Why Separation Logic is the Bee's Knees, and why you should care

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- Advances in computing are advances in formalism, and vice-versa.

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```
var   $reading, latest : bit$
      $slot :$ array $bit$ of $bit$
      $data :$ array $bit$ of array $bit$ of $datatype$

procedure  $write$    $(item : datatype);$
           var        $pair, index : bit;$
           begin
                      $pair :=$ not$(reading);$
                      $index :=$ not$(slot[pair]);$
                      $data[pair, index] := item;$
                      $slot[pair] := index;$
                      $latest := pair$
           end;

procedure  $read :$   $datatype;$
           var        $pair, index : bit;$
           begin
                      $pair := latest;$
                      $reading := pair;$
                      $index := slot[pair];$
                      $read := data[pair, index]$
           end;
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- (Concurrent programming programs are small: it’s no coincidence.)

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- Milner's CCS and Hoare's CSP were attempts to re-engineer concurrency in terms of message passing and identifiable processes.
- They were both impossible to use. They both rumble on in PhD theses, and will do so for ever.

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- Steve Brookes has said sorry for failure semantics, and pointed out that if you use asynchronous message-passing and sort-of-infinite buffers, it all gets easier still. And I now know how to fix Pascal-m.

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- Structured Programming was a Bloody Good Idea, in stark contrast to Software Engineering (UML, anybody?).

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- Types won when they reached C, because they helped people to program more safely with C pointers and procedure calls (though C syntax did its best to stop them).
- Bertrand Meyer (Eifell) thinks that OOP is based on the idea of types. Would that it were so! (The road to Hell is paved with good intentions.)

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- Pointers were *right out*, and probably anathema.

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- That train wreck haunts us still: half of you are here to laugh at my idiocy in still trying to ride the rails.

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- Here we are around our campfire, telling stories and wondering if the smoke will have gone before the dawn. You're all pretty demoralised.

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- This time, the hoo-hah is going to work for real.

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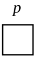

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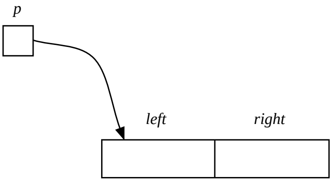

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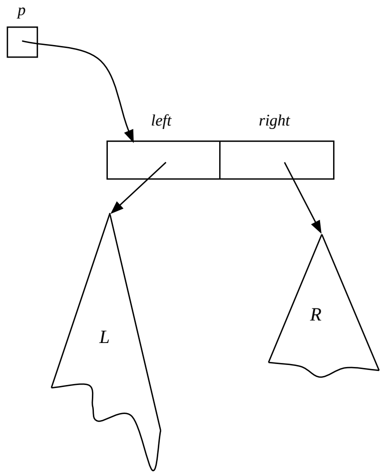

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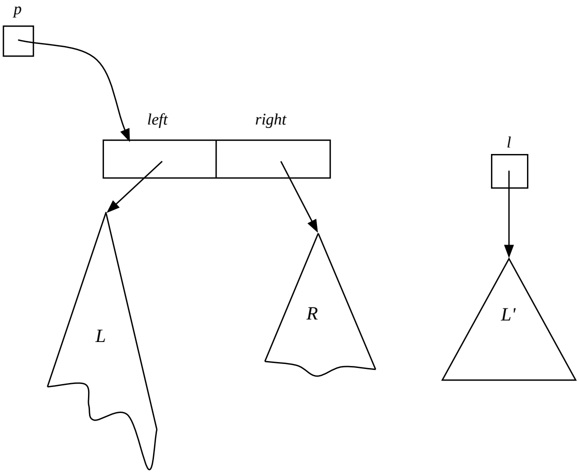

... and an alternative left subtree.

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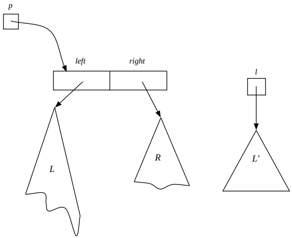

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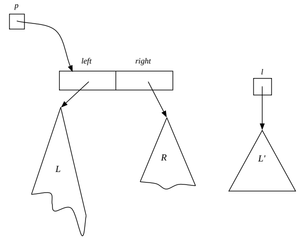

What could be easier?

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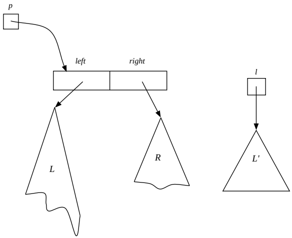

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$$\begin{aligned}&temp := p.left;\\&p.left := l;\\&\text{disposetree } temp\end{aligned}$$

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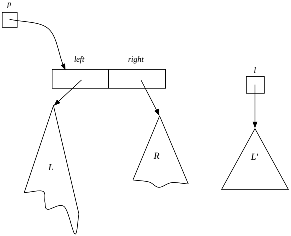

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$$temp := p.left;$$
$$p.left := l;$$
$$\text{disposetree } temp$$

(basic first-year undergrad stuff!)

How to describe a tree (Reynolds)

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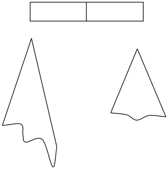
Trees come apart, into three separate sections.



How to describe a tree (Reynolds)

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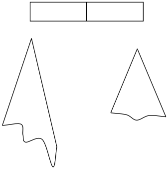

$$\begin{aligned} \text{tree}\ \mathsf{Empty}\ p &\ \hat{=}\ \ p = \mathrm{nil} \wedge \mathbf{emp} \\ \text{tree}\ \mathsf{Node}(\lambda, \rho)\ p &\ \hat{=}\ \ \exists l, r \cdot (p \mapsto l, r \star \text{tree}\ \lambda\ l \star \text{tree}\ \rho\ r) \end{aligned}$$

($p \mapsto l, r$ is a record, $A \star B$ is heap separation)

Separation logic

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- $A \star B$ is separation of heaps; $A \wedge B$, $A \vee B$, $\neg A$, $A \rightarrow B$, $\forall x \cdot P(x)$, $\exists x \cdot P(x)$ are as normal. $A \wedge B$ expresses coincidence of heaps; you don’t need to know about $A \mathrel{-\!\!\star} B$.

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- $A \star B$ is separation of heaps; $A \wedge B$, $A \vee B$, $\neg A$, $A \rightarrow B$, $\forall x \cdot P(x)$, $\exists x \cdot P(x)$ are as normal. $A \wedge B$ expresses coincidence of heaps; you don't need to know about $A \mathrel{-\!\!\star} B$.
- $E \mapsto F_0, F_1$ is just shorthand for $E \mapsto F_0 \star E + 1 \mapsto F_1$.

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- $\{Q\}\ C\ \{R\}$ is a resourced and partial correctness assertion. C will not go wrong (exceed its allocated resources) if started with resource Q, and will, if it terminates, deliver resource R.

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- The ‘small axioms’ of assignment are

$$
\begin{array}{l}
\{\mathbf{emp}\}\,x := \mathrm{new}()\;\{x \mapsto \_\} \\
\{E \mapsto \_\}\;\mathrm{dispose}\,E\;\{\mathbf{emp}\} \\
\{R[E/x]\}\,x := E\;\{R\} \qquad (\text{the Hoare axiom}) \\
\{E \mapsto F\}\,x := [E]\;\{x = F \wedge E \mapsto F\} \qquad (x \text{ not free in } E, F) \\
\{E \mapsto \_\}\;[E] := F\;\{E \mapsto F\}
\end{array}
$$

Three inference rules

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$$\frac{\{Q_1\}\ C_1\ \{R_1\} \quad \{Q_2\}\ C_2\ \{R_2\} \quad \ldots \quad \{Q_n\}\ C_n\ \{R_n\}}{\{Q_1 \star Q_2 \star \cdots \star Q_n\}\ C_1 \mid\mid C_2 \mid\mid \cdots \mid\mid C_n\ \{R_1 \star R_2 \star \cdots \star R_n\}}$$

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- The CCR rule (has *atrocious* side condition):

$$\frac{\{(Q \star I_b) \wedge G\}\ C\ \{R \star I_b\}}{\{Q\}\ \text{with}\ b\ \text{when}\ G\ \text{do}\ C\ \text{od}\ \{R\}}$$

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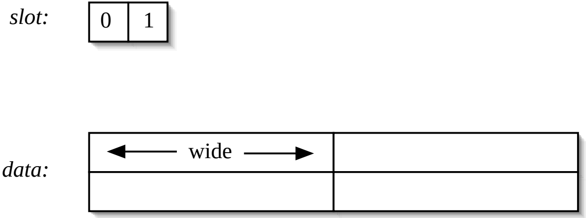
Recent simplifications (not explained here)

- Permissions (fractions of $\mapsto$, counts of $\rightarrowtail$) to allow sharing of heap;
- Variable permissions, to allow variables to be resource;
- Trivial side conditions;
- No side conditions at all (very new, this!).

Data structures: a bit array and a wide data array



slot:

0 1

data:

wide

Nine lines are now ten, with added auxiliary proof-variables

```
write:  with $bundle$ when true do $pair :=$ not$(reading)$; $wuse := pair$ od;
        $index :=$ not$(slot[pair])$;
        $data[pair, index] := item$;
        with $bundle$ when true do $slot[pair] := index$; $wuse := -1$ od;
        with $bundle$ when true do $latest := pair$ od

read:   with $bundle$ when true do $pair := latest$ od;
        with $bundle$ when true do $reading := pair$ od;
        with $bundle$ when true do $index := slot[pair]$; $ruse := index$ od;
        $read := data[pair, index]$;
        with $bundle$ when true do $ruse := -1$ od
```

What the writer owns

(A point of notation: I’ve used a special form of $\mapsto$ to describe a heap, just to make the slides easy to read.

For example, $data[pair, index] \mapsto \_$ replaces $data + 2 \star pair + index \mapsto \_$.

There is no change in meaning.)

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There is no change in meaning.)

$$latest_{0.5}, slot_{0.5}, data_{0.33}, wuse_{0.5}, pair, index$$

$$\models \left(\begin{array}{l} slot[0] \xmapsto[0.5]{\quad} \_ \star slot[1] \xmapsto[0.5]{\quad} \_ \star \\ \text{if } wuse \geq 0 \text{ then } data[pair, index] \mapsto \_ \text{ else } \mathbf{emp} \text{ fi} \end{array} \right)$$

What the reader owns

$$
\begin{array}{l}
reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \\
\quad \models \text{if } ruse \geq 0 \text{ then } data[pair, index] \mapsto \_ \text{ else } \mathbf{emp} \text{ fi}
\end{array}
$$

The bundle owns the rest

$latest_{0.5}, reading_{0.5}, slot_{0.5}, data_{0.33}, wuse_{0.5}, ruse_{0.5}$

$$\models \exists s \cdot \left(\begin{array}{l}
slot[0] \xmapsto[0.5]{} s(0) \star slot[1] \xmapsto[0.5]{} s(1) \star \\
\text{if } wuse \geq 0 \wedge ruse \geq 0 \text{ then} \\
\quad data[reading, \mathrm{not}(ruse)] \mapsto \_ \star data[wuse, s(wuse)] \mapsto \_ \\
\text{elsf } wuse \geq 0 \text{ then} \\
\quad data[wuse, s(wuse)] \mapsto \_ \star \\
\quad data[\mathrm{not}(wuse), s(\mathrm{not}(wuse))] \mapsto \_ \star data[\mathrm{not}(wuse), \mathrm{not}(s(\mathrm{not}(wuse)))] \mapsto \_ \\
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\quad data[\mathrm{not}(reading), s(\mathrm{not}(reading))] \mapsto \_ \star data[\mathrm{not}(reading), \mathrm{not}(s(\mathrm{not}(reading)))] \mapsto \_) \\
\text{else} \\
\quad data \mapsto \_, \_, \_, \_ \\
\text{fi}
\end{array} \right)$$

The writer

$$\left\{ \mathit{latest}_{0.5}, \mathit{slot}_{0.5}, \mathit{data}_{0.33}, \mathit{wuse}_{0.5}, \mathit{pair}, \mathit{index} \vDash \mathit{wuse} = -1 \wedge \mathit{slot}[0] \xmapsto[0.5]{} \_ \star \mathit{slot}[1] \xmapsto[0.5]{} \_ \right\}$$

with bundle when true do $\mathit{pair} := \mathrm{not}(\mathit{reading}); \mathit{wuse} := \mathit{pair}$ od;

$\mathit{index} := \mathrm{not}(\mathit{slot}[\mathit{pair}]);$

$\mathit{data}[\mathit{pair}, \mathit{index}] := \mathit{item};$

with bundle when true do $\mathit{slot}[\mathit{pair}] := \mathit{index}; \mathit{wuse} := -1$ od;

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$\text{with } bundle \text{ when true do } pair := \mathrm{not}(reading);\ wuse := pair \text{ od};$

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$index := \mathrm{not}(slot[pair]);$

$data[pair, index] := item;$

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with *bundle* when true do *pair* := not(*reading*); *wuse* := *pair* od;

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with *bundle* when true do *slot*[*pair*] := *index*; *wuse* := -1 od;

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with *bundle* when true do *latest* := *pair* od

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Details of the first writer step

```
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  with $bundle$ when true do

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    $wuse := pair$

  od;
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with *bundle* when true do

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pair := not(*reading*);

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wuse := *pair*

od;

$$\left\{\begin{array}{l} \mathit{latest}_{0.5}, \mathit{slot}_{0.5}, \mathit{data}_{0.33}, \mathit{wuse}_{0.5}, \mathit{pair}, \mathit{index} \\ \quad \vDash \mathit{wuse} = \mathit{pair} \wedge \exists i \cdot \left(\ \mathit{slot}[\mathit{pair}] \xmapsto[0.5]{} i \star \mathit{slot}[\mathrm{not}(\mathit{pair})] \xmapsto[0.5]{} \_ \star \mathit{data}[\mathit{pair}, \mathrm{not}(i)] \mapsto \_\ \right) \end{array}\right\}$$

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$$\left\{\ \mathit{latest}_{0.5}, \mathit{slot}_{0.5}, \mathit{data}_{0.33}, \mathit{wuse}_{0.5}, \mathit{pair}, \mathit{index} \models \mathit{wuse} = -1 \land \mathit{slot}[0] \underset{0.5}{\longmapsto} \_ \star \mathit{slot}[1] \underset{0.5}{\longmapsto} \_\ \right\}$$

with *bundle* when true do

$$\left\{\begin{array}{l} \mathit{latest}, \mathit{reading}_{0.5}, \mathit{slot}, \mathit{data}_{0.66}, \mathit{wuse}, \mathit{pair}, \mathit{index} \\ \models \exists s \cdot \left(\begin{array}{l} \mathit{wuse} = -1 \land \mathit{slot} \mapsto s(0), s(1) \star \\ \mathit{data}[\mathrm{not}(\mathit{reading}), s(\mathrm{not}(\mathit{reading}))] \mapsto \_ \star \mathit{data}[\mathrm{not}(\mathit{reading}), \mathrm{not}(s(\mathrm{not}(\mathit{reading})))] \mapsto \_ \star \\ \ \text{if } \mathit{ruse} \geq 0 \ \text{ then } \mathit{data}[\mathit{reading}, \mathrm{not}(\mathit{ruse})] \mapsto \_ \\ \qquad\qquad\quad \text{else } \mathit{data}[\mathit{reading}, s(\mathit{reading})] \mapsto \_ \star \mathit{data}[\mathit{reading}, \mathrm{not}(s(\mathit{reading}))] \mapsto \_ \\ \ \text{fi} \end{array}\right) \end{array}\right\}$$

$\mathit{pair} := \mathrm{not}(\mathit{reading});$

$$\left\{\begin{array}{l} \mathit{latest}, \mathit{reading}_{0.5}, \mathit{slot}, \mathit{data}_{0.66}, \mathit{wuse}, \mathit{pair}, \mathit{index} \\ \models \exists s \cdot \left(\begin{array}{l} \mathit{wuse} = -1 \land \mathit{pair} = \mathrm{not}(\mathit{reading}) \land \mathit{slot} \mapsto s(0), s(1) \star \\ \mathit{data}[\mathrm{not}(\mathit{reading}), s(\mathrm{not}(\mathit{reading}))] \mapsto \_ \star \mathit{data}[\mathrm{not}(\mathit{reading}), \mathrm{not}(s(\mathrm{not}(\mathit{reading})))] \mapsto \_ \star \\ \ \text{if } \mathit{ruse} \geq 0 \ \text{ then } \mathit{data}[\mathit{reading}, \mathrm{not}(\mathit{ruse})] \mapsto \_ \\ \qquad\qquad\quad \text{else } \mathit{data}[\mathit{reading}, s(\mathit{reading})] \mapsto \_ \star \mathit{data}[\mathit{reading}, \mathrm{not}(s(\mathit{reading}))] \mapsto \_ \\ \ \text{fi} \end{array}\right) \end{array}\right\}$$

$\mathit{wuse} := \mathit{pair}$

$$\left\{\begin{array}{l} \mathit{latest}, \mathit{reading}_{0.5}, \mathit{slot}, \mathit{data}_{0.66}, \mathit{wuse}, \mathit{pair}, \mathit{index} \\ \models \exists s \cdot \left(\begin{array}{l} \mathit{wuse} = \mathit{pair} \land \mathit{pair} = \mathrm{not}(\mathit{reading}) \land \mathit{slot} \mapsto s(0), s(1) \star \\ \mathit{data}[\mathrm{not}(\mathit{reading}), s(\mathrm{not}(\mathit{reading}))] \mapsto \_ \star \mathit{data}[\mathrm{not}(\mathit{reading}), \mathrm{not}(s(\mathrm{not}(\mathit{reading})))] \mapsto \_ \star \\ \ \text{if } \mathit{ruse} \geq 0 \ \text{ then } \mathit{data}[\mathit{reading}, \mathrm{not}(\mathit{ruse})] \mapsto \_ \\ \qquad\qquad\quad \text{else } \mathit{data}[\mathit{reading}, s(\mathit{reading})] \mapsto \_ \star \mathit{data}[\mathit{reading}, \mathrm{not}(s(\mathit{reading}))] \mapsto \_ \\ \ \text{fi} \end{array}\right) \end{array}\right\}$$

od;

$$\left\{\begin{array}{l} \mathit{latest}_{0.5}, \mathit{slot}_{0.5}, \mathit{data}_{0.33}, \mathit{wuse}_{0.5}, \mathit{pair}, \mathit{index} \\ \quad \models \mathit{wuse} = \mathit{pair} \land \exists i \cdot \left(\ \mathit{slot}[\mathit{pair}] \underset{0.5}{\longmapsto} i \star \mathit{slot}[\mathrm{not}(\mathit{pair})] \underset{0.5}{\longmapsto} \_ \star \mathit{data}[\mathit{pair}, \mathrm{not}(i)] \mapsto \_\ \right) \end{array}\right\}$$

The reader is even easier than the writer!

```
$\{\ reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \vDash ruse = -1\ \}$
  with $bundle$ when true do $pair := latest$ od;

  with $bundle$ when true do $reading := pair$ od;

  with $bundle$ when true do $index := slot[pair]; ruse := index$ od;

  $read := data[pair, index]$;


  with $bundle$ when true do $ruse := -1$ od
$\{\ reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \vDash ruse = -1\ \}$
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$\{\ reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \vDash ruse = -1 \wedge reading = pair\ \}$
  with $bundle$ when true do $index := slot[pair]$; $ruse := index$ od;

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with *bundle* when true do $index := slot[pair]; ruse := index$ od;
$\{\ reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \models ruse \geq 0 \land reading = pair \land data[pair, index] \mapsto \_\ \}$
$read := data[pair, index];$

with *bundle* when true do $ruse := -1$ od
$\{\ reading_{0.5}, ruse_{0.5}, data_{0.33}, pair, index \models ruse = -1\ \}$

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$\{\ \mathit{reading}_{0.5}, \mathit{ruse}_{0.5}, \mathit{data}_{0.33}, \mathit{pair}, \mathit{index} \vDash \mathit{ruse} = -1\ \}$

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$\mathit{read} := \mathit{data}[\mathit{pair}, \mathit{index}]$;

$$\left\{ \begin{array}{l} \mathit{reading}_{0.5}, \mathit{ruse}_{0.5}, \mathit{data}_{0.33}, \mathit{pair}, \mathit{index} \\ \quad \vDash \mathit{ruse} \geq 0 \wedge \mathit{reading} = \mathit{pair} \wedge \exists i \cdot \mathit{data}[\mathit{pair}, \mathit{index}] \mapsto i \wedge \mathit{read} = i \end{array} \right\}$$

with bundle when true do $\mathit{ruse} := -1$ od

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The rest of the reader is too easy to bother with

$$\mathrm{with}\ \mathit{bundle}\ \mathrm{when\ true\ do}\ \mathit{index} := \mathit{slot}[\mathit{pair}]; \mathit{ruse} := \mathit{index}$$

(in the reader) is very very *very* similar to

$$\mathrm{with}\ \mathit{bundle}\ \mathrm{when\ true\ do}\ \mathit{pair} := \mathsf{not}(\mathit{reading}); \mathit{wuse} := \mathit{pair}\ \mathrm{od}$$

(which I just showed you in detail from the writer),

so you don’t need to see it.

The rest of the reader is too easy to bother with

$$\text{with } bundle \text{ when true do } index := slot[pair];\, ruse := index$$

(in the reader) is very very *very* similar to

$$\text{with } bundle \text{ when true do } pair := \mathsf{not}(reading);\, wuse := pair \text{ od}$$

(which I just showed you in detail from the writer),

so you don’t need to see it.

And the rest of the reader is trivial.

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- I hope it has been worth the wait.

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- Matthew Parkinson, then Matthew Parkinson and I, did proofs of some old concurrency puzzlers.