 + 010 + 01001 + 01010 + 01100 +
```

```
 1(00 + 0001 + 0010 + 0100 + 1000))
val it = () : unit
- val (b, reg1000) = locSimp 1000 reg;
val b = false : bool
val reg1000 = - : reg
- assess reg1000;
val it =
  ([0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0],77,153,48,68,true) : int list * int * int * int * int * bool
- Reg.output("", reg1000);
% +
0
(0(0111 + 1(011 + 1(% + 01 + 10))) +
 1(% + 0(011 + 1(% + 01 + 10)) + 1(0(% + 01 + 10) + 100))) +
1
(0(% + 0(1(01 + 10) + (% + 01)1) + 1(0(% + 01 + 10) + 100)) +
 1(0(0(% + 01 + 10) + 100) + 1000))
val it = () : unit
- val (b, reg1500) = locSimp 1500 reg;
val b = false : bool
val reg1500 = - : reg
- assess reg1500;
val it =
  ([0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0],77,153,48,68,true) : int list * int * int * int * int * bool
- Reg.output("", reg1500);
% +
0
(0(0111 + 1(011 + 1(% + 01 + 10))) +
 1(% + 0(011 + 1(% + 01 + 10)) + 1(0(% + 01 + 10) + 100))) +
1
(0(% + 0(011 + 1(% + 01 + 10)) + 1(0(% + 01 + 10) + 100)) +
 1(0(0(% + 01 + 10) + 100) + 1000))
val it = () : unit
```

(It took about 10 minutes to carry out these simplifications on my laptop.) Note that `reg1000` and `reg1500` have the same complexity:

```
- Reg.compareComplexity(reg1000, reg1500);
val it = EQUAL : order
```

But `reg1500` is more symmetric than `1000`, as can be seen by manually reordering its unions:

```
% +
0
(0(1(1(% + 01 + 10) + 011) + 0111) +
 1(% + 0(1(% + 01 + 10) + 011) + 1(0(% + 01 + 10) + 100))) +
1
```

```
(1(0(0(% + 10 + 01) + 100) + 1000) +
 0(% + 1(0(% + 10 + 01) + 100) + 0(1(% + 10 + 01) + 011)))
```

Although `reg1500` is nicely symmetric, it seemed unlikely to be optimally simple, so I tried several approaches to guiding Forlan to a better result. The approach that worked best is detailed below.

First, we bind `fours` to the result of evaluating `equal 4`, i.e., to $\{\, w \in \{\mathtt{0},\mathtt{1}\}^* \mid |w| = 4 \text{ and } \mathbf{diff}\, w = 0 \,\}$:

```
- val fours = equal 4;
val fours = - : str set
- StrSet.output("", fours);
0011, 0101, 0110, 1001, 1010, 1100
val it = () : unit
```

Recall the elements of X:

```
- StrSet.output("", xs);
%, 01, 10, 0011, 0101, 0110, 1001, 1010, 1100, 000111, 001011, 001101, 001110,
010011, 010101, 010110, 011001, 011010, 011100, 100011, 100101, 100110, 101001,
101010, 101100, 110001, 110010, 110100, 111000
val it = () : unit
```

Because a majority of the elements of X end with one of the elements of `fours`, we will partition X into 8 sets: the elements of X ending in each of the 6 elements of `fours`, the elements of X with length no more than 2, and the length 6 elements of X that don't end with an element of `fours`:

```
- fun ends(x, ys) = Set.filter (fn y => Str.suffix(x, y)) ys
= val parts =
=       let val ps = Set.mapToList (fn y => ends(y, xs)) fours
=           val ws = StrSet.minus(xs, StrSet.genUnion ps)
=           val us = Set.filter (fn w => length w <= 2) ws
=           val vs = StrSet.minus(ws, us)
=       in vs :: us :: ps end;
val ends = fn : str * str set -> str set
val parts = [-,-,-,-,-,-,-,-] : str set list
- app (fn part => StrSet.output("", part)) parts;
000111, 001011, 001101, 001110, 110001, 110010, 110100, 111000
%, 01, 10
0011, 010011, 100011
0101, 010101, 100101
0110, 010110, 100110
1001, 011001, 101001
1010, 011010, 101010
1100, 011100, 101100
val it = () : unit
- StrSet.equal(StrSet.genUnion parts, xs);
val it = true : bool
```

So, the first element of parts consists of the length 6 elements of X that don't end with an element of fours, the next element is the elements of X with length no more than 2, and the remaining six elements are the elements of X ending in 0011, 0101, 0110, 1001, 1010 and 1100, respectively.

Next, we convert each element of parts into a regular expression that's the union of its elements, and simplify those regular expressions:

```
- val regs = map (fn ys => #2(locSimp 1000 (Reg.fromStrSet ys))) parts;
val regs = [-,-,-,-,-,-,-,-] : reg list
- app (fn reg => Reg.output("", reg)) regs;
00(11(01 + 10) + (01 + 10)11) + 11(00(01 + 10) + (01 + 10)00)
% + 01 + 10
(% + 01 + 10)0011
(% + 01 + 10)0101
(% + 01 + 10)0110
(% + 01 + 10)1001
(% + 01 + 10)1010
(% + 01 + 10)1100
val it = () : unit
```

Because all but the first of our regular expressions have a common subtree, we simplify the result of unioning those regular expressions together, resulting in reg':

```
- val reg' = #2(locSimp 1000 (Reg.genUnion(tl regs)));
val reg' = - : reg
- Reg.output("", reg');
(% + 01 + 10)(% + 0(011 + 1(01 + 10)) + 1(001 + (01 + 10)0))
val it = () : unit
```

Finally, we simplify the union the first element of regs and reg', calling the result reg'':

```
- val reg'' = #2(locSimp 1000 (Reg.union(hd regs, reg')));
val reg'' = - : reg
- assess reg'';
val it =
  ([0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
    0,0,0,0,0,0,0,0,0,0,0,0,0,0],52,103,35,50,true)
  : int list * int * int * int * int * bool
- Reg.output("", reg'');
00(11(01 + 10) + (01 + 10)11) + 11(00(01 + 10) + (01 + 10)00) +
(% + 01 + 10)(% + 0(011 + 1(01 + 10)) + 1(001 + (01 + 10)0))
val it = () : unit
```

We have that reg'' is correct by construction, but we can also directly verify its correctness:

```
- StrSet.equal(Reg.toStrSet reg'', xs);
val it = true : bool
```

Problem 2

Our regular expressions are $((01)^*)^*$ and $(0^*)^*(1^*)^*$. We can use Forlan to verify that our solution is correct, as follows:

```
- val reg1 = Reg.fromString "(01)**";
val reg1 = - : reg
- val reg2 = Reg.fromString "0**1**";
val reg2 = - : reg
- val cc1 = Reg.cc reg1;
val cc1 = - : Reg.cc
- val cc2 = Reg.cc reg2;
val cc2 = - : Reg.cc
- Reg.compareCC(cc1, cc2);
val it = EQUAL : order
- Reg.ccToList cc1;
val it = [2,2] : int list
- val size1 = Reg.size reg1;
val size1 = 5 : int
- val size2 = Reg.size reg2;
val size2 = 7 : int
- size1 = size2;
val it = false : bool
```

Problem 3

First, we define a function `locSimpTr` for locally simplifying a regular expression, with tracing turned on, using `Reg.obviousSubset` as the approximation to subset testing, and considering up to n structural reorganizations at each recursive call.

```
- fun locSimpTr n =
=       Reg.locallySimplifyTrace(SOME n, Reg.obviousSubset);
val locSimpTr = fn : int -> reg -> bool * reg
```

Then we use this function to illustrate how reduction rule (20) works:

```
- locSimpTr 100 (Reg.fromString "(11 + 111 + 11111 + 111111111)*");
exploration of structural reorganizations of (11 + 111 + 11111 + 111111111)*
curtailed
(11 + 111 + 11111 + 111111111)* transformed by reduction rule 20 at position []
to % + (11)1* weakly simplifies to % + 111*
considered all 12 structural reorganizations of % + 111*
% + 111* is locally simplified
val it = (true,-) : bool * reg
- locSimpTr 100
= (Reg.fromString "(111 + 1111 + 11111 + 1111111 + 1111111111)*");
exploration of structural reorganizations of
(111 + 1111 + 11111 + 1111111 + 1111111111)* curtailed
(111 + 1111 + 11111 + 1111111 + 1111111111)* transformed by reduction rule 20 at
position [] to % + (111)1* weakly simplifies to % + 1111*
considered all 40 structural reorganizations of % + 1111*
% + 1111* is locally simplified
val it = (true,-) : bool * reg
- locSimpTr 100
```

```
= (Reg.fromString
=  "(1111 + 11111 + 111111 + 1111111 + 1111111111 + 1111111111111)*");
exploration of structural reorganizations of
(1111 + 11111 + 111111 + 1111111 + 1111111111 + 1111111111111)* curtailed
(1111 + 11111 + 111111 + 1111111 + 1111111111 + 1111111111111)* transformed by
reduction rule 20 at position [] to % + (1111)1* weakly simplifies to % + 11111*
exploration of structural reorganizations of % + 11111* curtailed
% + 11111* may not be locally simplified
val it = (false,-) : bool * reg
- val reg = Reg.input "";
@ ((0+1)(0+1)(0+1)(0+1) + (0+1)(0+1)(0+1)(0+1)(0+1) + (0+1)(0+1)(0+1))*
@ .
val reg = - : reg
- locSimpTr 100 reg;
((0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
weakly simplifies to
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
exploration of structural reorganizations of
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
curtailed
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
transformed by structural rule 2 at position [1] to
(((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)) +
 (0 + 1)(0 + 1)(0 + 1))*
transformed by structural rule 5 at position [1, 1] to
(((0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1)) +
 (0 + 1)(0 + 1)(0 + 1))*
transformed by reduction rule 22 at position [1, 1] to
((% + 0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1))*
exploration of structural reorganizations of
((% + 0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1))* curtailed
((% + 0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1))* transformed
by structural rule 5 at position [1] to
((0 + 1)(0 + 1)(0 + 1) + (% + 0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1))* transformed
by structural rule 4 at position [1, 2] to
((0 + 1)(0 + 1)(0 + 1) + ((% + 0 + 1)(0 + 1))(0 + 1)(0 + 1)(0 + 1))* transformed
by reduction rule 22 at position [1] to
((% + (% + 0 + 1)(0 + 1))(0 + 1)(0 + 1)(0 + 1))*
exploration of structural reorganizations of
((% + (% + 0 + 1)(0 + 1))(0 + 1)(0 + 1)(0 + 1))* curtailed
((% + (% + 0 + 1)(0 + 1))(0 + 1)(0 + 1)(0 + 1))* may not be locally simplified
val it = (false,-) : bool * reg
- locSimpTr 1000 reg;
((0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) +
```

```
 (0 + 1)(0 + 1)(0 + 1))*
weakly simplifies to
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
exploration of structural reorganizations of
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
curtailed
((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1))*
transformed by structural rule 2 at position [1] to
(((0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)) +
 (0 + 1)(0 + 1)(0 + 1))*
transformed by structural rule 5 at position [1] to
((0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1)(0 + 1))*
transformed by structural rule 5 at position [1, 2] to
((0 + 1)(0 + 1)(0 + 1) + (0 + 1)(0 + 1)(0 + 1)(0 + 1) +
 (0 + 1)(0 + 1)(0 + 1)(0 + 1)(0 + 1))*
transformed by reduction rule 20 at position [] to
% + ((0 + 1)(0 + 1)(0 + 1))(0 + 1)* weakly simplifies to
% + (0 + 1)(0 + 1)(0 + 1)(0 + 1)*
considered all 640 structural reorganizations of
% + (0 + 1)(0 + 1)(0 + 1)(0 + 1)*
% + (0 + 1)(0 + 1)(0 + 1)(0 + 1)* is locally simplified
val it = (true,-) : bool * reg
```

The last two examples show how a large number of structural reorganizations must sometimes be considered before one to which rule (20) applies is found.

Problem 4

(a)

Our α is

$$(0(01)^*1 + 1(10)^*0)^*\ (\% + 0(01)^*(\% + 0) + 1(10)^*(\% + 1)).$$

(b)

Let

$$\begin{aligned} A_0 &= \{0\}\{01\}^*, \\ A_1 &= \{1\}\{10\}^*, \text{ and} \\ B &= (A_0\{1\} \cup A_1\{0\})^*\ (\{\%\} \cup A_0\{\%, 0\} \cup A_1\{\%, 1\}). \end{aligned}$$

Then $L(\alpha) = B$, so it will suffice to show $B = Y$. We show that $B \subseteq Y \subseteq B$.

For $l, m, n \in \mathbb{Z}$ such that $l \le 0$, $m \ge 0$ and $l \le n \le m$, define:

$$\begin{aligned} Y^{l,m} &= \{\, w \in \{\mathsf{0},\mathsf{1}\}^* \mid \text{for all prefixes } v \text{ of } w,\ l \le \mathbf{diff}\, v \le m \,\},\ \text{and} \\ Y^{l,m}_n &= \{\, w \in \{\mathsf{0},\mathsf{1}\}^* \mid w \in Y^{l,m} \text{ and } \mathbf{diff}\, w = n \,\} \end{aligned}$$

Thus:

- for all $l, m, n \in \mathbb{Z}$ such that $l \le 0$, $m \ge 0$ and $l \le n \le m$, $Y^{l,m}_n \subseteq Y^{l,m}$;
- for all $l, l', m, m' \in \mathbb{Z}$, if $l' \le l \le 0$ and $0 \le m \le m'$, then $Y^{l,m} \subseteq Y^{l',m'}$; and
- for all $l, l', m, m', n \in \mathbb{Z}$, if $l' \le l \le 0$, $0 \le m \le m'$ and $l \le n \le m$, then $Y^{l,m}_n \subseteq Y^{l',m'}_n$.

Lemma PS3.4.1

(1) $\% \in Y^{0,0}_0$.

(2) $\mathsf{0} \in Y^{-1,0}_{-1}$.

(3) $\mathsf{1} \in Y^{0,1}_1$.

(4) For all $l, l', m, m' \in \mathbb{Z}$, if $l, l' \le 0$ and $m, m' \ge 0$ then

$$Y^{l,m} \cup Y^{l',m'} \subseteq Y^{\mathbf{min}(l,l'),\mathbf{max}(m,m')}.$$

(5) For all $l, l', m, m', n \in \mathbb{Z}$, if $l, l' \le 0$, $m, m' \ge 0$, $l \le n \le m$ and $l' \le n \le m'$, then

$$Y^{l,m}_n \cup Y^{l',m'}_n \subseteq Y^{\mathbf{min}(l,l'),\mathbf{max}(m,m')}_n.$$

(6) For all $l, l', m, m', n \in \mathbb{Z}$, if $l, l' \le 0$, $m, m' \ge 0$ and $l \le n \le m$, then

$$Y^{l,m}_n Y^{l',m'} \subseteq Y^{\mathbf{min}(l,n+l'),\mathbf{max}(m,n+m')}.$$

(7) For all $l, l', m, m', n, n' \in \mathbb{Z}$, if $l, l' \le 0$, $m, m' \ge 0$, $l \le n \le m$ and $l' \le n' \le m'$, then

$$Y^{l,m}_n Y^{l',m'}_{n'} \subseteq Y^{\mathbf{min}(l,n+l'),\mathbf{max}(m,n+m')}_{n+n'}.$$

(8) For all $l, m \in \mathbb{Z}$, if $l \le 0$ and $m \ge 0$, then $(Y^{l,m}_0)^* \subseteq Y^{l,m}_0$.

Proof.

(1) Follows since $\mathbf{diff}\,\% = 0$, and $\%$ is the only prefix of itself.

(2) Follows since $\mathbf{diff}\,\% = 0$, $\mathbf{diff}\,\mathsf{0} = -1$ and the only prefixes of $\mathsf{0}$ are $\%$ and $\mathsf{0}$.

(3) Follows since $\mathbf{diff}\,\% = 0$, $\mathbf{diff}\,\mathsf{1} = 1$ and the only prefixes of $\mathsf{1}$ are $\%$ and $\mathsf{1}$.

(4) Suppose $w \in Y^{l,m} \cup Y^{l',m'}$. There are two cases to consider.

  - Suppose $w \in Y^{l,m}$. To see that $w \in Y^{\mathbf{min}(l,l'),\mathbf{max}(m,m')}$, suppose v is a prefix of w. Then $\mathbf{min}(l, l') \le l \le \mathbf{diff}\, v \le m \le \mathbf{max}(m, m')$.

- Suppose $w \in Y^{l',m'}$. The proof is similar to the other case.

(5) Follows immediately from part (4).

(6) Suppose $w \in Y_n^{l,m} Y^{l',m'}$, so that $w = xy$ for some $x \in Y_n^{l,m}$ and $y \in Y^{l',m'}$. To see that $w \in Y^{\mathbf{min}(l,n+l'),\mathbf{max}(m,n+m')}$, suppose v is a prefix of w. There are two cases to consider.

- Suppose v is a prefix of x. Then $\mathbf{min}(l, n+l') \leq l \leq \mathbf{diff}\, v \leq m \leq \mathbf{max}(m, n+m')$.
- Suppose $v = xu$ for a prefix u of y. Hence $l' \leq \mathbf{diff}\, u \leq m'$, so that $\mathbf{min}(l, n+l') \leq n+l' \leq n+\mathbf{diff}\, u \leq n+m' \leq \mathbf{max}(m, n+m')$. But $\mathbf{diff}\, v = \mathbf{diff}(xu) = \mathbf{diff}\, x + \mathbf{diff}\, u = n + \mathbf{diff}\, u$, so that $\mathbf{min}(l, n+l') \leq \mathbf{diff}\, v \leq \mathbf{max}(m, n+m')$.

(7) Suppose $w \in Y_n^{l,m} Y_{n'}^{l',m'}$, so that $w = xy$ for some $x \in Y_n^{l,m}$ and $y \in Y_{n'}^{l',m'}$. Thus $\mathbf{diff}\, w = \mathbf{diff}(xy) = \mathbf{diff}\, x + \mathbf{diff}\, y = n + n'$. And the rest follows by part (6).

(8) We use mathematical induction to show that, for all $n \in \mathbb{N}$, $(Y_0^{l,m})^n \subseteq Y_0^{l,m}$.

(Basis Step) We have that $(Y_0^{l,m})^0 = \{\%\} \subseteq Y_0^{0,0} \subseteq Y_0^{l,m}$, by part (1).

(Inductive Step) Suppose $n \in \mathbb{N}$, and assume the inductive hypothesis: $(Y_0^{l,m})^n \subseteq Y_0^{l,m}$. Then $(Y_0^{l,m})^{n+1} = Y_0^{l,m}(Y_0^{l,m})^n \subseteq Y_0^{l,m} Y_0^{l,m} \subseteq Y_{0+0}^{\mathbf{min}(l,0+l),\mathbf{max}(m,0+m)} = Y_0^{l,m}$, by the inductive hypothesis and part (7).

Now, suppose $w \in (Y_0^{l,m})^*$. Then $w \in (Y_0^{l,m})^n$, for some $n \in \mathbb{N}$. Hence $w \in (Y_0^{l,m})^n \subseteq Y_0^{l,m}$.

□

Lemma PS3.4.2

(1) $\{\mathsf{01}\}^* \subseteq Y_0^{-1,0}$.

(2) $\{\mathsf{10}\}^* \subseteq Y_0^{0,1}$.

(3) $A_\mathsf{0} \subseteq Y_{-1}^{-2,0}$.

(4) $A_\mathsf{1} \subseteq Y_1^{0,2}$.

(5) $A_\mathsf{0}\{\mathsf{1}\} \subseteq Y_0^{-2,0}$.

(6) $A_\mathsf{1}\{\mathsf{0}\} \subseteq Y_0^{0,2}$.

(7) $A_\mathsf{0}\{\mathsf{1}\} \cup A_\mathsf{1}\{\mathsf{0}\} \subseteq Y_0^{-2,2}$.

(8) $(A_\mathsf{0}\{\mathsf{1}\} \cup A_\mathsf{1}\{\mathsf{0}\})^* \subseteq Y_0^{-2,2}$.

(9) $\{\%, \mathsf{0}\} \subseteq Y^{-1,0}$.

(10) $\{\%, \mathsf{1}\} \subseteq Y^{0,1}$.

(11) $A_\mathsf{0}\{\%, \mathsf{0}\} \subseteq Y^{-2,0}$.

(12) $A_\mathsf{1}\{\%, \mathsf{1}\} \subseteq Y^{0,2}$.

(13) $\{\%\} \cup A_\mathsf{0}\{\%, \mathsf{0}\} \cup A_\mathsf{1}\{\%, \mathsf{1}\} \subseteq Y^{-2,2}$.

(14) $B \subseteq Y^{-2,2}$.

We use Lemma PS3.4.1 repeatedly, without reference, in the following proof.

Proof.

(1) We have that $\{\mathsf{01}\} = \{\mathsf{0}\}\{\mathsf{1}\} \subseteq Y_{-1}^{-1,0} Y_1^{0,1} \subseteq Y_{-1+1}^{\mathbf{min}(-1,-1+0),\mathbf{max}(0,-1+1)} = Y_0^{-1,0}$. Thus $\{\mathsf{01}\}^* \subseteq (Y_0^{-1,0})^* \subseteq Y_0^{-1,0}$.

(2) We have that $\{\mathsf{10}\} = \{\mathsf{1}\}\{\mathsf{0}\} \subseteq Y_1^{0,1} Y_{-1}^{-1,0} \subseteq Y_{1+-1}^{\mathbf{min}(0,1+-1),\mathbf{max}(1,1+0)} = Y_0^{0,1}$. Thus $\{\mathsf{10}\}^* \subseteq (Y_0^{0,1})^* \subseteq Y_0^{0,1}$.

(3) Since $\{\mathsf{0}\} \subseteq Y_{-1}^{-1,0}$, we have that $A_{\mathsf{0}} = \{\mathsf{0}\}\{\mathsf{01}\}^* \subseteq Y_{-1}^{-1,0} Y_0^{-1,0} \subseteq Y_{-1+0}^{\mathbf{min}(-1,-1+-1),\mathbf{max}(0,-1+0)} = Y_{-1}^{-2,0}$, by part (1)

(4) Since $\{\mathsf{1}\} \subseteq Y_1^{0,1}$, we have that $A_{\mathsf{1}} = \{\mathsf{1}\}\{\mathsf{10}\}^* \subseteq Y_1^{0,1} Y_0^{0,1} \subseteq Y_{1+0}^{\mathbf{min}(0,1+0),\mathbf{max}(1,1+1)} = Y_1^{0,2}$, by part (2).

(5) $A_{\mathsf{0}}\{\mathsf{1}\} \subseteq Y_{-1}^{-2,0} Y_1^{0,1} \subseteq Y_{-1+1}^{\mathbf{min}(-2,-1+0),\mathbf{max}(0,-1+1)} = Y_0^{-2,0}$, by part (3).

(6) $A_{\mathsf{1}}\{\mathsf{0}\} \subseteq Y_1^{0,2} Y_{-1}^{-1,0} \subseteq Y_{1+-1}^{\mathbf{min}(0,1+-1),\mathbf{max}(2,1+0)} = Y_0^{0,2}$, by part (4).

(7) $A_{\mathsf{0}}\{\mathsf{1}\} \cup A_{\mathsf{1}}\{\mathsf{0}\} \subseteq Y_0^{-2,0} \cup Y_0^{0,2} \subseteq Y_0^{\mathbf{min}(-2,0),\mathbf{max}(0,2)} = Y_0^{-2,2}$, by parts (5) and (6).

(8) Since $A_{\mathsf{0}}\{\mathsf{1}\} \cup A_{\mathsf{1}}\{\mathsf{0}\} \subseteq Y_0^{-2,2}$, by part (7), we have that $(A_{\mathsf{0}}\{\mathsf{1}\} \cup A_{\mathsf{1}}\{\mathsf{0}\})^* \subseteq (Y_0^{-2,2})^* \subseteq Y_0^{-2,2}$.

(9) $\{\%, \mathsf{0}\} = \{\%\} \cup \{\mathsf{0}\} \subseteq Y^{0,0} \cup Y^{-1,0} \subseteq Y^{\mathbf{min}(0,-1),\mathbf{max}(0,0)} = Y^{-1,0}$.

(10) $\{\%, \mathsf{1}\} = \{\%\} \cup \{\mathsf{1}\} \subseteq Y^{0,0} \cup Y^{0,1} \subseteq Y^{\mathbf{min}(0,0),\mathbf{max}(0,1)} = Y^{0,1}$.

(11) $A_{\mathsf{0}}\{\%, \mathsf{0}\} \subseteq Y_{-1}^{-2,0} Y^{-1,0} \subseteq Y^{\mathbf{min}(-2,-1+-1),\mathbf{max}(0,-1+0)} = Y^{-2,0}$, by parts (3) and (9)

(12) $A_{\mathsf{1}}\{\%, \mathsf{1}\} \subseteq Y_1^{0,2} Y^{0,1} \subseteq Y^{\mathbf{min}(0,1+0),\mathbf{max}(2,1+1)} = Y^{0,2}$, by parts (4) and (10).

(13) $\{\%\} \cup A_{\mathsf{0}}\{\%, \mathsf{0}\} \cup A_{\mathsf{1}}\{\%, \mathsf{1}\} \subseteq Y^{0,0} \cup Y^{-2,0} \cup Y^{0,2} \subseteq Y^{\mathbf{min}(0,-2),\mathbf{max}(0,0)} \cup Y^{0,2} = Y^{-2,0} \cup Y^{0,2} \subseteq Y^{\mathbf{min}(-2,0),\mathbf{max}(0,2)} = Y^{-2,2}$, by parts (11) and (12).

(14) $B = (A_{\mathsf{0}}\{\mathsf{1}\} \cup A_{\mathsf{1}}\{\mathsf{0}\})^*(\{\%\} \cup A_{\mathsf{0}}\{\%, \mathsf{0}\} \cup A_{\mathsf{1}}\{\%, \mathsf{1}\}) \subseteq Y_0^{-2,2} Y^{-2,2} \subseteq Y^{\mathbf{min}(-2,0+-2),\mathbf{max}(2,0+2)} = Y^{-2,2}$, by parts (8) and (13).

□

By Lemma PS3.4.2(14), we have that $B \subseteq Y^{-2,2} = Y$. So, it remains to show that $Y \subseteq B$.

Lemma PS3.4.3
For all $x, y \in \{\mathsf{0}, \mathsf{1}\}^*$, if $xy \in Y$ and $\mathbf{diff}\, x = 0$, then $y \in Y$.

Proof. Suppose $x, y \in \{\mathsf{0}, \mathsf{1}\}^*$, $xy \in Y$ and $\mathbf{diff}\, x = 0$. To show that $y \in Y$, suppose v is a prefix of y. Hence xv is a prefix of xy, so that $-2 \leq \mathbf{diff}(xv) \leq 2$. But $\mathbf{diff}(xv) = \mathbf{diff}\, x + \mathbf{diff}\, v = 0 + \mathbf{diff}\, v = \mathbf{diff}\, v$, so that $-2 \leq \mathbf{diff}\, v \leq 2$, as required. □

Lemma PS3.4.4
$Y \subseteq B$.

Proof. Since $Y \subseteq \{0,1\}^*$, it will suffice to show that, for all $w \in \{0,1\}^*$,

$$\text{if } w \in Y, \text{ then } w \in B.$$

We proceed by strong string induction. Suppose $w \in \{0,1\}^*$, and assume the inductive hypothesis: for all $x \in \{0,1\}^*$, if x is a proper substring of w, then,

$$\text{if } x \in Y, \text{ then } x \in B.$$

We must show that,

$$\text{if } w \in Y, \text{ then } w \in B.$$

Suppose $w \in Y$. We must show that $w \in B$. There are three cases to consider.

- Suppose $w = \%$. Then

$$w = \% = \%\% \in (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%, 0\} \cup A_1\{\%, 1\}) = B.$$

- Suppose $w = 0x$, for some $x \in \{0,1\}^*$. Let y be the longest prefix of x that is an element of $\{01\}^*$ (y is well-defined, because it could be $\%$), and $z \in \{0,1\}^*$ be such that $x = yz$. Thus $w = 0x = 0yz$ and $0y \in \{0\}\{01\}^* = A_0$. There are three subcases to consider.
  - Suppose $z = \%$. Then

  $$\begin{aligned} w = 0yz = 0y\% = 0y = \%(0y)\% &\in (A_0\{1\} \cup A_1\{0\})^* A_0\{\%, 0\} \\ &\subseteq (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%, 0\} \cup A_1\{\%, 1\}) = B. \end{aligned}$$

  - Suppose $z = 0u$, for some $u \in \{0,1\}^*$. Thus $x = yz = y0u$ and $w = 0x = 0y0u$.
    Suppose, toward a contradiction, that $u \neq \%$. There are two cases to consider.
    * Suppose $u = 0v$, for some $v \in \{0,1\}^*$. Then $w = 0y0u = 0y00v$. By Lemma PS3.4.2(1), we have that $y \in \{01\}^* \subseteq Y_0^{-1,0}$, so that $\mathbf{diff}\, y = 0$. Hence $\mathbf{diff}(0y00) = \mathbf{diff}\, 0 + \mathbf{diff}\, y + \mathbf{diff}\, 0 + \mathbf{diff}\, 0 = -1 + 0 + -1 + -1 = -3$. But $0y00$ is a prefix of $w \in Y$—contradiction.
    * Suppose $u = 1v$, for some $v \in \{0,1\}^*$. Then $x = y0u = y01v$. Since $y \in \{01\}^*$, it follows that $y01 \in \{01\}^*\{01\} \subseteq \{01\}^*$. But $y01$ is a longer prefix of x than y, contradicting the definition of y.

    Since we obtained a contradiction in both cases, we have an overall contradiction. Thus $u = \%$.

    Since $u = \%$, we have that

  $$\begin{aligned} w = 0y0u = 0y0\% = 0y0 = \%(0y)0 &\in (A_0\{1\} \cup A_1\{0\})^* A_0\{\%, 0\} \\ &\subseteq (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%, 0\} \cup A_1\{\%, 1\}) = B. \end{aligned}$$

– Suppose $z = 1u$, for some $u \in \{0,1\}^*$. Thus $w = 0yz = 0y1u$. By Lemma PS3.4.2(5), $0y1 \in A_0\{1\} \subseteq Y_0^{-2,0}$, so that $\mathbf{diff}(0y1) = 0$. Thus, since $0y1u = w \in Y$, Lemma PS3.4.3 tells us that $u \in Y$. Since u is a proper substring of w, the inductive hypothesis tells us that $u \in B$. Hence

$$\begin{aligned} w = 0y1u &\in A_0\{1\}B \subseteq (A_0\{1\} \cup A_1\{0\})B \subseteq (A_0\{1\} \cup A_1\{0\})^*B \\ &= (A_0\{1\} \cup A_1\{0\})^*(A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) \\ &= (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) = B. \end{aligned}$$

- Suppose $w = 1x$, for some $x \in \{0,1\}^*$. Let y be the longest prefix of x that is an element of $\{10\}^*$ (y is well-defined, because it could be $\%$), and $z \in \{0,1\}^*$ be such that $x = yz$. Thus $w = 1x = 1yz$ and $1y \in \{1\}\{10\}^* = A_1$. There are three subcases to consider.

  – Suppose $z = \%$. Then

$$\begin{aligned} w = 1yz = 1y\% = 1y = \%(1y)\% &\in (A_0\{1\} \cup A_1\{0\})^*A_1\{\%,1\} \\ &\subseteq (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) = B. \end{aligned}$$

  – Suppose $z = 1u$, for some $u \in \{0,1\}^*$. Thus $x = yz = y1u$ and $w = 1x = 1y1u$.

  Suppose, toward a contradiction, that $u \neq \%$. There are two cases to consider.

    * Suppose $u = 1v$, for some $v \in \{0,1\}^*$. Then $w = 1y1u = 1y11v$. By Lemma PS3.4.2(2), we have that $y \in \{10\}^* \subseteq Y_0^{0,1}$, so that $\mathbf{diff}\, y = 0$. Hence $\mathbf{diff}(1y11) = \mathbf{diff}\,1 + \mathbf{diff}\,y + \mathbf{diff}\,1 + \mathbf{diff}\,1 = 1 + 0 + 1 + 1 = 3$. But $1y11$ is a prefix of $w \in Y$—contradiction.
    * Suppose $u = 0v$, for some $v \in \{0,1\}^*$. Then $x = y1u = y10v$. Since $y \in \{10\}^*$, it follows that $y10 \in \{10\}^*\{10\} \subseteq \{10\}^*$. But $y10$ is a longer prefix of x than y, contradicting the definition of y.

  Since we obtained a contradiction in both cases, we have an overall contradiction. Thus $u = \%$.

  Since $u = \%$, we have that

$$\begin{aligned} w = 1y1u = 1y1\% = 1y1 = \%(1y)1 &\in (A_0\{1\} \cup A_1\{0\})^*A_1\{\%,1\} \\ &\subseteq (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) = B. \end{aligned}$$

  – Suppose $z = 0u$, for some $u \in \{0,1\}^*$. Thus $w = 1yz = 1y0u$. By Lemma PS3.4.2(6), $1y0 \in A_1\{0\} \subseteq Y_0^{0,2}$, so that $\mathbf{diff}(1y0) = 0$. Thus, since $1y0u = w \in Y$, Lemma PS3.4.3 tells us that $u \in Y$. Since u is a proper substring of w, the inductive hypothesis tells us that $u \in B$. Hence

$$\begin{aligned} w = 1y0u &\in A_1\{0\}B \subseteq (A_0\{1\} \cup A_1\{0\})B \subseteq (A_0\{1\} \cup A_1\{0\})^*B \\ &= (A_0\{1\} \cup A_1\{0\})^*(A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) \\ &= (A_0\{1\} \cup A_1\{0\})^*(\{\%\} \cup A_0\{\%,0\} \cup A_1\{\%,1\}) = B. \end{aligned}$$

□