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Additional Notes on

A Model for

COMMUNICATING SEQUENTIAL PROCESSES

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Summary: These notes contain copies of the overhead projector slides presented at the Communicating Sequential Processes Symposium in Wollongong which were not included in the original preprint 80-1 issued at the Symposium.

ALGEBRAIC PROPERTIES.

\square is associative
 commutative
 idempotent
 with unit:
 and "zero":

$$P \square (Q \square R) = (P \square Q) \square R$$

$$P \square Q = Q \square P$$

$$P \square P = P$$

$$P \square \text{ABORT} = P$$

$$P \square (\bar{P})^* = (\bar{P})^*$$

\parallel is associative
 commutative
 with unit:
 and zero:

$$P \parallel (Q \parallel R) = (P \parallel Q) \parallel R$$

$$P \parallel Q = Q \parallel P$$

$$P \parallel (\bar{P})^* = P$$

$;$ is associative
 with unit:
 and zero:
 and distributes:

$$P; (Q; R) = (P; Q); R$$

$$\text{SKIP}; P = P$$

$$\text{ABORT}; P = \text{ABORT}$$

$$(a \rightarrow P); Q = a \rightarrow (P; Q)$$

$$(P \square Q); R = (P; R) \square (Q; R)$$

\gg is associative
 and distributes:

$$P \gg (Q \gg R) = (P \gg Q) \gg R$$

$$(ABORT \gg ABORT) = (ABORT \gg (?x:T \rightarrow Q(x)))$$

$$=(?!x; P) \gg ABORT) = ABORT$$

$$(!v; P) \gg (?x:T \rightarrow Q(x)) = P \gg Q(v) \quad \text{for } v \in T.$$

$$() \gg () = ABORT \quad \text{for } v \notin T$$

$$(!v; P) \gg (!x; Q) = !x; ((!v; P) \gg Q) \quad "$$

$$(?x:S \rightarrow P(x)) \gg (?y:T \rightarrow Q(y)) =$$

$$(?x:S \rightarrow (P(x) \gg (?y:T \rightarrow Q(y))))$$

$$(?v:S \rightarrow P(v)) \gg (!x; Q) =$$

$$(?v:S \rightarrow (P(v) \gg (!x; Q)))$$

$$\square (!x; ((?v:S \rightarrow P(v)) \gg Q))$$

$$(?v:S \rightarrow P(v)) = (?w:S \rightarrow P(w))$$

$$(?v:\{\} \rightarrow P(v)) = ABORT.$$

RECURSION

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Def. A process with alphabet A is a non-empty prefix-closed subset of A^*

Thm. If P_i are processes with alphabet A for all i in T , then so are

$\bigcup_{i \in T} P_i$ Thus processes form a complete lattice under \subseteq , with ABORT as bottom and A^* as top

Def. A function F from processes to processes is distributive if for all sets $\{P_i \mid i \in T\}$

$$F\left(\bigcup_{i \in T} P_i\right) = \bigcup_{i \in T} F(P_i)$$

Thm. $\rightarrow, \sqcap, \parallel, ;, m:, \setminus$ are distributive (and hence continuous and monotonic) in each of their arguments.

hm (Tarski, Scott). If F is continuous,
 then the least p satisfying

$$p = F(p) = (\dots; \overset{\leftarrow}{p} \dots \overset{\leftarrow}{p} \dots \overset{\leftarrow}{p} \dots)$$

$$\text{is } \bigcup_{i \in \mathbb{N}} F^i(\text{ABORT}) \quad \stackrel{\text{def}}{=} \mu p. F(p)$$

$$\text{where } F^0(q) = q \quad F(A)$$

$$F^{n+1}(q) = F^n(F(q))$$

When a process is defined by recursion,
 we intend it to be the least solution
 of its defining equation.

And the same is true for sets of
 mutually recursive equations.

$$\text{Proof RHS} \Rightarrow F\left(\bigcup_{i \in \mathbb{N}} F^i(\text{ABORT})\right) = \bigcup_{i \in \mathbb{N}} F(F^i(\text{ABORT})) \quad [\text{continuity}]$$

$$= \bigcup_{i \in \mathbb{N}} F^{i+1}(\text{ABORT}) \quad [\text{def } F^{i+1}]$$

$$= \text{ABORT} \cup \bigcup_{i > 0} F^i(\text{ABORT}) \quad [\text{ABORT} \subseteq \text{any}]$$

$$= \bigcup_{i \in \mathbb{N}} F^i(\text{ABORT}),$$

Unique fixed Points.

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If $F(p)$ is an expression in which p appears only to the right of \rightarrow , (and F does not contain localisation), then the solution to $p = F(p)$ is unique.

Proof: $F(p)$ always does something before making the recursive call on p . So

$F^n(p)$ does at least n things before calling on p ; these are the same things as for $F^n(q)$.

Suppose $p = F(p)$ & $q = F(q)$. Let $s \in p$ be of length n . Since $p = F^m(p)$ for all m , $s \in F^n(p)$. so $s \in F^n(q)$. Thus $p \subseteq q$. Similarly, $q \subseteq p$.

$\therefore p = q$

The same is true for sets of mutually recursive equations.

RECURSION INDUCTION

$$\text{COUNT}_0 = (\text{iszero} \rightarrow \text{COUNT}_0 \parallel \text{up} \rightarrow \text{COUNT}_1)$$

$$\text{COUNT}_n = (\text{down} \rightarrow \text{COUNT}_n \parallel \text{up} \rightarrow \text{COUNT}_{n+2})$$

$$\text{POS} = (\text{down} \rightarrow \text{SKIP} \parallel \text{up} \rightarrow \text{POS}; \text{POS})$$

$$\text{ZERO} = (\text{iszero} \rightarrow \text{ZERO} \parallel \text{up} \rightarrow \text{POS}; \text{ZERO}).$$

Theorem. $\text{ZERO} = \text{COUNT}_0.$

Proof. Define $C_0 = (\text{iszero} \rightarrow C_0 \parallel \text{up} \rightarrow C_2)$

$$C_{n+1} = \text{POS}; C_n$$

$$C_{n+1} = (\text{down} \rightarrow \text{SKIP}; C_n \parallel \text{up} \rightarrow (\text{POS}; \text{POS}); C_n) \quad \begin{array}{l} \text{def } C_{n+1} \\ \& \text{ distr } ; \end{array}$$

$$= (\text{down} \rightarrow C_n \parallel \text{up} \rightarrow \text{POS}; (\text{POS}; C_n)) \quad \text{prop } ;$$

$$= (\text{down} \rightarrow C_n \parallel \text{up} \rightarrow \text{POS}; C_{n+1}) \quad \text{def } C_{n+1}$$

$$= (\text{down} \rightarrow C_n \parallel \text{up} \rightarrow C_{n+2}) \quad \text{def } C_{n+1}$$

$$\therefore C_n = \text{COUNT}_n \quad \text{for all } n. \quad \dots (1)$$

but $C_0 = (\text{iszero} \rightarrow C_0 \parallel \text{up} \rightarrow \text{POS}; C_0)$

$$\therefore C_0 = \text{ZERO} \quad \dots (2)$$

Conclusion follows from (1), (2).

YET ANOTHER COUNT.

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$$Z = (\text{iszero} \rightarrow Z \square \text{up} \rightarrow (p:Z \parallel X); Z)$$

$$\text{where } X = (\text{up} \rightarrow p.\text{up} \rightarrow X$$

$$\square \text{down} \rightarrow (p.\text{iszero} \rightarrow \text{SKIP}$$

$$\square p.\text{down} \rightarrow X$$

$$)$$

Theorem. $Z = \text{ZERO}$

RELATIONS.

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Let $R : (\text{ins}(\alpha P))^* \leftrightarrow (\text{outs}(\alpha P))^*$

$P \text{ sat } R = \text{df } \forall s (s \in P \rightarrow (\text{ins}(s), \text{outs}(s)) \in R)$

- at all times, the sequence of values input by P bears relation R to the sequence of values output by P .

e.g. let f : be a monotonic function of traces.

let $R_f = \{(i, o) \mid o \leq f(i)\}$

If $P \text{ sat } R_f$, P is said to be a pipe for f .

We shall often represent R as a predicate on the variables "in" and "out"

e.g. $P \text{ sat } (\text{out} \leq \text{in}) = P \text{ sat } \{(in, out) \mid \text{out} \leq \text{in}\}$

- means that P is a buffer

i.e. a pipe for the identity function.

Theorem. $Q \text{ sat } R \ \& \ R \subseteq S \Rightarrow Q \text{ sat } S$

$(\forall i \ Q_i \text{ sat } R) \Rightarrow (\bigcup_i Q_i) \text{ sat } R$

IF $\text{ABORT} \text{ sat } R \ \& \ \forall p. p \text{ sat } R \Rightarrow F(p) \text{ sat } R$

then $(\mu p. F(p)) \text{ sat } R.$ (Fixed point induction)

$$\textcircled{1} \quad \text{ABORT} \underline{\text{sat}} R \equiv R \begin{matrix} \text{in} & \text{out} \\ \leftrightarrow & \leftrightarrow \end{matrix}$$

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$$\textcircled{2} \quad (!x; P) \underline{\text{sat}} R \equiv P \underline{\text{sat}} R \begin{matrix} \text{out} \\ \langle x \rangle \text{out} \end{matrix}$$

where $R \begin{matrix} \text{out} \\ \langle x \rangle \text{out} \end{matrix} = \{(i, o) \mid (i, \langle x \rangle o) \in R\}$

i.e. replace "out" by " $\langle x \rangle \text{out}$ " in R

$$\textcircled{3} \quad (?x: T \rightarrow P(x)) \underline{\text{sat}} R \equiv \forall x: T. (P(x) \underline{\text{sat}} R \begin{matrix} \text{in} \\ \langle x \rangle \text{in} \end{matrix})$$

i.e. it works for all input values.

$$\begin{aligned} \text{by } \textcircled{2} \quad (!x; B) \underline{\text{sat}} \text{out} \leq \langle x \rangle \text{in} &\equiv B \underline{\text{sat}} (\langle x \rangle \text{out} \leq \langle x \rangle \text{in}) \\ &\equiv B \underline{\text{sat}} \text{out} \leq \text{in}. \end{aligned}$$

$$\begin{aligned} \text{by } \textcircled{3} \quad ((?x: T \rightarrow !x; B) \underline{\text{sat}} \text{out} \leq \text{in}) \\ &\equiv \forall x: T. (!x; B) \underline{\text{sat}} \text{out} \leq \langle x \rangle \text{in} \\ &\equiv B \underline{\text{sat}} \text{out} \leq \text{in} \quad (\text{just proved}) \end{aligned}$$

$$\text{by } \textcircled{1} \quad \text{ABORT} \underline{\text{sat}} \text{out} \leq \text{in}. \quad (\text{because } \text{outs}(\langle \rangle) = \text{ins}(\langle \rangle) = \langle \rangle)$$

$$\therefore \text{ if } B =_{\text{df.}} (?x: T \rightarrow !x; B)$$

then B is a buffer. (Fixed point induction)

$$T = \text{outs}(aP) = \text{ins}(aQ)$$

$$(P \text{ sat } R) \ \& \ (Q \text{ sat } S) \Rightarrow$$

$$(P \gg Q) \text{ sat } \exists s (R_s^{\text{out}} \ \& \ S_s^{\text{in}})$$

which is $(R; S)$ — relational composition of R and S .

Proof. $t \in (P \gg Q)$, $P \text{ sat } R$, $Q \text{ sat } S$ — assume

$$\therefore \exists u. t = u \uparrow T \quad \& \quad \exists v \in P \quad \exists w \in Q$$

$$\text{and } \text{ins}(v) = \text{ins}(u) \ \& \ \text{outs}(u) = \text{outs}(u) = \text{outs}(t)$$

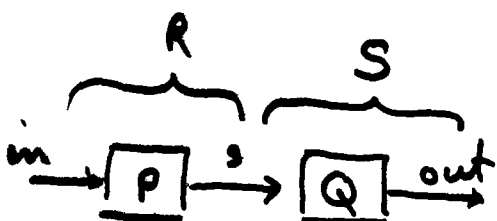
$$\ \& \ \text{outs}(v) = \text{ins}(w) = u \uparrow T$$

$$\therefore (\text{ins}(v), \text{outs}(v)) \in R \ \& \ (\text{ins}(w), \text{outs}(w)) \in S$$

$$\Rightarrow (\text{ins}(u), u \uparrow T) \in R \ \& \ (u \uparrow T, \text{outs}(u)) \in S$$

$$\Rightarrow \exists s (\text{ins}(t), s) \in R \ \& \ (s, \text{outs}(t)) \in S$$

$$\Rightarrow (\text{ins}(t), \text{outs}(t)) \in (R; S).$$



If f and g are monotonic:

$$(P \text{ sat } \text{outs} \leq f(\text{ins})) \ \& \ (Q \text{ sat } \text{outs} \leq g(\text{ins}))$$

$$\Rightarrow (P \gg Q) \text{ sat } \exists s \ s \leq f(\text{ins}) \ \& \ \text{outs} \leq g(s)$$

$$\Rightarrow (P \gg Q) \text{ sat } \text{outs} \leq g(f(\text{ins}))$$

theorem If P is a pipe for f and Q for g
then $P \gg Q$ is a pipe for $g \circ f$.

If P and Q are buffers, so is $P \gg Q$

(a buffer is a pipe for the identity function).

since $B_1 = (?x:T \rightarrow !x; B_1)$ is a buffer.

so is $B_{n+1} = B_n \gg B_1$ for all $n \geq 1$.

Proof. induction on n

WARNING sat defines only a form
of partial correctness - does not prove absence
of deadlock. eg. the following are buffers.

ABORT, $;$ $(?x:\{3\} \rightarrow !3; B_1), B_a$ where

$$B_s = (?x:T \rightarrow (?y:T \rightarrow !s_0; B_{s' \langle x \rangle \langle y \rangle}))$$

COMMUNICATIONS.

A communications protocol consists of a transmitting process P and a receiving process Q such that $P \gg Q$ is a buffer, i.e. its outputs are at all times an initial segment of its inputs

Theorem. If for all $\alpha:T$, $P_\alpha \gg Q_\alpha$ is a buffer

then so is $(\lambda \alpha:T \rightarrow (P_\alpha \gg (!\alpha; Q_\alpha))) \dots \dots$ (1)

Proof. Let t be a trace of (1)

then $\text{first}(\text{ins}(t)) = \text{first}(\text{outs}(t)) \dots \dots$ (2)

Let t' be formed from t by omitting its first input and its first output. t' must be a trace of $P_\alpha \gg Q_\alpha$, which is a buffer.

$$\therefore \text{outs}(t') \leq \text{ins}(t') \quad (3)$$

$$\text{but } \text{ins}(t) = \langle \text{first}(\text{ins}(t)) \rangle \text{ins}(t') \quad (4)$$

$$\text{and } \text{outs}(t) = \langle \text{first}(\text{outs}(t)) \rangle \text{outs}(t') \quad (5)$$

$$\therefore \text{outs}(t) \leq \text{ins}(t) \quad \text{from (2, 3, 4, 5)}$$

If for all $x:T$

$$P_x \gg Q_x = (\exists y:T \rightarrow P_y \gg (!y; Q_y))$$

then $P_x \gg Q_x$ is a buffer for all $x:T$.

Proof. induction on length of trace of $P_x \gg Q_x$.

t is OK \iff $\text{outs}(t) \subseteq \text{ins}(t)$, so \Leftarrow is OK.

assume all t of length $\leq n$ in $P_x \gg Q_x$ are OK (forall x)

now let $t' \in P_x \gg Q_x$ be ^{of length} ~~longer~~ $n+1$.

If t' is all inputs, it's OK

otherwise $t' \in \text{RHS}$, so on removal of its first input and output (which are equal), it is still in $P_y \gg Q_y$ for some y . By induction hypothesis, it's still OK

If $P_1 \gg Q_1$ and $P_2 \gg Q_2$ are buffers

then so ^{is} ~~some~~ $(P_1 \gg P_2) \gg (Q_1 \gg Q_2)$

(Composition of protocols).

Phase encoding.

$$P = (?x: \{0, 1\} \rightarrow (!x; !(1-x); P))$$

$$(Q = ?x: \{0, 1\} \rightarrow (?y: \{1-x\} \rightarrow (!x; Q)))$$

$$\begin{aligned} (!0; !1; R) \gg P &= !0; !1; ((!1; R) \gg P) \\ &= !0; !1; !1; !0; (R \gg P) \end{aligned}$$

Theorem. $P \gg Q$ is a buffer.

Proof $P \gg Q =$

$$= ?x: B \rightarrow (!x; !(1-x); P) \gg (?y: B \rightarrow ?z: \{1-y\} \rightarrow (!y; Q))$$

$$= ?x: B \rightarrow ((!(1-x); P) \gg (?z: \{1-x\} \rightarrow (!x; Q)))$$

$$= ?x: B \rightarrow (P \gg (!x; Q))$$

$\therefore P \gg Q$ is a buffer.

NRZ Protocol

$P_0 \gg Q_0$

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$$P_0 = ?x: \{0,1\} \rightarrow !x; P_x$$

x needs previous input bit.

$$P_1 = ?x: \{0,1\} \rightarrow !(1-x); P_x$$

$$\begin{aligned} (!1; 0!; !0; !1; R) \gg P_0 &= !1; ((!0; !0; 1; R) \gg P_1) \\ &= !1; !1; ((!0; !1; R) \gg P_0) \\ &= !1; !1; !0; ((!1; R) \gg P_0) \\ &= !1; !1; !0; !1; (R \gg P_1) \end{aligned}$$

P copies first bit

then outputs 0 if input value remains same
1 if input value changes.

$$Q_0 = ?x: \{0,1\} \rightarrow !x; Q_x$$

$$Q_1 = ?x: \{0,1\} \rightarrow !(1-x); Q_{(1-x)}$$

$$(!1; !1; !0; !1; R) \gg Q_0 = !1; !0; !0; !1; (R \gg Q_1)$$

Q copies first bit

then copies if previous output was 0
inverts if previous output was 1.

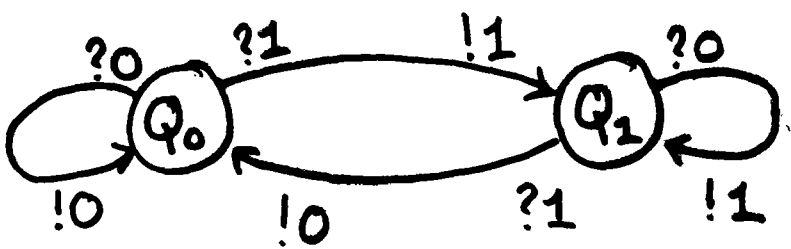
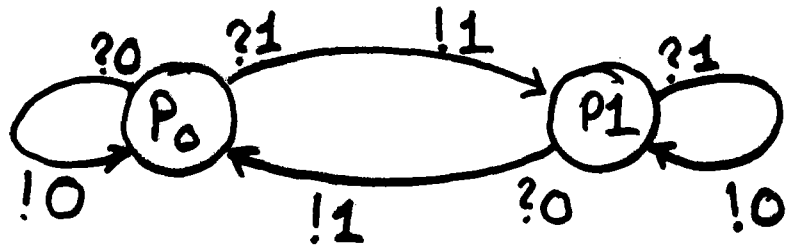
Prove that $P_x \gg Q_x$ is a buffer. for $x = 0, 1$

$$\begin{aligned}
 P_0 \gg Q_0 &= ?x: \{0, 1\} \rightarrow (!x; P_x) \gg Q_0 \\
 &= ?x: \{0, 1\} \rightarrow (P_x \gg (!x; Q_x))
 \end{aligned}$$

$$\begin{aligned}
 P_1 \gg Q_1 &= ?x: \{0, 1\} \rightarrow (!1-x; P_x) \gg Q_1 \\
 &= ?x: \{0, 1\} \rightarrow P_x \gg (!1-(1-x)); Q_{(1-(1-x))} \\
 &= ?x: \{0, 1\} \rightarrow P_x \gg (!x; Q_x)
 \end{aligned}$$

So $P_y \gg Q_y = (?x: \{0, 1\} \rightarrow P_x \gg (!x; Q_x))$
 for $y = 0, 1$

Therefore they are buffers.



A MODEL OF
NON-DETERMINISM
IN COMMUNICATING
SEQUENTIAL PROCESSES.

with thanks to
Steve Brooks, Bill Roscoe

March 1980

The problem

Consider $R = (x \rightarrow a \rightarrow P \parallel y \rightarrow b \rightarrow Q) \setminus \{x, y\}$

Clearly, on its first step, it can accept "a",
and it can accept "b". BUT also, it

can refuse "a" (if "y" happened) and it

can refuse "b" (if "x" happened). In our

simple model, $R = (a \rightarrow P \parallel b \rightarrow Q)$, and

the possibilities of refusal have not been

represented. We need a more complex model.

Let P be a process with finite alphabet A .

Let $\text{traces}(P)$ be the subset of A^*

denoting traces of the possible behaviour of P .

So $\text{traces}(P)$ is nonempty & prefix-closed.

Define $P^0 = \{a \mid \langle a \rangle \in \text{traces}(P)\}$

P^0 is the set of events possible for P
on the very first step.

Let X be a subset of A denoting the events possible for the environment of P .

" P canrefuse X " means that P can deadlock in this environment.

So P canrefuse $\{\}$

$$P \text{ canrefuse } X \Rightarrow P \text{ canrefuse } X \cap Y$$

$$P \text{ canrefuse } X \Rightarrow P \text{ canrefuse } X \cup (A - P^0).$$

$(A - P^0)$ is a set which P must refuse

Let s be in traces (P) . Then " P after s "

denotes the future behaviour of P if s is a trace of its past behaviour.

$$\text{So } P \text{ after } \langle \rangle = P$$

$$P \text{ after } st = (P \text{ after } s) \text{ after } t$$

Proposition: A process is defined by what it can do and what it can refuse.

So if $\text{alphabet}(P) = \text{alphabet}(Q)$
 and $\text{traces}(P) = \text{traces}(Q)$
 and $\forall X (P \text{ canrefuse } X \equiv Q \text{ canrefuse } X)$
 and $\forall a (a \in P^0 \Rightarrow P \text{ after } \langle a \rangle = Q \text{ after } \langle a \rangle)$
 then $P = Q$

We therefore define a process P as a relation:

for s in A^* and $X \subseteq A$

$(s, X) \in P$ means $s \in \text{traces}(P) \& (P \text{ after } s) \text{ canrefuse } X$.

So $\text{traces}(P) =_{df} \{s \mid (s, \{\}) \in P\}$

$P \text{ canrefuse } X =_{df} (\langle \rangle, X) \in P$

$P \text{ after } s =_{df} \{(t, X) \mid (st, X) \in P\}$

$\text{traces}(P)$ must be nonempty & prefix-closed
 $\{X \mid P \text{ canrefuse } X\}$ must be nonempty & left closed
 and closed under union with $\text{traces}(P)^0$

EXAMPLES. with alphabet A .

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$STOP_A$ can't do anything
must refuse everything.

$$STOP_A =_{df} \{(\langle \rangle, X) \mid X \subseteq A\}$$

RUN_A can do anything
can't refuse anything.

$$RUN_A =_{df} \{(s, \{\}) \mid s \in A^*\}$$

$CHAOS_A$ can do anything
can refuse anything.

$$CHAOS_A =_{df} \{(s, X) \mid s \in A^* \& X \subseteq A\}$$

for all $s \in A^*$: RUN_A after s = RUN_A

$CHAOS_A$ after s = $CHAOS_A$.



Let F be a function from A to processes.

Let $B \subseteq A$. Then

$(x: B \rightarrow F(x))$ first accepts any x in B ,
and then behaves like $F(x)$

$$(x: B \rightarrow F(x)) =_{df} \{(\langle \rangle, X) \mid X \subseteq A - B\} \\ \cup \{(x \rangle s, X) \mid x \in B \ \& \ (s, X) \in F(x)\}$$

$(b \rightarrow P)$ is short for $(x: \{b\} \rightarrow P)$

$$(x: B \rightarrow F(x)) \text{ after } b = F(b) \quad \text{for all } b \in B.$$

$$(x: \{\} \rightarrow F(x)) = \text{STOP}_A$$

$$(x: B \rightarrow F(x)) = (y: B \rightarrow F(y))$$

PARALLEL COMPOSITION.

P and Q have same alphabet A .

$P \parallel Q$ can accept anything acceptable to both P and Q

and if P can refuse X and Q can refuse Y , $P \parallel Q$ can refuse $X \cup Y$

$$(P \parallel Q) =_{df.} \{ (s, X \cup Y) \mid (s, X) \in P \ \& \ (s, Y) \in Q \}$$

$$\text{traces}(P \parallel Q) = \text{traces}(P) \cap \text{traces}(Q)$$

$$(P \parallel Q) \text{ after } s = (P \text{ after } s) \parallel (Q \text{ after } s) \quad \text{for } s \in \text{traces}(P \parallel Q)$$

\parallel is associative, & commutative,

with unit RUN_A and zero $STOP_A$.

$$(x: B \rightarrow F(x)) \parallel (y: C \rightarrow G(y)) = (z: B \cap C \rightarrow (F(z) \parallel G(z)))$$

NONDETERMINISM.

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$P \cap Q$ behaves non-deterministically, either like P or like Q .

It can do anything that P or Q can do.
It can refuse anything that P or Q can refuse.

$$P \cap Q =_{df} P \cup Q$$

\cap is associative, commutative, and idempotent with zero CHAOS_A .

$$\text{traces}(P \cap Q) = \text{traces}(P) \cup \text{traces}(Q)$$

$$\begin{aligned} (P \cap Q) \underline{\text{after}} s &= P \underline{\text{after}} s && \text{if } s \in \text{traces}(P) - \text{traces}(Q) \\ &= Q \underline{\text{after}} s && \text{if } s \in \text{traces}(Q) - \text{traces}(P) \\ &= (P \underline{\text{after}} s) \cap (Q \underline{\text{after}} s) && \text{if } s \in \text{traces}(P) \cap \text{traces}(Q) \end{aligned}$$

If we admit the EMPTY relation as a process, it wd be the unit of \cap .

UNION

8

$P \sqcup Q$ behaves like P or like Q ; the choice can be influenced by its environment, but only on the first step.

It can do anything P or Q can do.
It can refuse anything that both P and Q can refuse.

$$P \sqcup Q = \{(\langle \rangle, X) \mid (\langle \rangle, X) \in P \cap Q\} \\ \cup \{(s, X) \mid s \neq \langle \rangle \ \& \ (s, X) \in (P \cup Q)\}$$

\sqcup is associative, commutative and idempotent with unit $STOP_A$.

$$\text{traces}(P \sqcup Q) = \text{traces}(P) \cup \text{traces}(Q)$$

$$(x: B \rightarrow F(b)) \sqcup (y: C \rightarrow G(c)) = (z: B \cup C \rightarrow$$

$$\underline{\text{if}} \ z \in B-C \ \underline{\text{then}} \ F(z) \ \underline{\text{else}} \ \underline{\text{if}} \ z \in C-B \ \underline{\text{then}} \ G(z) \\ \underline{\text{else}} \ F(z) \sqcap G(z))$$

LIMITS.

9.

$P \sqsubseteq Q$ means Q is more deterministic than P .
& therefore more predictable, controllable, useful.

Everything Q can do so can P

Everything Q can refuse, so can P .

$$P \sqsubseteq Q \stackrel{\text{df}}{=} Q \subseteq P \quad \text{or} \quad P \sqcap Q = P$$

e.g. $P \sqcap Q \sqsubseteq P \sqcup Q$ $\text{CHAOS}_A \sqsubseteq P$

$$P \sqcap (P \sqcup Q \sqcup R) \sqsubseteq P \sqcup Q.$$

If $P_i \sqsubseteq P_{i+1}$ for all i , then we write

$$\bigsqcup_i P_i \stackrel{\text{df}}{=} \bigcap_i P_i$$

The relation \sqsubseteq is a complete partial order
with CHAOS_A as its bottom.

If we add EMPTY , processes form a
complete lattice with EMPTY as an
isolated top.

SYMBOL CHANGE.

10

Let F be a total function from alphabet B onto alphabet A

Let P have alphabet A .

Then $F^{-1}(P)$ can do b (in B) whenever

P can do $F(b)$, and can refuse X ($\subseteq B$)

whenever P can refuse $F(X) = \{F(x) \mid x \in X\}$

$F^{-1}(P) = \{(s, X) \mid (F(s), F(X)) \in P\}$ with alphabet B .

$$\text{traces}(F^{-1}(P)) = \{s \mid F(s) \in \text{traces}(P)\}$$

$$(F^{-1}(P))^{\circ} = F^{-1}(P^{\circ})$$

$$(F^{-1}(P))_{\text{after } s} = F^{-1}(P_{\text{after } F(s)})$$

$$F^{-1}(x: C \rightarrow F(x)) =$$

$$F^{-1}(P \parallel Q) =$$

$$F^{-1}(P \sqcup Q) =$$

If F is one-one, write $F(P)$ for $(F^{-1})^{-1}(P)$

ALPHABET EXTENSION

12

Let P be a process with alphabet A
 then $P_{\text{ext}} B$ is a process with alphabet
 $A \cup B$, which behaves like P , except that
 it is always prepared for any event in
 $B - A$, which it then ignores.

$$P_{\text{ext}} B = \{(s, X) \mid s \in (A \cup B)^* \ \& \ (s_A, X) \in P\}$$

where s_A is formed from s by omitting all
 symbols outside A .

$$(P_{\text{ext}} B)^{\circ} = P^{\circ} \cup (B - A)$$

$$(P_{\text{ext}} B) \text{ canrefuse } X \equiv P \text{ canrefuse } X$$

$$(P_{\text{ext}} B) \text{ after } s = (P \text{ after } s_A)_{\text{ext}} B$$

$$P_{\text{ext}} A = P, \quad (P_{\text{ext}} B)_{\text{ext}} C = P_{\text{ext}} (B \cup C)$$

If Q has alphabet B then

$$P \parallel Q =_{df} (P_{\text{ext}} B) \parallel (Q_{\text{ext}} A)$$

\parallel is associative and commutative, etc.

ALPHABET CONTRACTION

Let P have alphabet A . Let B be a set of events to be regarded as internal to P . Then $P \setminus B$ is the process which behaves like P , but events in B may occur whenever they are possible, without participation or even the knowledge of the environment of P .

$$(P \setminus B)^{\circ} \supseteq P^{\circ} - B$$

$$P \text{ can refuse } X \ \& \ X \cap B = \{\} \Rightarrow (P \setminus B) \text{ can refuse } X$$

$$s \in \text{traces}(P) \Rightarrow s_{A-B} \in \text{traces}(P \setminus B)$$

$$(P \setminus B) \text{ after } s_{A-B} \sqsubseteq (P \text{ after } s) \setminus B.$$

These properties are satisfied by

$$\boxed{P \setminus B} = \{(s_{A-B}, X) \mid X \cap B = \{\} \ \& \ (s, X \cup B) \in P\}$$

But $\{(b^n, X) \mid X \subseteq \{a\}\} \setminus \{b\}$ is empty, i.e.
not a process

The trouble lies in the infinite trace consisting of hidden symbols. The process may choose to follow this path forever and never engage in any further external interactions. or it may not. But you can't rely on anything. It's as bad as CHAOS. So let's make it so.

$$P \setminus B = \boxed{P \setminus B} \cup \{(st, X) \mid \{u \mid u \in P \& u_{A-B} = s\} \text{ is infinite}\}$$

$$P \setminus \{\epsilon\} = P$$

$$(P \setminus B) \setminus C = P \setminus (B \cup C)$$

NOTE - we rely on finitude of alphabets

MONOTONICITY

$P \in R$ means that for all purposes R is better than P . Let F be a function on processes. Regard $F(P)$ as an assembly into which P has been plugged. We would like that replacement of P by a better component can only improve the assembly. For this, F must be monotonic, i.e.

$$F(P) \in F(R) \quad \text{whenever} \quad P \in R.$$

All functions defined so far are monotonic.

DISTRIBUTIVITY.

15

Let F be a monotonic function of processes.
Suppose we wish to implement

$$F(P) \cap F(Q)$$

An easy way to do this may be first to implement $(P \cap Q)$ and then apply F to the result. This is valid only if F is distributive. i.e.

$$F(P) \cap F(Q) = F(P \cap Q)$$

All functions defined so far are distributive.

RECURSION.

16

A function F from processes to processes is continuous if for all ascending chains

$$\{P_i \mid i \in \mathbb{N} \ \& \ \forall i \ P_i \sqsubseteq P_{i+1}\}$$

$$F(\bigsqcup_i P_i) = \bigsqcup_i F(P_i).$$

If F is continuous, the least solution of

$$p = F(p)$$

is given by $p = \bigsqcup_i F^i(\text{CHAOS}_A)$

where F^i is the i -fold composition of F

All functions defined so far are continuous.

THE UNIVERSITY OF WOLLONGONG
DEPARTMENT OF COMPUTING SCIENCE

symposium on

COMMUNICATING SEQUENTIAL PROCESSES

PROGRAMME

Pentagon Lecture Theatre 2.

Saturday March 22, 1980.

8.30 - 9.30	Registration		
9.30 - 10.30		Hoare C.A.R.	CSP Lecture I
10.30 - 11.00	Morning Tea		
11.00 - 12.00		Hoare C.A.R.	CSP Lecture II
12.00 - 13.00		Dromey R.G.	Text Searching
13.00 - 14.00	Lunch		
14.00 - 15.00		Hoare C.A.R.	CSP Lecture III
15.00 - 15.30	Afternoon Tea		
15.30 - 16.30		Stanton R.B.	Primitives for Concurrency
16.30 - 17.30		Barter C.J.	CSP Language and Implementation
17.30 - 18.00	Happy Hour		
18.00 - 21.00	Dinner	Reinfelds J.	Software Science

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Sunday March 23, 1980.

9.30 - 10.30		Hoare C.A.R.	CSP Lecture IV
10.30 - 11.00	Morning Tea		
11.00 - 12.00		Hoare C.A.R.	CSP Lecture V
12.00 - 13.00		Mateti P.	Correctness Proof of Indenting Pro- gram
13.00 - 14.00	Lunch		
14.00 - 15.00		Hoare C.A.R.	CSP Lecture VI
15.00 - 15.30	Afternoon Tea		
15.30 - 16.30		Tobias J.M.	Single User Multi Processor Around High Level Language

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