

Exercise 1 (Monic arrows in Ω -set). An arrow $f : A \rightarrow B$ in Ω -set is monic iff it satisfies

$$f(a_0, b) \wedge f(a_1, b) \leq \llbracket a_0 = a_1 \rrbracket_A \quad (1)$$

Proof. Let $g : C \rightarrow A$ in Ω -set.

We first prove that (19) implies

$$g(c, a_0) = \bigsqcup_{b \in B} g \circ f(c, b) \wedge f(a_0, b) \quad (2)$$

for any c, a_0 . To do this we show each of

$$g(c, a_0) \leq \bigsqcup_{b \in B} g \circ f(c, b) \wedge f(a_0, b) \quad (3)$$

and

$$g(c, a_0) \geq \bigsqcup_{b \in B} g \circ f(c, b) \wedge f(a_0, b) \quad (4)$$

For (3):

$$g(c, a_0) = g(c, a_0) \wedge \llbracket a_0 = a_0 \rrbracket \quad (5)$$

$$= \bigsqcup_{b \in B} g(c, a_0) \wedge f(a_0, b) \quad (6)$$

$$= \bigsqcup_{b \in B} \left(\bigsqcup_{a \in A} g(c, a) \wedge f(a, b) \right) \wedge f(a_0, b) \wedge g(c, a_0) \quad (7)$$

$$= \bigsqcup_{b \in B} f \circ g(c, b) \wedge f(a_0, b) \wedge g(c, a_0) \quad (8)$$

which latter is what we want.

For (4), let $b \in B$. We have:

$$\left(\bigsqcup_{a \in A} g(c, a) \wedge f(a, b) \right) \wedge f(a_0, b) = \bigsqcup_{a \in A} g(c, a) \wedge f(a, b) \wedge f(a_0, b) \quad (9)$$

$$\leq \bigsqcup_{a \in A} g(c, a) \wedge \llbracket a = a_0 \rrbracket_A \quad (10)$$

$$\leq g(c, a_0) \quad (11)$$

where the transition from (9) to (10) uses (19), and the transition from (10) to (11) uses (v) p 277. (Is equality true?)

From here it is easy. Suppose $g \circ f(c, b) = h \circ f(c, b)$ for all c and b . Then for any a , $\bigsqcup_{b \in B} g \circ f(c, b) \wedge f(a, b) = \bigsqcup_{b \in B} h \circ f(c, b) \wedge f(a, b)$. Hence $g(c, a) = f(c, a)$ by (2). \square

Exercise 2 (Ω axiom in Ω -set). Show that with $\Omega(p, q) := p \Leftrightarrow q$ and $\top(0, p) = p$ we get the Ω axiom for

$$\chi_f = \llbracket Ed \rrbracket \wedge \llbracket s_f(d) = p \rrbracket_\Omega \quad (12)$$

Proof. Let $f : \mathbf{A} \rightarrow \mathbf{D}$ be monic. Note that

$$\top \circ ! (a, 0) = \bigsqcup_{x \in 1} \llbracket Ea \rrbracket \wedge p = \llbracket Ea \rrbracket \wedge p \quad (13)$$

Second, since $s_f(d) = \bigsqcup_{a \in A} f(a, d)$ (12) implies

$$\chi_f(d, p) = \llbracket Ed \rrbracket \wedge \bigsqcup_{a \in A} f(a, d) \Leftrightarrow p \quad (14)$$

which then implies

$$\chi_f \circ f(a, p) = \bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (15)$$

putting (13), (15) together, it suffices show

$$\llbracket Ea \rrbracket \wedge p = \bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (16)$$

to show the square commutes.

Using the Heyting algebra validities

$$p \wedge q = p \wedge p \wedge q,$$

$$p \wedge (q \Leftrightarrow r) = p \wedge q \Leftrightarrow p \wedge r,$$

$$p \Leftrightarrow (p \wedge q) = p \Leftrightarrow q,$$

$$p \wedge (p \Leftrightarrow q) = p \wedge q,$$

and the law of distribution one can deduce each of

$$\bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p = \bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge f(a, d) \Leftrightarrow p \quad (17)$$

and

$$\bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge f(a, d) \Leftrightarrow p = \bigsqcup_{d \in D} \llbracket Ed \rrbracket \wedge f(a, d) \wedge p \quad (18)$$

but putting (17) and (18) together implies (16) by v and vii on p 277.

To show uniqueness, we need to show that

$$\llbracket Ea \rrbracket \wedge p = \bigsqcup_{d \in D} f(a, d) \wedge g(d, p) \quad (19)$$

implies

$$g(d, p) = \llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (20)$$

i.e.

$$g(d, p) \leq \llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (21)$$

and

$$g(d, p) \geq \llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (22)$$

For (21), 277 gives $g(d, p) \leq \llbracket Ed \rrbracket$, so we must show $g(d, p) \leq \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p$. For this, it is enough to show

$$g(d, p) \wedge \bigsqcup_{a' \in A} f(a', d) \leq p \quad (23)$$

$$g(d, p) \wedge p \leq \bigsqcup_{a' \in A} f(a', d). \quad (24)$$

For (23) we want

$$\bigsqcup_{a' \in A} f(a', d) \wedge g(d, p) \leq p \quad (25)$$

now for a particular value of a' , (19) implies $f(a', d) \wedge g(d, p) \leq \llbracket Ea \rrbracket \wedge p$. So by the def of least upper bound, $\bigsqcup_{a' \in A} f(a', d) \wedge g(d, p) \leq \llbracket Ea \rrbracket \wedge p$. But then the result follows trivially.

For (24), we have

$$g(d, p) \wedge p \wedge \bigsqcup_{a' \in A} f(a', d) = g(d, p) \wedge p \wedge \bigsqcup_{a' \in A} f(a', d) \wedge g(d, p)$$

thus by (25)

$$g(d, p) \wedge p \wedge \bigsqcup_{a' \in A} f(a', d) \wedge g(d, p) = g(d, p) \wedge p \wedge p = g(d, p) \wedge p$$

and (21) follows.

For (22), consider

$$g(d, p) \wedge \llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \Leftrightarrow p \quad (26)$$

this equals

$$\llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \wedge g(d, p) \Leftrightarrow g(d, p) \wedge p \quad (27)$$

by (24), this is just

$$\llbracket Ed \rrbracket \wedge \bigsqcup_{a' \in A} f(a', d) \wedge g(d, p) \Leftarrow g(d, p) \wedge p \quad (28)$$

□

Exercise 3 (h is continuous (5, p305)). Show that the unique arrow h derived from x and f in $Bn(I)$ is continuous in $Top(I)$.

Proof. We need to show that whenever $h[X]$ is open for some $X \subseteq I \times \omega$, X itself is open in that space. For each n , let $X_n = \{x : \langle x, n \rangle \in X\}$. Note $X = \bigcup_n X_n \times \{n\}$. It therefore suffices to prove that $X_n \times \{n\}$ is open for each n , which reduces to just showing X_n is open since ω has the discrete topology.

In case $n = 0$, note that $h[X_0 \times 0] = x[X_0]$, using $h(i, 0) = x(i)$. But if $x[X_0]$ is open, so is X_0 , since x is continuous.

In case $n = k+1$, $h[X_n \times \{n\}] = f \circ h[X_k \times \{k\}]$ using $h(i, k+1) = f(h(i, k))$. Then the result follows by the IH and continuity of f . □