Mathematical proofs
in complement of the book

Principles of Abstract Interpretation

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1 Mathematical proofs of chapter 4

Proof of Lemma 4.18 The lemma trivially holds if $\mathsf{escape}[\![\mathtt{S}]\!] = \mathtt{ff}$. Otherwise $\mathsf{escape}[\![\mathtt{S}]\!] = \mathtt{tt}$ and the proof is by induction on the distance $\delta(\mathtt{S})$ of $\mathtt{S}$ to the root of the abstract syntax tree of $\mathtt{P}$ (where $\delta(\mathtt{P}) = 0$).

- For $\mathtt{Sl} ::= \mathtt{Sl}'\ \mathtt{S}$, $\delta(\mathtt{Sl}') = \delta(\mathtt{S}) = \delta(\mathtt{Sl})+1$. So, in case $\mathsf{escape}[\![\mathtt{Sl}]\!] = \mathtt{tt}$, we have $\mathsf{break\text{-}to}[\![\mathtt{Sl}]\!] \neq \mathsf{after}[\![\mathtt{Sl}]\!]$ by induction hypothesis. By def. $\mathsf{escape}[\![\mathtt{Sl}]\!] \triangleq \mathsf{escape}[\![\mathtt{Sl}']\!] \vee \mathsf{escape}[\![\mathtt{S}]\!]$, there are two subcases.
  - If $\mathsf{escape}[\![\mathtt{Sl}']\!] = \mathtt{tt}$ then, on one hand, $\mathtt{Sl} \neq \mathtt{\{\ \ldots\{\ \epsilon\ \}\ldots\ \}}$, $\mathsf{after}[\![\mathtt{Sl}']\!] = \mathsf{at}[\![\mathtt{S}]\!]$, $\mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \triangleq \mathsf{break\text{-}to}[\![\mathtt{Sl}]\!]$, $\mathsf{at}[\![\mathtt{S}]\!] \in \mathsf{in}[\![\mathtt{S}]\!]$ by Lemma 4.15, so $\mathsf{after}[\![\mathtt{Sl}']\!] \in \mathsf{in}[\![\mathtt{S}]\!]$.
    On the other hand $\mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \notin \mathsf{in}[\![\mathtt{S}]\!]$ since otherwise $\mathsf{break\text{-}to}[\![\mathtt{Sl}]\!] = \mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \in \mathsf{in}[\![\mathtt{S}]\!] \subseteq \mathsf{in}[\![\mathtt{Sl}]\!]$ in contradiction with Lemma 4.17, proving $\mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \neq \mathsf{after}[\![\mathtt{Sl}']\!]$;
  - If $\mathsf{escape}[\![\mathtt{S}]\!] = \mathtt{tt}$ then $\mathtt{S} \neq \mathtt{\{\ \ldots\{\ \epsilon\ \}\ldots\ \}}$, $\mathsf{after}[\![\mathtt{S}]\!] = \mathsf{after}[\![\mathtt{Sl}]\!]$, $\mathsf{break\text{-}to}[\![\mathtt{S}]\!] \triangleq \mathsf{break\text{-}to}[\![\mathtt{Sl}]\!]$, $\mathsf{break\text{-}to}[\![\mathtt{Sl}]\!] \neq \mathsf{after}[\![\mathtt{Sl}]\!]$ by induction hypothesis, so $\mathsf{break\text{-}to}[\![\mathtt{S}]\!] \neq \mathsf{after}[\![\mathtt{S}]\!]$.
- If $\mathtt{S} ::= \mathtt{if}\ \ell\ \mathtt{(B)}\ \mathtt{S}_t$ then $\mathsf{escape}[\![\mathtt{S}_t]\!] = \mathsf{escape}[\![\mathtt{S}]\!] = \mathtt{tt}$, $\mathsf{after}[\![\mathtt{S}_t]\!] = \mathsf{after}[\![\mathtt{S}]\!]$, $\mathsf{break\text{-}to}[\![\mathtt{S}_t]\!] = \mathsf{break\text{-}to}[\![\mathtt{S}]\!]$, and $\mathsf{break\text{-}to}[\![\mathtt{S}]\!] \neq \mathsf{after}[\![\mathtt{S}]\!]$ by induction hypothesis since $\delta(\mathtt{S}_t) = \delta(\mathtt{S}) + 1$, so $\mathsf{break\text{-}to}[\![\mathtt{S}_t]\!] \neq \mathsf{after}[\![\mathtt{S}_t]\!]$.
- The proof is similar for $\mathtt{S} ::= \mathtt{if}\ \ell\ \mathtt{(B)}\ \mathtt{S}_t\ \mathtt{else}\ \mathtt{S}_f$ and $\mathtt{S} ::= \mathtt{\{\ Sl\ \}}$. □

2 Mathematical proofs of chapter 41

Proof of Theorem 41.24 • For the ***statement list*** $\mathtt{Sl} ::= \mathtt{Sl}'\ \mathtt{S}$, by (17.3) (following (6.13), and (6.14)), we have $\mathcal{S}^*[\![\mathtt{Sl}]\!] = \mathcal{S}^*[\![\mathtt{Sl}']\!] \cup \{\langle\pi_1,\ \pi_2 \frown \pi_3\rangle \mid \langle\pi_1,\ \pi_2\rangle \in \mathcal{S}^*[\![\mathtt{Sl}']\!] \wedge \langle\pi_1 \frown \pi_2,\ \pi_3\rangle \in \mathcal{S}^*[\![\mathtt{S}]\!]\}$.

– A first case is when $\mathtt{Sl}' = \epsilon$ is empty. Then,

$$\begin{aligned}
&\alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{Sl}]\!](\mathcal{S}^*[\![\mathtt{Sl}]\!])\,L_b, L_e\\
=\ &\bigcup\{\alpha^{l}_{\mathsf{use,mod}}[\![\ \epsilon\ \mathtt{S}]\!]\,L_b, L_e\,\langle\pi_0,\ \pi_1\rangle \mid \langle\pi_0,\ \pi_1\rangle \in \mathcal{S}^*[\![\ \epsilon\ \mathtt{S}]\!]\}\\
&\qquad\qquad \text{(def. (41.3) of } \alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{S}]\!] \text{ for } \mathtt{Sl} ::= \epsilon\ \mathtt{S})\\
=\ &\bigcup\{\alpha^{l}_{\mathsf{use,mod}}\ L_b, L_e\,\langle\pi_0\ell,\ \pi_1\rangle \mid \langle\pi_0\ell,\ \pi_1\rangle \in \mathcal{S}^*[\![\ \epsilon\ ]\!] \cup \{\langle\pi_0\ell,\ \pi_2 \frown \pi_3\rangle \mid \langle\pi_0\ell,\ \pi_2\rangle \in\\
&\mathcal{S}^+[\![\ \epsilon\ ]\!] \wedge \langle\pi_0\ell \frown \pi_2,\ \pi_3\rangle \in \mathcal{S}^*[\![\mathtt{S}]\!]\}\} \qquad \text{(def. } \mathcal{S}^*[\![\ \epsilon\ \mathtt{S}]\!])\\
=\ &\bigcup\{\alpha^{l}_{\mathsf{use,mod}}\ L_b, L_e\,\langle\pi_0,\ \pi_1\rangle \mid \langle\pi_0,\ \pi_1\rangle \in \mathcal{S}^*[\![\mathtt{S}]\!]\}\}\\
&\qquad \text{((6.15) so that } \mathcal{S}^*[\![\ \epsilon\ ]\!] = \{\langle\pi_0\mathsf{at}[\![\mathtt{S}]\!],\ \mathsf{at}[\![\mathtt{S}]\!]\rangle \mid \pi_0\mathsf{at}[\![\mathtt{S}]\!] \in \mathbb{T}^+\} \text{ and } \langle\pi_0\mathsf{at}[\![\mathtt{S}]\!],\ \mathsf{at}[\![\mathtt{S}]\!]\rangle \in\\
&\qquad \mathcal{S}^*[\![\mathtt{S}]\!] \text{ by (6.11))}\\
=\ &\alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{Sl}]\!]\ (\mathcal{S}^*[\![\mathtt{S}]\!])\,L_b, L_e \qquad \text{(def. (41.3) of } \alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{S}]\!])\\
=\ &\alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{S}]\!]\ (\mathcal{S}^*[\![\mathtt{S}]\!])\,L_b, L_e\\
&\qquad \text{((41.3) since } \mathsf{after}[\![\mathtt{Sl}]\!] = \mathsf{after}[\![\mathtt{S}]\!],\ \mathsf{escape}[\![\mathtt{Sl}]\!] = \mathsf{escape}[\![\mathtt{S}]\!], \text{ and } \mathsf{break\text{-}to}[\![\mathtt{Sl}]\!] =\\
&\qquad \mathsf{break\text{-}to}[\![\mathtt{S}]\!] \text{ when } \mathtt{Sl}' = \epsilon\ )\\
\subseteq\ &\widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{S}]\!]\ L_b, L_e \qquad \text{(ind. hyp. for Theorem 41.24)}\\
=\ &\widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{S}]\!]\ L_b, (\widehat{\mathcal{S}}^{\,\exists l}[\![\ \epsilon\ ]\!]\ L_b, L_e) \qquad \text{(since } \widehat{\mathcal{S}}^{\,\exists l}[\![\ \epsilon\ ]\!]\ L_b, L_e \triangleq L_e \text{ by (41.22))}
\end{aligned}$$

proving (41.22) when $\mathtt{Sl}' = \epsilon$.

– A second case is when $\mathtt{S} = \{\ \ldots\{\ \epsilon\ \}\ldots\ \}$ is empty. Then, as required by (41.22), we have, by induction hypothesis, $\alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{Sl}]\!]\ L_b, L_e = \alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{Sl}']\!]\ L_b, L_e \subseteq \widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{Sl}']\!]\ L_b, (\widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{S}]\!]\ L_b, L_e) \triangleq \widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{Sl}]\!]\ L_b, L_e$ since $\widehat{\mathcal{S}}^{\,\exists l}[\![\mathtt{S}]\!]\ L_b, L_e = L_e$ when $\mathtt{S}$ is empty.

– Otherwise, $\mathtt{Sl}' \neq \epsilon$ and $\mathtt{S} \neq \{\ \ldots\{\ \epsilon\ \}\ldots\ \}$ so, by Lemma 4.16, $\mathsf{after}[\![\mathtt{S}]\!] \notin \mathsf{in}[\![\mathtt{S}]\!]$. In that case, let us calculate

$$\begin{aligned}
&\alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{Sl}]\!]\ L_b, L_e\\
=\ &\bigcup\{\alpha^{l}_{\mathsf{use,mod}}[\![\mathtt{Sl}]\!]\ L_b, L_e\,\langle\pi_0,\ \pi_1\rangle \mid \langle\pi_0,\ \pi_1\rangle \in \mathcal{S}^*[\![\mathtt{Sl}]\!]\} \qquad \text{(def. (41.3) of } \alpha^{\exists l}_{\mathsf{use,mod}}[\![\mathtt{S}]\!])
\end{aligned}$$

$= \bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \ell_n = \mathsf{after}[\![\mathsf{Sl}]\!] \mathbin{?} L_e \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{Sl}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_1 \rangle \in \mathcal{S}^*[\![\mathsf{Sl}]\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n\}$ ⦃By Lemma 41.8, omitting the useless parameters of use and mod⦄

$= \bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \ell_n = \mathsf{after}[\![\mathsf{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_1 \rangle \in \mathcal{S}^*[\![\mathsf{Sl}']\!] \cup \{\langle \pi_0 \frown \pi_2, \pi_2 \frown \pi_3 \rangle \mid \langle \pi_0, \pi_2 \rangle \in \mathcal{S}^+[\![\mathsf{Sl}']\!] \wedge \langle \pi_0 \frown \pi_2, \pi_3 \rangle \in \mathcal{S}^*[\![\mathsf{S}]\!]\} \wedge \pi_1 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n\}$

⦃def. $\mathcal{S}^*[\![\mathsf{Sl}]\!]$, $\mathsf{after}[\![\mathsf{Sl}]\!] = \mathsf{after}[\![\mathsf{S}]\!]$ in Section 4.2.2, $\mathsf{escape}[\![\mathsf{Sl}]\!] \triangleq \mathsf{escape}[\![\mathsf{Sl}']\!] \vee \mathsf{escape}[\![\mathsf{S}]\!]$, and $\mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \triangleq \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \triangleq \mathsf{break\text{-}to}[\![\mathsf{Sl}]\!]$ in Section 4.2.4⦄

$= \bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \ell_n = \mathsf{after}[\![\mathsf{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_1 \rangle \in \mathcal{S}^*[\![\mathsf{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n\} \cup$
$\bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \ell_n = \mathsf{after}[\![\mathsf{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_2 \rangle \in \mathcal{S}^+[\![\mathsf{Sl}']\!] \wedge \langle \pi_0 \frown \pi_2, \pi_3 \rangle \in \mathcal{S}^*[\![\mathsf{S}]\!] \wedge \pi_2 \frown \pi_3 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n\}$

⦃def. $\cup$ and def. $\in$ so $\langle \pi_0, \pi_1 \rangle = \langle \pi_0 \frown \pi_2, \pi_2 \frown \pi_3 \rangle$⦄

$\subseteq \bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, m-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_m = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_1 \rangle \in \mathcal{S}^*[\![\mathsf{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{m-1}} \ell_m\} \cup$
$\bigcup\{\{\mathsf{x} \in \mathbb{V} \mid \exists i \in [1, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathsf{x} \notin \mathsf{mod}[\![\mathsf{a}_j]\!] \wedge \mathsf{x} \in \mathsf{use}[\![\mathsf{a}_i]\!]\} \cup (\!| \ell_n = \mathsf{after}[\![\mathsf{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing |\!) \cup (\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!) \mid \langle \pi_0, \pi_1 \rangle \in \mathcal{S}^+[\![\mathsf{Sl}']\!] \wedge \langle \pi'_0, \pi_3 \rangle \in \mathcal{S}^*[\![\mathsf{S}]\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{m-1}} \ell_m \wedge \ell_m = \mathsf{after}[\![\mathsf{Sl}']\!] \wedge \pi_3 = \ell_m \xrightarrow{\mathsf{a}_m} \ell_{m+1} \xrightarrow{\mathsf{a}_{m+1}} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n\}$

⦃— For the first term, $\langle \pi_0, \pi_1 \rangle \in \mathcal{S}^*[\![\mathsf{Sl}']\!]$, π_1 ends in ℓ_n, and $\ell_n = \mathsf{after}[\![\mathsf{S}]\!]$ is impossible since Sl' and S are not empty. Moreover, if $\ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!]$ then a_{n-1} is a break, so $\mathsf{escape}[\![\mathsf{Sl}']\!]$ holds. L_b is included in $(\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!)$ and so $(\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!)$ is redundant. Finally, renaming $n \leftarrow m$.⦄

⦃— For the second term, if $\ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] = \mathsf{break\text{-}to}[\![\mathsf{S}]\!]$ then a_{n-1} is a break, so $\mathsf{escape}[\![\mathsf{S}]\!]$ holds. L_b is included in $(\!| \mathsf{escape}[\![\mathsf{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!)$ and so $(\!| \mathsf{escape}[\![\mathsf{Sl}']\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathsf{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing |\!)$ is redundant. Moreover, $\pi_2 \frown \pi_3 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n$ is decomposed into $\pi_2 = \ell_1 \xrightarrow{\mathsf{a}_1} \ell_2 \xrightarrow{\mathsf{a}_2} \ldots \xrightarrow{\mathsf{a}_{m-1}} \ell_m$ and $\pi_3 = \ell_m \xrightarrow{\mathsf{a}_m} \ell_{m+1} \xrightarrow{\mathsf{a}_{m+1}} \ldots \xrightarrow{\mathsf{a}_{n-1}} \ell_n$ where, by $\langle \pi_0, \pi_2 \rangle \in \mathcal{S}^+[\![\mathsf{Sl}']\!]$ and $\langle \pi_0 \frown \pi_2, \pi_3 \rangle \in \mathcal{S}^*[\![\mathsf{S}]\!]$, $\ell_m = \mathsf{after}[\![\mathsf{Sl}']\!] = \mathsf{at}[\![\mathsf{S}]\!]$. Moreover, $\pi_0 \frown \pi_2$ is generalized to π'_0 (whence inclusion) and π_2 is renamed into π_1.⦄

$$= \bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [1, m-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \mathsf{escape}[\![\mathtt{Sl}']\!] \wedge \ell_m = \mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi_0,\ \pi_1 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathtt{a}_1} \ell_2 \xrightarrow{\mathtt{a}_2} \dots \xrightarrow{\mathtt{a}_{m-1}} \ell_m\} \cup \bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [m, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_n = \mathsf{after}[\![\mathtt{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathtt{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi_0,\ \pi_1 \rangle \in \boldsymbol{\mathcal{S}}^+[\![\mathtt{Sl}']\!] \wedge \langle \pi'_0,\ \pi_3 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{S}]\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathtt{a}_1} \ell_2 \xrightarrow{\mathtt{a}_2} \dots \xrightarrow{\mathtt{a}_{m-1}} \ell_m \wedge \ell_m = \mathsf{after}[\![\mathtt{Sl}']\!] \wedge \pi_3 = \ell_m \xrightarrow{\mathtt{a}_m} \ell_{m+1} \xrightarrow{\mathtt{a}_{m+1}} \dots \xrightarrow{\mathtt{a}_{n-1}} \ell_n\}$$

≀since the case $i \in [1, m-1]$ of the second term is already incorporated in the first term≀

$$= \bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [1, m-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_m = \mathsf{after}[\![\mathtt{Sl}']\!] \mathbin{?} \Big(\bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [m, n-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_n = \mathsf{after}[\![\mathtt{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathtt{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi'_0,\ \pi_3 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{S}]\!] \wedge \pi_3 = \ell_m \xrightarrow{\mathtt{a}_m} \ell_{m+1} \xrightarrow{\mathtt{a}_{m+1}} \dots \xrightarrow{\mathtt{a}_{n-1}} \ell_n\}\Big) \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{Sl}']\!] \wedge \ell_m = \mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi_0,\ \pi_1 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathtt{a}_1} \ell_2 \xrightarrow{\mathtt{a}_2} \dots \xrightarrow{\mathtt{a}_{m-1}} \ell_m\}$$

≀incorporating the second term in the first term, in case $\ell_m = \mathsf{after}[\![\mathtt{Sl}']\!]$≀

$$\subseteq \bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [1, m-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_m = \mathsf{after}[\![\mathtt{Sl}']\!] \mathbin{?} (\bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [m, n-1] \,.\, \forall j \in [m, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_n = \mathsf{after}[\![\mathtt{S}]\!] \mathbin{?} L_e \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{S}]\!] \wedge \ell_n = \mathsf{break\text{-}to}[\![\mathtt{S}]\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi'_0,\ \pi_3 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{S}]\!] \wedge \pi_3 = \ell_m \xrightarrow{\mathtt{a}_m} \ell_{m+1} \xrightarrow{\mathtt{a}_{m+1}} \dots \xrightarrow{\mathtt{a}_{n-1}} \ell_n\}) \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{Sl}']\!] \wedge \ell_m = \mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi_0,\ \pi_1 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathtt{a}_1} \ell_2 \xrightarrow{\mathtt{a}_2} \dots \xrightarrow{\mathtt{a}_{m-1}} \ell_m\}$$

≀dropping the test $\forall j \in [1, m-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!]$≀

$$= \bigcup \{\{\mathtt{x} \in \mathbb{V} \mid \exists i \in [1, m-1] \,.\, \forall j \in [1, i-1] \,.\, \mathtt{x} \notin \mathtt{mod}[\![\mathtt{a}_j]\!] \wedge \mathtt{x} \in \mathtt{use}[\![\mathtt{a}_i]\!]\} \cup (\!|\, \ell_m = \mathsf{after}[\![\mathtt{Sl}']\!] \mathbin{?} (\bigcup \{\alpha^{l}_{\mathtt{use},\mathtt{mod}}[\![\mathtt{S}]\!]\ L_b, L_e\ \langle \pi'_0,\ \pi_3 \rangle \mid \langle \pi'_0,\ \pi_3 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{S}]\!]\}) \mathbin{:} \varnothing \,|\!) \cup (\!|\, \mathsf{escape}[\![\mathtt{Sl}']\!] \wedge \ell_m = \mathsf{break\text{-}to}[\![\mathtt{Sl}']\!] \mathbin{?} L_b \mathbin{:} \varnothing \,|\!) \mid \langle \pi_0,\ \pi_1 \rangle \in \boldsymbol{\mathcal{S}}^*[\![\mathtt{Sl}']\!] \wedge \pi_1 = \ell_1 \xrightarrow{\mathtt{a}_1} \ell_2 \xrightarrow{\mathtt{a}_2} \dots \xrightarrow{\mathtt{a}_{m-1}} \ell_m\}$$

≀Lemma 41.8≀

$$\subseteq \bigcup \{\alpha^{l}_{\mathtt{use},\mathtt{mod}}[\![\mathtt{Sl}']\!]\ L_b, (\boldsymbol{\mathcal{S}}^{\exists l}[\![\mathtt{S}]\!]\ L_b, L_e)\ \langle \pi_0,\ \pi_1 \rangle \mid \langle \pi_0,\ \pi_1 \rangle \in \widehat{\boldsymbol{\mathcal{S}}}^*[\![\mathtt{Sl}']\!]\}$$

≀Lemma 41.8 and (41.3)≀

$$= \alpha^{\exists l}_{\mathtt{use},\mathtt{mod}}[\![\mathtt{Sl}']\!](\boldsymbol{\mathcal{S}}^*[\![\mathtt{Sl}']\!])\ L_b, (\widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{S}]\!]\ L_b, L_e)$$

≀def. (41.3) of $\alpha^{\exists l}_{\mathtt{use},\mathtt{mod}}$≀

$$\subseteq \widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{Sl}']\!]\ L_b, (\widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{S}]\!]\ L_b, L_e)$$

≀ind. hyp. of Theorem 41.24: $\alpha^{\exists l}_{\mathtt{use},\mathtt{mod}}[\![\mathtt{Sl}']\!](\widehat{\boldsymbol{\mathcal{S}}}^*[\![\mathtt{Sl}']\!])\ L_b, (\widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{S}]\!]\ L_b, L_e) \subseteq \widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{Sl}']\!]\ L_b, (\widehat{\boldsymbol{\mathcal{S}}}^{\exists l}[\![\mathtt{S}]\!]\ L_b, L_e)$, Q.E.D.≀

- For the ***empty statement list*** $\texttt{Sl} ::= \epsilon$, we have $\mathcal{S}^*[\![\texttt{Sl}]\!] = \{\langle\pi_0\ell, \ell\rangle\}$ by (6.15), where $\ell = \mathsf{at}[\![\texttt{Sl}]\!]$ and so

$$
\begin{aligned}
& \alpha^{\exists l}_{\mathsf{use,mod}}[\![\texttt{Sl}]\!]\ (\mathcal{S}^*[\![\texttt{Sl}]\!])\ L_b, L_e \\
={}& \bigcup\{\alpha^{l}_{\mathsf{use,mod}}[\![\texttt{Sl}]\!]\ L_b, L_e\ \langle\pi_0,\ \pi_1\rangle \mid \langle\pi_0,\ \pi_1\rangle\ \in\ \mathcal{S}^*[\![\texttt{Sl}]\!]\} && \wr(41.3)\wr \\
={}& \bigcup\{\alpha^{l}_{\mathsf{use,mod}}[\![\texttt{Sl}]\!]\ L_b, L_e\ \langle\pi_0,\ \pi_1\rangle \mid \langle\pi_0,\ \pi_1\rangle\ \in\ \{\langle\pi_0\ell,\ \ell\rangle\}\} && \wr\text{def. } \mathcal{S}^*[\![\texttt{Sl}]\!]\wr \\
={}& \alpha^{\exists l}_{\mathsf{use,mod}}[\![\texttt{Sl}]\!]\ L_b, L_e\ \langle\pi_0\ell,\ \ell\rangle && \wr\text{def. } \in \text{ and } \cup\wr \\
={}& \{\mathsf{x} \in \mathbb{V} \mid (\ell = \mathsf{after}[\![\texttt{Sl}]\!] \wedge \mathsf{x} \in L_e) \vee (\mathsf{escape}[\![\texttt{Sl}]\!] \wedge \ell = \mathsf{break\text{-}to}[\![\texttt{Sl}]\!] \wedge \mathsf{x} \in L_b)\} && \wr(41.3)\wr \\
={}& L_e \quad \wr\ell = \mathsf{at}[\![\texttt{Sl}]\!] = \mathsf{after}[\![\texttt{Sl}]\!] \text{ in Appendix } \mathbf{4.2.1} \text{ and } \mathsf{escape}[\![\texttt{Sl}]\!] = \mathsf{ff} \text{ in } \mathbf{4.2.4} \text{ when } \texttt{Sl} = \epsilon\wr
\end{aligned}
$$

□

Proof of Theorem 41.27 The proof is by structural induction and essentially consists in applying De Morgan laws for complement. For example,

$$
\begin{aligned}
& \widehat{\mathcal{S}}^{\forall d}[\![\texttt{if (B) S}_t]\!]\ D_b, D_e \\
={}& \neg\widehat{\mathcal{S}}^{\exists l}[\![\texttt{if (B) S}_t]\!]\ \neg D_b, \neg D_e && \wr\text{definition of } \widehat{\mathcal{S}}^{\forall d}[\![\texttt{S}]\!] \text{ as dual of } \widehat{\mathcal{S}}^{\exists l}[\![\texttt{S}]\!]\wr \\
={}& \neg(\mathbb{use}[\![\texttt{B}]\!] \cup \neg D_e \cup \widehat{\mathcal{S}}^{\exists l}[\![\texttt{S}_t]\!]\ \neg D_b, \neg D_e) && \wr(41.22)\wr \\
={}& \neg\,\mathbb{use}[\![\texttt{B}]\!] \cap \neg\neg D_e \cap \neg\widehat{\mathcal{S}}^{\exists l}[\![\texttt{S}_t]\!]\ \neg D_b, \neg D_e) && \wr\text{De Morgan laws}\wr \\
={}& \neg\,\mathbb{use}[\![\texttt{B}]\!] \cap D_e \cap \widehat{\mathcal{S}}^{\forall d}[\![\texttt{S}_t]\!]\ D_b, D_e && \wr\text{structural induction hypothesis}\wr
\end{aligned}
$$

All other cases are similar. □

3 Mathematical proofs of chapter 44

Proof of Theorem 44.38 • In case (44.41) of an empty temporal specification ε, we have

$$
\begin{aligned}
& \mathcal{M}^{+}[\![\texttt{S}]\!]\langle\underline{\varrho},\ \varepsilon\rangle \\
\triangleq{}& \mathcal{M}^{+}\langle\underline{\varrho},\ \varepsilon\rangle(\widehat{\mathcal{S}}^{*}_{\mathbb{s}}[\![\texttt{S}]\!]) && \wr(44.26)\wr \\
={}& \{\langle\pi,\ \texttt{R}'\rangle \mid \pi \in \widehat{\mathcal{S}}^{*}_{\mathbb{s}}[\![\texttt{S}]\!] \wedge \langle\mathsf{tt},\ \texttt{R}'\rangle = \mathcal{M}^{t}\langle\rho,\ \varepsilon\rangle\pi\} && \wr(44.25)\wr \\
={}& \{\langle\pi,\ \varepsilon\rangle \mid \pi \in \widehat{\mathcal{S}}^{*}_{\mathbb{s}}[\![\texttt{S}]\!]\} && \wr\text{since } \mathcal{M}^{t}\langle\underline{\varrho},\ \varepsilon\rangle\pi \triangleq \langle\mathsf{tt},\ \varepsilon\rangle \text{ by } (44.24)\wr \\
\triangleq{}& \widehat{\mathcal{M}}^{+}[\![\texttt{S}]\!]\langle\underline{\varrho},\ \varepsilon\rangle && \wr(44.41)\wr
\end{aligned}
$$

- In case (44.43) of an empty statement list $\texttt{Sl} ::= \epsilon$

$$
\begin{aligned}
& \mathcal{M}^{+}[\![\texttt{Sl}]\!]\ \langle\underline{\varrho},\ \texttt{R}\rangle \\
={}& \mathcal{M}^{+}\langle\underline{\varrho},\ \texttt{R}\rangle(\widehat{\mathcal{S}}^{*}_{\mathbb{s}}[\![\texttt{Sl}]\!]) && \wr(44.26)\wr \\
={}& \{\langle\pi,\ \texttt{R}'\rangle \mid \pi \in \widehat{\mathcal{S}}^{*}_{\mathbb{s}}[\![\texttt{Sl}]\!] \wedge \langle\mathsf{tt},\ \texttt{R}'\rangle = \mathcal{M}^{t}\langle\underline{\varrho},\ \texttt{R}\rangle\pi\} && \wr(44.25)\wr
\end{aligned}
$$

$$= \{\langle\pi,\ \mathtt{R}'\rangle \mid \pi \in \{\langle \mathsf{at}[\![\mathtt{Sl}]\!],\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\} \wedge \langle \mathsf{tt},\ \mathtt{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}\rangle\pi\} \qquad \text{(42.10)}$$

$$= \{\langle\langle \mathsf{at}[\![\mathtt{Sl}]\!],\ \rho\rangle,\ \mathtt{R}'\rangle \mid \rho \in \mathbb{E}\mathbb{v} \wedge \langle \mathsf{tt},\ \mathtt{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}\rangle(\langle \mathsf{at}[\![\mathtt{Sl}]\!],\ \rho\rangle)\} \qquad \text{(def. } \in\text{)}$$

$$= \{\langle\langle \mathsf{at}[\![\mathtt{Sl}]\!],\ \rho\rangle,\ \mathtt{R}'\rangle \mid \rho \in \mathbb{E}\mathbb{v} \wedge \langle \mathtt{L : B},\ \mathtt{R}'\rangle = \mathsf{fstnxt}(\mathtt{R}) \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathtt{Sl}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathtt{L : B}]\!]\}$$

$$\text{(44.24) with } \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}'\rangle\ni = \langle \mathsf{tt},\ \mathtt{R}'\rangle$$

$$= \widehat{\mathcal{M}}^{\dagger}[\![\mathtt{Sl}]\!]\langle \underline{\varrho},\ \mathtt{R}\rangle \qquad \text{(44.43)}$$

- In case (44.44) of a skip statement $\mathtt{S} ::= \mathtt{;}$

$$\mathcal{M}^{\dagger}[\![\mathtt{S}]\!]\ \langle \underline{\varrho},\ \mathtt{R}\rangle$$

$$= \{\langle\pi,\ \mathtt{R}'\rangle \mid \pi \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathtt{S}]\!] \wedge \langle \mathsf{tt},\ \mathtt{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}\rangle\pi\} \qquad \text{(44.26) and (44.25)}$$

$$= \{\langle\pi,\ \mathtt{R}'\rangle \mid \pi \in \{\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\} \wedge \langle \mathsf{tt},\ \mathtt{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}\rangle\pi\} \qquad \text{(42.11)}$$

$$= \{\langle\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle,\ \mathtt{R}'\rangle \mid \rho \in \mathbb{E}\mathbb{v} \wedge \langle \mathsf{tt},\ \mathtt{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}\rangle(\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle)\} \qquad \text{(def. } \in\text{)}$$

$$= \{\langle\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle,\ \mathtt{R}'\rangle \mid \rho \in \mathbb{E}\mathbb{v} \wedge \langle \mathtt{L : B},\ \mathtt{R}'\rangle = \mathsf{fstnxt}(\mathtt{R}) \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathtt{L : B}]\!]\}$$

$$\text{(44.24) with } \mathcal{M}^t\langle \underline{\varrho},\ \mathtt{R}'\rangle\ni = \langle \mathsf{tt},\ \mathtt{R}'\rangle$$

$$= \widehat{\mathcal{M}}^{\dagger}[\![\mathtt{S}]\!]\langle \underline{\varrho},\ \mathtt{R}\rangle \qquad \text{(44.44)}$$

- In case (44.49) of an iteration statement $\mathtt{S} ::= \mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b$, we apply Corollary 18.31 so we have to calculate the abstract transformer that satisfies the commutation property for an iterate X of the concrete transformer $\mathcal{F}^{*}_{\mathbb{S}}[\![\mathtt{S}]\!]$ (which traces must be of the form $\pi\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle$).

$$\mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\mathcal{F}^{*}_{\mathbb{S}}[\![\mathtt{S}]\!]\ X)$$

$$= \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\{\langle \ell,\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\} \cup \{\pi_2\langle \ell',\ \rho\rangle\langle \mathsf{after}[\![\mathtt{S}]\!],\ \rho\rangle \mid \pi_2\langle \ell',\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathtt{B}]\!]\,\rho = \mathsf{ff} \wedge \ell' = \ell\} \cup \{\pi_2\langle \ell',\rho\rangle\langle \mathsf{at}[\![\mathtt{S}_b]\!],\rho\rangle\cdot\pi_3 \mid \pi_2\langle \ell',\rho\rangle \in X \wedge \mathcal{B}[\![\mathtt{B}]\!]\rho = \mathsf{tt} \wedge \langle \mathsf{at}[\![\mathtt{S}_b]\!],\rho\rangle\cdot\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathtt{S}_b]\!] \wedge \ell' = \ell\}) \qquad \text{(42.6)}$$

$$= \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\{\langle \ell,\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\}) \cup \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\{\pi_2\langle \ell',\ \rho\rangle\langle \mathsf{after}[\![\mathtt{S}]\!],\ \rho\rangle \mid \pi_2\langle \ell',\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathtt{B}]\!]\,\rho = \mathsf{ff} \wedge \ell' = \ell\}) \cup \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\{\pi_2\langle \ell',\ \rho\rangle\langle \mathsf{at}[\![\mathtt{S}_b]\!],\ \rho\rangle\cdot\pi_3 \mid \pi_2\langle \ell',\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathtt{B}]\!]\,\rho = \mathsf{tt} \wedge \langle \mathsf{at}[\![\mathtt{S}_b]\!],\ \rho\rangle\cdot\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathtt{S}_b]\!] \wedge \ell' = \ell\})$$

$$\text{Galois connection (44.30), so that, by Lemma 11.37, } \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle \text{ preserves joins}$$

To avoid repeating (44.41), we assume that $\mathtt{R} \notin \mathbb{R}_{\varepsilon}$ so we can let $\langle \mathtt{L' : B'},\ \mathtt{R}'\rangle = \mathsf{fstnxt}(\mathtt{R})$. There are three subcases.

— The first case is that of an observation of the execution that stops at loop entry $\ell = \mathsf{at}[\![\mathtt{S}]\!]$. This is similar to the above proof *e.g.* of (44.44) for a skip statement, and we get

$$\mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathtt{R}\rangle(\{\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\}$$

$$= \{\langle\langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle,\ \mathtt{R}'\rangle \mid \rho \in \mathbb{E}\mathbb{v} \wedge \langle \mathtt{L' : B'},\ \mathtt{R}'\rangle = \mathsf{fstnxt}(\mathtt{R}) \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathtt{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathtt{L' : B'}]\!]\}$$

— The second case is that of the loop exit

$\mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle(\{\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff}\})$

$= \{\langle \pi,\ \mathsf{R}'\rangle \mid \pi \in \{\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff}\} \wedge \langle \mathrm{tt},\ \mathsf{R}'\rangle = \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle\pi\}$ ≀(44.25)≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}'\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \langle \mathrm{tt},\ \mathsf{R}'\rangle = \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle(\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle)\}$ ≀def. $\in$≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}'\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \exists \mathsf{R}'' \in \mathbb{R}\ .\ \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle(\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle) = \langle \mathrm{tt}, \mathsf{R}''\rangle \wedge \mathcal{M}^{t}\langle \underline{\varrho}, \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!], \rho\rangle) = \langle \mathrm{tt}, \mathsf{R}'\rangle\}$ ≀Lemma 44.37≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \{\langle \pi, \mathsf{R}''\rangle \mid \pi \in X \wedge \langle \mathrm{tt}, \mathsf{R}''\rangle = \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle\pi\} \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'\rangle\}$

≀X is an iterate of the concrete transformer $\mathcal{F}^{*}_{\mathbb{S}}[\![\mathsf{S}]\!]$ so its traces must be of the form $\pi\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle$≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'\rangle\}$ ≀(44.25)≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff}\} \cup \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'\rangle\}$

≀case analysis and $\mathcal{M}^{t}\langle \underline{\varrho},\ \varepsilon\rangle\pi \triangleq \langle \mathrm{tt},\ \varepsilon\rangle$ in (44.24)≀

$= \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff}\} \cup \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}'\ \mathtt{:}\ \mathsf{B}',\ \mathsf{R}'\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \mathsf{R}' \in \mathbb{R}_{\varepsilon} \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}'\ \mathtt{:}\ \mathsf{B}']\!]\} \cup \{\langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{ff} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}'\ \mathtt{:}\ \mathsf{B}',\ \mathsf{R}'''\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}'\ \mathtt{:}\ \mathsf{B}']\!] \wedge \mathsf{R}''' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}''\ \mathtt{:}\ \mathsf{B}'',\ \mathsf{R}'\rangle = \mathsf{fstnxt}(\mathsf{R}''') \wedge \langle \underline{\varrho},\ \langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}''\ \mathtt{:}\ \mathsf{B}'']\!]\}$

≀since $(\langle \mathrm{tt}, \mathsf{R}'\rangle = \mathcal{M}^{t}\langle \underline{\varrho}, \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{after}[\![\mathsf{S}]\!], \rho\rangle)) \Leftrightarrow ((\langle \mathsf{L}'\ \mathtt{:}\ \mathsf{B}', \mathsf{R}'\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \mathsf{R}' \in \mathbb{R}_{\varepsilon} \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}'\ \mathtt{:}\ \mathsf{B}']\!]) \vee (\langle \mathsf{L}'\ \mathtt{:}\ \mathsf{B}',\ \mathsf{R}'''\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}'\ \mathtt{:}\ \mathsf{B}']\!] \wedge \mathsf{R}''' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}''\ \mathtt{:}\ \mathsf{B}'',\ \mathsf{R}'\rangle = \mathsf{fstnxt}(\mathsf{R}''') \wedge \langle \underline{\varrho},\ \langle \mathsf{after}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{\mathsf{r}}[\![\mathsf{L}''\ \mathtt{:}\ \mathsf{B}'']\!])$ as shown above while proving the second term in case (44.46) of a conditional statement $\mathsf{S} ::= \mathtt{if}\ ^{\ell}\ \mathtt{(B)}\ \mathsf{S}_t$≀

— The third and last case is that of an iteration executing the loop body.

$\mathcal{M}^{\dagger}\langle \underline{\varrho},\ \mathsf{R}\rangle(\{\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle \cdot \pi_3 \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathsf{S}_b]\!]\})$

$= \{\langle\pi,\ \mathsf{R}'\rangle \mid \pi \in \{\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!]\} \wedge \langle \mathrm{tt},\ \mathsf{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}\rangle\pi\}$ ≀(44.25)∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge \langle \mathrm{tt},\ \mathsf{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}\rangle(\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3)\}$ ≀def. ∈∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \mid \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge \exists \mathsf{R}'' \in \mathbb{R}\ .\ \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}\rangle(\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}''\rangle \wedge \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3) = \langle \mathrm{tt},\ \mathsf{R}'\rangle\}$ ≀Lemma 44.37∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3, \mathsf{R}'\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \{\langle\pi, \mathsf{R}''\rangle \mid \pi \in X \wedge \langle \mathrm{tt}, \mathsf{R}''\rangle = \mathcal{M}^t\langle \underline{\varrho}, \mathsf{R}\rangle\pi\} \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge \mathcal{M}^t\langle \underline{\varrho}, \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3) = \langle \mathrm{tt}, \mathsf{R}'\rangle\}$

≀def. ∈ and X is an iterate of the concrete transformer $\mathcal{F}^*_{\mathbb{S}}[\![\mathsf{S}]\!]$ so its traces must be of the form $\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle$∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3, \mathsf{R}'\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho}, \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3) = \langle \mathrm{tt},\ \mathsf{R}'\rangle\}$ ≀(44.25)∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3, \mathsf{R}'\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho}, \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge (\exists \mathsf{R}''' \in \mathbb{R}\ .\ \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'''\rangle \wedge \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}'''\rangle(\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3) = \langle \mathrm{tt},\ \mathsf{R}'\rangle)\}$ ≀Lemma 44.37∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3, \mathsf{R}'\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho}, \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \exists \mathsf{R}''' \in \mathbb{R}\ .\ \langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \{\langle\pi,\ \mathsf{R}'\rangle \mid \pi \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!] \wedge \langle \mathrm{tt},\ \mathsf{R}'\rangle = \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}'''\rangle\pi\} \wedge \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'''\rangle\}$

≀def. ∈ and def. $\widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!]$ in Chapter 42 so that its traces must be of the form $\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3$∫

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!], \rho\rangle\pi_3, \mathsf{R}'\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho}, \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'''\rangle \wedge \langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle\}$

≀(44.26) and (44.25), ∧ commutative∫

There are two subcases depending on whether $\mathsf{R}'' \in \mathbb{R}_\varepsilon$ or not.

— If $\mathsf{R}'' \in \mathbb{R}_\varepsilon$, then

$= \{\langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \varepsilon\rangle \mid \langle\pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \varepsilon\rangle \in \mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathrm{tt} \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!]\}$

≀since $\mathsf{R}'' \in \mathbb{R}_\varepsilon$ and $\mathcal{M}^t\langle \underline{\varrho},\ \mathsf{R}''\rangle(\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle) = \langle \mathrm{tt},\ \mathsf{R}'''\rangle$ imply that $\mathsf{R}''' = \varepsilon$ by (44.24) and so $\langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle = \{\langle\pi,\ \varepsilon\rangle \mid \pi \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!]\}$ by (44.26) and (44.25) implies $\mathsf{R}' = \varepsilon$ and $\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{s}}[\![\mathsf{S}_b]\!]$∫

— Otherwise $\mathsf{R}'' \notin \mathbb{R}_\varepsilon$

$= \{\langle \pi_2 \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathsf{tt} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}\ \mathtt{:}\ \mathsf{B}, \mathsf{R}''''\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho}, \langle \mathsf{at}[\![\mathsf{S}]\!], \rho\rangle\rangle \in \mathcal{S}^{r}[\![\mathsf{L}\ \mathtt{:}\ \mathsf{B}]\!] \wedge \mathcal{M}^{t}\langle \underline{\varrho}, \mathsf{R}''''\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle = \langle \mathsf{tt},\ \mathsf{R}'''\rangle \wedge \langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle\}$ ⦃(44.24)⦄

There are two subsubcases, depending on whether R'''' is empty or not.

– If $\mathsf{R}'''' \in \mathbb{R}_{\varepsilon}$ then, as shown before, $\mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}''''\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle = \langle \mathsf{tt}, \mathsf{R}'''\rangle$ implies that $\mathsf{R}''' \in \mathbb{R}_{\varepsilon}$ and so $\langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle$ if and only if $\mathsf{R}' \in \mathbb{R}_{\varepsilon}$ and $\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathsf{S}_b]\!]$. We get

$= \{\langle \pi_2 \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \varepsilon\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathsf{tt} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}\ \mathtt{:}\ \mathsf{B},\ \varepsilon\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{r}[\![\mathsf{L}\ \mathtt{:}\ \mathsf{B}]\!] \wedge \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3 \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathsf{S}_b]\!]\}$
⦃(44.24)⦄

– Otherwise $\mathsf{R}'''' \notin \mathbb{R}_{\varepsilon}$.

$= \{\langle \pi_2 \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathsf{tt} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}\ \mathtt{:}\ \mathsf{B},\ \mathsf{R}''''\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{r}[\![\mathsf{L}\ \mathtt{:}\ \mathsf{B}]\!] \wedge \mathsf{R}'''' \notin \mathbb{R}_{\varepsilon} \wedge \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}''''\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle = \langle \mathsf{tt},\ \mathsf{R}'''\rangle \wedge \langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle\}$

$= \{\langle \pi_2 \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \mid \langle \pi_2\langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle,\ \mathsf{R}''\rangle \in \mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X \wedge \mathcal{B}[\![\mathsf{B}]\!]\,\rho = \mathsf{tt} \wedge \mathsf{R}'' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}\ \mathtt{:}\ \mathsf{B},\ \mathsf{R}''''\rangle = \mathsf{fstnxt}(\mathsf{R}'') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}]\!],\ \rho\rangle\rangle \in \mathcal{S}^{r}[\![\mathsf{L}\ \mathtt{:}\ \mathsf{B}]\!] \wedge \mathsf{R}'''' \notin \mathbb{R}_{\varepsilon} \wedge \langle \mathsf{L}'\ \mathtt{:}\ \mathsf{B}',\ \mathsf{R}'''\rangle = \mathsf{fstnxt}(\mathsf{R}'''') \wedge \langle \underline{\varrho},\ \langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\rangle \in \mathcal{S}^{r}[\![\mathsf{L}'\ \mathtt{:}\ \mathsf{B}']\!] \wedge \langle\langle \mathsf{at}[\![\mathsf{S}_b]\!],\ \rho\rangle\pi_3,\ \mathsf{R}'\rangle \in \mathcal{M}^{+}[\![\mathsf{S}_b]\!]\langle \underline{\varrho},\ \mathsf{R}'''\rangle\}$
⦃(44.24)⦄

— Grouping all cases together we get the term (44.50) defining $\widehat{\mathcal{F}}^{+}[\![\mathsf{S}]\!]\langle \underline{\varrho},\ \mathsf{R}\rangle\ (\mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle X)$ and so Corollary 18.31 and the commutation condition $\mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle(\mathcal{F}^{*}_{\mathbb{S}}[\![\mathsf{S}]\!](X)) = \widehat{\mathcal{F}}^{+}[\![\mathsf{S}]\!]\langle \underline{\varrho},\ \mathsf{R}\rangle\ (\mathcal{M}^{+}\langle \underline{\varrho},\ \mathsf{R}\rangle(X))$ for the iterates X of $\mathcal{F}^{*}_{\mathbb{S}}[\![\mathsf{S}]\!]$ yield $\widehat{\mathcal{M}}^{+}[\![\mathsf{S}]\!]\langle \underline{\varrho},\ \mathsf{R}\rangle \triangleq \mathsf{lfp}^{\subseteq}\,(\widehat{\mathcal{F}}^{+}[\![\mathsf{S}]\!]\langle \underline{\varrho},\ \mathsf{R}\rangle)$ that is (44.49).

- In case (44.48) of a break statement $\mathsf{S} ::= \ell\ \mathbf{break}\ \mathtt{;}$

$\mathcal{M}^{+}[\![\mathsf{S}]\!]\ \langle \underline{\varrho},\ \mathsf{R}\rangle$

$= \{\langle \pi,\ \mathsf{R}'\rangle \mid \pi \in \widehat{\mathcal{S}}^{\,*}_{\mathbb{S}}[\![\mathsf{S}]\!] \wedge \langle \mathsf{tt},\ \mathsf{R}'\rangle = \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle\pi\}$ ⦃(44.26) and (44.25)⦄

$= \{\langle \pi,\ \mathsf{R}'\rangle \mid \pi \in \{\langle \ell,\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\} \cup \{\langle \ell,\ \rho\rangle\langle \mathsf{break\text{-}to}[\![\mathsf{S}]\!],\ \rho\rangle \mid \rho \in \mathbb{E}\mathbb{v}\} \wedge \langle \mathsf{tt},\ \mathsf{R}'\rangle = \mathcal{M}^{t}\langle \underline{\varrho},\ \mathsf{R}\rangle\pi\}$
⦃(42.14)⦄

$= \{\langle\langle \ell, \rho\rangle, \mathsf{R}''\rangle \mid \langle \mathsf{tt}, \mathsf{R}''\rangle = \mathcal{M}^{t}\langle \underline{\varrho}, \mathsf{R}\rangle\langle \ell, \rho\rangle\} \cup \{\langle\langle \ell, \rho\rangle\langle \mathsf{break\text{-}to}[\![\mathsf{S}]\!], \rho\rangle, \mathsf{R}''\rangle \mid \langle \mathsf{tt}, \mathsf{R}''\rangle = \mathcal{M}^{t}\langle \underline{\varrho}, \mathsf{R}\rangle(\langle \ell,\ \rho\rangle\langle \mathsf{break\text{-}to}[\![\mathsf{S}]\!],\ \rho\rangle)\}$ ⦃def. ∪ and ∈⦄

$$= \mathsf{let}\ \langle \mathsf{L} : \mathsf{B}, \mathsf{R}' \rangle = \mathsf{fstnxt}(\mathsf{R})\ \mathsf{in}\ \{\langle\langle \ell, \rho\rangle, \mathsf{R}'\rangle \mid \langle \underline{\varrho}, \langle \ell, \rho\rangle\rangle \in \mathcal{S}^{\mathrm{r}}\llbracket \mathsf{L} : \mathsf{B}\rrbracket\} \cup \{\langle\langle \ell, \rho\rangle\langle \mathsf{break\text{-}to}\llbracket \mathsf{S}\rrbracket, \rho\rangle, \varepsilon\rangle \mid \mathsf{R}' \in \mathbb{R}_\varepsilon \wedge \langle \underline{\varrho}, \langle \ell, \rho\rangle\rangle \in \mathcal{S}^{\mathrm{r}}\llbracket \mathsf{L} : \mathsf{B}\rrbracket\} \cup \{\langle\langle \ell, \rho\rangle\langle \mathsf{break\text{-}to}\llbracket \mathsf{S}\rrbracket, \rho\rangle, \mathsf{R}''\rangle \mid \mathsf{R}' \notin \mathbb{R}_\varepsilon \wedge \langle \underline{\varrho}, \langle \ell, \rho\rangle\rangle \in \mathcal{S}^{\mathrm{r}}\llbracket \mathsf{L} : \mathsf{B}\rrbracket \wedge \langle \mathsf{L}' : \mathsf{B}', \mathsf{R}''\rangle = \mathsf{fstnxt}(\mathsf{R}') \wedge \langle \underline{\varrho}, \langle \mathsf{break\text{-}to}\llbracket \mathsf{S}\rrbracket, \rho\rangle\rangle \in \mathcal{S}^{\mathrm{r}}\llbracket \mathsf{L}' : \mathsf{B}'\rrbracket\}$$

$$\text{⟅}\mathsf{R} \notin \mathbb{R}_\varepsilon, \text{ case analysis on } \mathsf{R}' \in \mathbb{R}_\varepsilon, \text{ and}(44.24)\text{⟆} \quad \square$$

4 Mathematical proofs of chapter 47

Proof (47.47) There are three cases depending on whether the program label ℓ is at or after statement S, or in the true branch S_t.

— (1) — The cases $\ell = \mathsf{at}\llbracket \mathsf{S}\rrbracket$ was handled in (47.41) and $\ell \notin \mathsf{labx}\llbracket \mathsf{S}\rrbracket$ in (47.42).

— (2) — Assume $\ell = \mathsf{after}\llbracket \mathsf{S}\rrbracket$.

$$\alpha^{\mathrm{d}}(\{\mathcal{S}^{+\infty}\llbracket \mathsf{S}\rrbracket\})\ \mathsf{after}\llbracket \mathsf{S}\rrbracket$$

$$= \alpha^{\mathrm{d}}(\{\mathcal{S}^{*}\llbracket \mathsf{S}\rrbracket\})\ \mathsf{after}\llbracket \mathsf{S}\rrbracket \qquad \text{⟅Lemma 47.23⟆}$$

$$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathcal{S}^{*}\llbracket \mathsf{S}\rrbracket \in \mathcal{D}(\mathsf{after}\llbracket \mathsf{S}\rrbracket)\langle \mathsf{x}', \mathsf{y}\rangle\} \qquad \text{⟅def. (47.25) of } \alpha^{\mathrm{d}}\text{⟆}$$

$$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \mathcal{S}^{*}\llbracket \mathsf{S}\rrbracket \ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \ .\ \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket \mathsf{y}\rrbracket(\mathsf{after}\llbracket \mathsf{S}\rrbracket)(\pi_0, \pi_1), \mathsf{seqval}\llbracket \mathsf{y}\rrbracket(\mathsf{after}\llbracket \mathsf{S}\rrbracket)(\pi'_0, \pi'_1))\} \qquad \text{⟅def. (47.19) of } \mathcal{D}^{\ell}\langle \mathsf{x}', \mathsf{y}\rangle\text{⟆}$$

$$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \{\langle \pi\mathsf{at}\llbracket \mathsf{S}\rrbracket, \mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\neg(\mathsf{B})} \mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{ff}\} \cup \{\langle \pi\mathsf{at}\llbracket \mathsf{S}\rrbracket, \mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{tt} \wedge \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket \in \widehat{\mathcal{S}}^{+\infty}\llbracket \mathsf{S}_t\rrbracket(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket)\} \ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \ .\ \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket \mathsf{y}\rrbracket(\mathsf{after}\llbracket \mathsf{S}\rrbracket)(\pi_0, \pi_1), \mathsf{seqval}\llbracket \mathsf{y}\rrbracket(\mathsf{after}\llbracket \mathsf{S}\rrbracket)(\pi'_0, \pi'_1))\}$$

$$\text{⟅def. } \mathcal{S}^{*}\llbracket \mathsf{S}\rrbracket \text{ in (6.9), (6.19), and (6.18) so that } \mathsf{after}\llbracket \mathsf{S}\rrbracket = \mathsf{after}\llbracket \mathsf{S}_t\rrbracket\text{⟆}$$

$$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle, \langle \pi'_0, \pi'_1\mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle \in \{\langle \pi\mathsf{at}\llbracket \mathsf{S}\rrbracket, \mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\neg(\mathsf{B})} \mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{ff}\} \cup \{\langle \pi\mathsf{at}\llbracket \mathsf{S}\rrbracket, \mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket\rangle \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{tt} \wedge \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket \in \widehat{\mathcal{S}}^{+\infty}\llbracket \mathsf{S}_t\rrbracket(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket)\} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \ .\ \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\varrho(\pi_0 \mathbin{\frown} \pi_1\mathsf{after}\llbracket \mathsf{S}\rrbracket)\mathsf{y}, \varrho(\pi'_0 \mathbin{\frown} \pi'_1\mathsf{after}\llbracket \mathsf{S}\rrbracket)\mathsf{y})\}$$

$$\text{⟅def. } \in \text{ so that } \pi_1 \text{ and } \pi'_1 \text{ must end with } \mathsf{after}\llbracket \mathsf{S}\rrbracket \text{ and def. (47.16) of } \mathsf{seqval}\llbracket \mathsf{y}\rrbracket\text{⟆}$$

$$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0\mathsf{at}\llbracket \mathsf{S}\rrbracket\pi_1\mathsf{after}\llbracket \mathsf{S}\rrbracket, \pi'_0\mathsf{at}\llbracket \mathsf{S}\rrbracket\pi'_1\mathsf{after}\llbracket \mathsf{S}\rrbracket \in \{\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\neg(\mathsf{B})} \mathsf{after}\llbracket \mathsf{S}\rrbracket \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{ff}\} \cup \{\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket \mid \mathcal{B}\llbracket \mathsf{B}\rrbracket\varrho(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket) = \mathsf{tt} \wedge \mathsf{at}\llbracket \mathsf{S}_t\rrbracket\pi'\mathsf{after}\llbracket \mathsf{S}\rrbracket \in \widehat{\mathcal{S}}^{+\infty}\llbracket \mathsf{S}_t\rrbracket(\pi\mathsf{at}\llbracket \mathsf{S}\rrbracket \xrightarrow{\mathsf{B}} \mathsf{at}\llbracket \mathsf{S}_t\rrbracket)\} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \ .\ \varrho(\pi_0\mathsf{at}\llbracket \mathsf{S}\rrbracket)\mathsf{z} = \varrho(\pi'_0\mathsf{at}\llbracket \mathsf{S}\rrbracket)\mathsf{z}) \wedge \mathsf{diff}(\varrho(\pi_0\mathsf{at}\llbracket \mathsf{S}\rrbracket\pi_1\mathsf{after}\llbracket \mathsf{S}\rrbracket)\mathsf{y}, \varrho(\pi'_0\mathsf{at}\llbracket \mathsf{S}\rrbracket\pi'_1\mathsf{after}\llbracket \mathsf{S}\rrbracket)\mathsf{y})\}$$

$$\wr\text{def. } \in \text{ and trace concatenation } \frown \wr$$

$$= \{\langle \mathtt{x}',\ \mathtt{y}\rangle \mid \exists \pi_0\mathsf{at}[\![\mathtt{S}]\!]\pi_1\mathsf{after}[\![\mathtt{S}]\!], \pi'_0\mathsf{at}[\![\mathtt{S}]\!]\pi'_1\mathsf{after}[\![\mathtt{S}]\!] \in \{\pi\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!] \mid \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff}\} \cup \{\pi\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_t]\!]\pi'\mathsf{after}[\![\mathtt{S}]\!] \mid \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{tt} \wedge \mathsf{at}[\![\mathtt{S}_t]\!]\pi'\mathsf{after}[\![\mathtt{S}]\!] \in \widehat{\mathscr{S}}^{+\infty}[\![\mathtt{S}_t]\!](\pi\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_t]\!])\} \wedge (\forall \mathtt{z} \in \mathbb{V} \setminus \{\mathtt{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z} = \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z}) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!]\pi_1\mathsf{after}[\![\mathtt{S}]\!])\mathtt{y} \neq \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]\pi'_1\mathsf{after}[\![\mathtt{S}]\!])\mathtt{y})\} \quad (1)$$

$$\wr\text{def. (47.18) of diff}\wr$$

There are four subcases, depending upon which branch of the conditional is taken by the two executions $\pi_0\mathsf{at}[\![\mathtt{S}]\!]\pi_1\mathsf{after}[\![\mathtt{S}]\!]$ and $\pi'_0\mathsf{at}[\![\mathtt{S}]\!]\pi'_1\mathsf{after}[\![\mathtt{S}]\!]$.

— (2.a) — If both executions $\pi_0\mathsf{at}[\![\mathtt{S}]\!]\pi_1\mathsf{after}[\![\mathtt{S}]\!]$ and $\pi'_0\mathsf{at}[\![\mathtt{S}]\!]\pi'_1\mathsf{after}[\![\mathtt{S}]\!]$ are through the false branch, we have,

(1)

$$= \{\langle \mathtt{x}',\ \mathtt{y}\rangle \mid \exists \pi_0\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!], \pi'_0\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!] \,.\, \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff} \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff} \wedge (\forall \mathtt{z} \in \mathbb{V} \setminus \{\mathtt{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z} = \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z}) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!])\mathtt{y} \neq \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!])\mathtt{y})\}$$

$$\wr\text{case } \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff} \text{ and } \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff}\wr$$

$$= \{\langle \mathtt{x}',\ \mathtt{y}\rangle \mid \exists \pi_0\mathsf{at}[\![\mathtt{S}]\!], \pi'_0\mathsf{at}[\![\mathtt{S}]\!] \,.\, \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff} \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]) = \mathrm{ff} \wedge (\forall \mathtt{z} \in \mathbb{V} \setminus \{\mathtt{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z} = \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z}) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{y} \neq \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]))\mathtt{y})\}$$

$$\wr\text{def. (6.6) of } \varrho \text{ so that } \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!] \xrightarrow{\neg(\mathtt{B})} \mathsf{after}[\![\mathtt{S}]\!])\mathtt{y} = \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!]\mathtt{y})\wr$$

$$= \{\langle \mathtt{x}',\ \mathtt{y}\rangle \mid \exists \rho, \nu \,.\, \mathscr{B}[\![\mathtt{B}]\!]\rho = \mathrm{ff} \wedge \mathscr{B}[\![\mathtt{B}]\!]\rho[\mathtt{x}' \leftarrow \nu] = \mathrm{ff} \wedge \rho(\mathtt{y}) \neq \rho[\mathtt{x}' \leftarrow \nu]\mathtt{y}\}$$

≀letting $\rho = \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])$, $\nu = \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{x}'$ so that $\forall \mathtt{z} \in \mathbb{V} \setminus \{\mathtt{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z} = \varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])\mathtt{z}$ implies $\varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!]) = \rho[\mathtt{x}' \leftarrow \nu]$ and, conversely Exercise 6.8, so that any environment ρ can be computed as the result $\varrho(\pi'_0\mathsf{at}[\![\mathtt{S}]\!])$ of an appropriate initialization trace ${}'_0\mathsf{at}[\![\mathtt{S}]\!]$ (otherwise, this is $\subseteq$)≀

$$= \{\langle \mathtt{x}',\ \mathtt{x}'\rangle \mid \exists \rho, \nu \,.\, \rho(\mathtt{x}') \neq \nu \wedge \mathscr{B}[\![\mathtt{B}]\!]\rho = \mathrm{ff} \wedge \mathscr{B}[\![\mathtt{B}]\!]\rho[\mathtt{x}' \leftarrow \nu] = \mathrm{ff}\}$$

$$\wr\text{since } \rho[\mathtt{x}' \leftarrow \nu](\mathtt{y}) = \rho(\mathtt{y}) \text{ when } \mathtt{y} \neq \mathtt{x}'\wr$$

$$= \{\langle \mathtt{x}',\ \mathtt{x}'\rangle \mid \mathtt{x}' \in \mathsf{nondet}(\neg\mathtt{B}, \neg\mathtt{B})\} \qquad \wr\text{def. (47.48) of nondet}\wr$$

$$= \mathbb{1}_{\mathbb{V}} \rceil \mathsf{nondet}(\neg\mathtt{B}, \neg\mathtt{B}) \qquad \wr\text{def. left restriction } \rceil\wr$$

$$\subseteq \mathbb{1}_{\mathbb{V}}$$

In words for that first case, the initial value of $\mathtt{x}'$ flows to the value of $\mathtt{x}'$ by the false branch of the conditional `if (B) S`$_t$ when there are at least two different values of $\mathtt{x}'$ for which `B` is false. (If there is only one, x' is constant on the false branch. This can be disproved by a constancy analysis [3, 4, 6, 7, 9, 10] or a determinacy analysis [5, 8].) A classical coarser over-approximation is to ignore values *i.e.* that variables may have only one value making the test false.

— (2.b) — Else, if both executions $\pi_0\mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!]$ and $\pi'_0\mathsf{at}[\![\mathsf{S}]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!]$ are through the true branch, we have,

(1)

$$= \{\langle\mathsf{x}',\ \mathsf{y}\rangle \mid \exists\pi_0\mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!], \pi'_0\mathsf{at}[\![\mathsf{S}]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!] \in \{\pi\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\mathsf{after}[\![\mathsf{S}]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\} \wedge (\forall\mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\}\ .\ \boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge (\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$$

$$\text{\{case } \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \text{ and } \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{ff}\text{\}}$$

$$= \{\langle\mathsf{x}',\ \mathsf{y}\rangle \mid \exists\pi_0, \pi_1, \pi'_0, \pi'_1\ .\ \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) \wedge \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\forall\mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\}\ .\ \boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge (\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$$

$$\text{\{def. } \in\text{\}}$$

$$= \{\langle\mathsf{x}',\ \mathsf{y}\rangle \mid \exists\langle\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!],\ \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}_t]\!]\pi_2\rangle, \langle\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!],\ \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2\rangle \in \mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!]\ .\ \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge (\forall\mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\}\ .\ \boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \pi_1 \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \pi'_1 \wedge (\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$$

$$\text{\{}\mathsf{after}[\![\mathsf{S}]\!] = \mathsf{after}[\![\mathsf{S}_t]\!], \pi_2 = \pi'_2 = \ni, \text{def. (6.6) of } \boldsymbol{\varrho}\text{\}}$$

$$= \{\langle\mathsf{x}',\ \mathsf{y}\rangle \mid \exists\langle\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!],\ \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}_t]\!]\pi_2\rangle, \langle\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!],\ \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2\rangle \in \mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!]\ .\ \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge (\forall\mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\}\ .\ \boldsymbol{\varrho}(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \boldsymbol{\varrho}(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \pi_1 \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \pi'_1 \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!] \frown \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}_t]\!],\ \mathsf{after}[\![\mathsf{S}_t]\!]\pi_2),\ \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!] \frown \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\mathsf{after}[\![\mathsf{S}_t]\!],\ \mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2))\}$$

$$\text{\{def. (47.18) of } \mathsf{diff} \text{ and (47.16) of } \mathsf{seqval}[\![\mathsf{y}]\!]\text{\}}$$

$$\subseteq \{\langle\mathsf{x}',\ \mathsf{y}\rangle \mid \exists\langle\bar{\pi}_0,\ \bar{\pi}_1\mathsf{after}[\![\mathsf{S}_t]\!]\pi_2\rangle, \langle\bar{\pi}_0{}',\ \bar{\pi}_1{}'\mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2\rangle \in \mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!]\ .\ \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\bar{\pi}_0) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\boldsymbol{\varrho}(\bar{\pi}_0{}') = \mathsf{tt} \wedge (\forall\mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\}\ .\ \boldsymbol{\varrho}(\bar{\pi}_0)\mathsf{z} = \boldsymbol{\varrho}(\bar{\pi}_0{}')\mathsf{z}) \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \bar{\pi}_1 \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \bar{\pi}_1{}' \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\bar{\pi}_0 \frown \bar{\pi}_1\mathsf{after}[\![\mathsf{S}_t]\!],\ \mathsf{after}[\![\mathsf{S}_t]\!]\pi_2),\ \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\bar{\pi}_0{}' \frown \bar{\pi}_1{}'\mathsf{after}[\![\mathsf{S}_t]\!],\ \mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2))\}$$

$$\text{\{letting } \bar{\pi}_0 = \pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!],\ \bar{\pi}_1 = \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1,\ \bar{\pi}_0{}' = \pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!], \text{ and } \bar{\pi}_1{}' = \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\text{\}}$$

$\subseteq \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \bar{\pi}_0, \bar{\pi}_1 \mathsf{after}[\![\mathsf{S}_t]\!]\pi_2\rangle, \langle \bar{\pi}_0{}', \bar{\pi}_1{}' \mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2\rangle \in \mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!] \,.\, (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\bar{\pi}_0)\mathsf{z} = \varrho(\bar{\pi}_0{}')\mathsf{z}) \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \bar{\pi}_1 \wedge \mathsf{after}[\![\mathsf{S}_t]\!] \notin \bar{\pi}_1{}' \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\bar{\pi}_0 \frown \bar{\pi}_1 \mathsf{after}[\![\mathsf{S}_t]\!], \mathsf{after}[\![\mathsf{S}_t]\!]\pi_2), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}_t]\!])(\bar{\pi}_0{}' \frown \bar{\pi}_1{}' \mathsf{after}[\![\mathsf{S}_t]\!], \mathsf{after}[\![\mathsf{S}_t]\!]\pi'_2))\}$

$\wr$letting $\rho = \varrho(\bar{\pi}_0)$ and $\nu = \varrho(\bar{\pi}_0{}')(\mathsf{x}')$$\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!] \in \mathcal{D}(\mathsf{after}[\![\mathsf{S}_t]\!])\langle \mathsf{x}', \mathsf{y}\rangle\}$ $\wr$def. (47.19) of $\mathcal{D}^{\ell}\langle \mathsf{x}', \mathsf{y}\rangle$$\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \alpha^{\mathsf{d}}(\{\mathcal{S}^{+\infty}[\![\mathsf{S}_t]\!]\})\,\mathsf{after}[\![\mathsf{S}_t]\!]$

$\wr$def. $\subseteq$ and def. (47.25) of $\alpha^{\mathsf{d}}$$\wr$

In words for that second case, the initial value of x' flows to the value of y by the true branch of the conditional `if (B)` S_t when there are at least two different values of x' for which B is true and x' flows to the value of y in S_t.

$\subseteq \widehat{\overline{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_t]\!]\,\mathsf{after}[\![\mathsf{S}_t]\!] \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})$

$\wr$by structural ind. hyp. , def. (47.48) of nondet, and def. of the left restriction $\rceil$ of a relation in Section 2.2.2$\wr$

$\subseteq \widehat{\overline{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_t]\!]\,\mathsf{after}[\![\mathsf{S}_t]\!]$ $\wr$A coarse over-approximation ignoring values$\wr$

— (2.c–d) — Otherwise, one execution is through the true branch (say $\pi_0 \mathsf{at}[\![\mathsf{S}]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!]$) and the other is through the false branch (say $\pi'_0 \mathsf{at}[\![\mathsf{S}]\!]\pi'_1 \mathsf{after}[\![\mathsf{S}]\!]$), we have (the other case is symmetric),

(1)

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0 \mathsf{at}[\![\mathsf{S}]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!] \in \{\pi \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi' \mathsf{after}[\![\mathsf{S}]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi' \mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\} \,.\, \exists \pi'_0 \mathsf{at}[\![\mathsf{S}]\!]\pi'_1 \mathsf{after}[\![\mathsf{S}]\!] \in \{\pi \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{ff}\} \,.\, (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge (\varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!]\pi'_1 \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$

$\wr$case $\mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt}$ and $\mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{ff}$$\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0, \pi_1, \pi'_0 \,.\, \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0 \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge (\varrho(\pi_0 \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$ $\wr$def. $\in$$\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \bar{\pi}_0, \pi_1, \pi'_0 \,.\, \mathcal{B}[\![\mathsf{B}]\!]\varrho(\bar{\pi}_0 \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\bar{\pi}_0 \mathsf{at}[\![\mathsf{S}_t]\!]) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\bar{\pi}_0 \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge (\varrho(\bar{\pi}_0 \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1 \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'_0 \mathsf{at}[\![\mathsf{S}]\!])\mathsf{y}\}$

$\wr$letting $\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!] = \pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]$ so that by def. (6.6) of ϱ, $\varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!]) = \varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!])$ so $\mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathcal{B}[\![\mathsf{B}]\!]\varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!])$ and $\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{y}$$\int$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists\bar{\pi}_0, \pi_1, \pi'_0 \;.\; \mathcal{B}[\![\mathsf{B}]\!]\varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge (\varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}\}$

$\wr$by def. (6.6) of ϱ so that $\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]) = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])$$\int$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \;.\; (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}\}$

$\wr$letting $\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!] = \pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]$, commutativity of $\wedge$$\int$

$= \{\langle \mathsf{x}', \mathsf{x}'\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \;.\; (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{x}' \neq \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{x}'\}$
$\cup \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathsf{x}' \neq \mathsf{y} \wedge \exists\pi_0, \pi_1, \pi'_0 \;.\; (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}\}$

$\wr$since when $\mathsf{x}' \neq \mathsf{y}$, $\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y} = \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}$$\int$

In words for that third case, x' flows to x' if and only if changing x' changes the boolean expression B and when B is true, S_t changes x' to a value different from that when B is false. A counter-example is `if (x' != 1) x' = 1 ;`.

Moreover, x' flows to $\mathsf{y} \neq \mathsf{x}'$ if and only if changing x' changes the boolean expression B and when B is true, S_t changes y.

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \;.\; (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}\}$ $\wr$grouping cases together$\int$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \;.\; (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{ff} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{y}\} \;\rceil\; \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$

$\wr$letting $\rho = \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])$, $\nu = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{x}'$ so that $\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}'\} \;.\; \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}$ implies $\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]) = \rho[\mathsf{x}' \leftarrow \nu]$. It follows that $\exists\rho, \nu \;.\; \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{ff}$. Therefore, by def. (47.48) of nondet, $\mathsf{x}' \in \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$$\int$

$\subseteq \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathsf{x}' \in \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \wedge \mathsf{y} \in \mathsf{mod}[\![\mathsf{S}_t]\!]\}$

$\wr$Since $\{\mathsf{x} \mid \exists \pi_0, \pi_1 . \mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^*[\![\mathsf{S}]\!](\pi_0\mathsf{at}[\![\mathsf{S}]\!]) \wedge \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{x} \neq \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{x}\} \subseteq \mathsf{mod}[\![\mathsf{S}]\!]$, a simple coarse approximation is to consider the variables y appearing to the left of an assignment in S_t, a necessary condition for y to be modified by the execution of S_t where the set $\mathsf{mod}[\![\mathsf{S}]\!]$ of variables that may be modified by the execution of S is syntactically defined as in (47.50). $\wr$

$= \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_t]\!]$ $\quad\wr$def. cartesian product$\wr$

$\subseteq \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathsf{x}' \in \mathbb{vars}[\![\mathsf{B}]\!] \wedge \mathsf{y} \in \mathsf{mod}[\![\mathsf{S}_t]\!]\}$

$\wr\mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$ can be over-approximated by the set of variables x' occurring in the boolean expression B as defined in Exercise 3.3$\wr$

Exercise 2 Prove that for all program components $\mathsf{S} \in \mathbb{P}c$,

$$\{\mathsf{x} \mid \exists \pi_0, \pi_1 . \mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!] \in \widehat{\mathcal{S}}^{+\infty}[\![\mathsf{S}]\!](\pi_0\mathsf{at}[\![\mathsf{S}]\!]) \wedge \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!]\pi_1\mathsf{after}[\![\mathsf{S}]\!])\mathsf{x} \neq \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{x}\} \quad \subseteq \quad \mathsf{mod}[\![\mathsf{S}]\!]. \qquad \square$$

— (3) — Finally, assume $\ell \in \mathsf{in}[\![\mathsf{S}_t]\!]$.

$\alpha^{\mathrm{d}}(\{\mathcal{S}^*[\![\mathsf{S}]\!]\})\,\ell$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathcal{S}^*[\![\mathsf{S}]\!] \in \mathcal{D}^\ell\langle \mathsf{x}', \mathsf{y}\rangle\}$ $\quad\wr$def. (47.25) of $\alpha^{\mathrm{d}}\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \mathcal{S}^*[\![\mathsf{S}]\!] . (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} . \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0, \pi'_1))\}$ $\quad\wr$def. (47.19) of $\mathcal{D}^\ell\langle \mathsf{x}', \mathsf{y}\rangle\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \{\langle \pi\mathsf{at}[\![\mathsf{S}]\!], \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\ell\pi''\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\ell\pi'' \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\} . (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} . \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0, \pi'_1))\}$ $\quad\wr$def. (6.19) of $\mathcal{S}^*[\![\mathsf{S}]\!]\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \{\langle \pi\mathsf{at}[\![\mathsf{S}]\!], \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\ell\pi''\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'\ell\pi'' \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\} . (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} . \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0, \pi'_1))\}$

$\wr$since if $\langle \pi_0, \pi_1\rangle$ (or $\langle \pi'_0, \pi'_1\rangle$) has the form $\langle \pi\mathsf{at}[\![\mathsf{S}]\!], \mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle$ then ℓ does not appear in π_1 (resp. π'_1) so that, by (47.16), $\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0, \pi_1) = \ni$ (resp. $\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0, \pi'_1) = \ni$ and therefore, by (47.18), $\mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\ell)(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!](\ell)(\pi'_0, \pi'_1))$ is false$\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0, \pi_1, \pi_2, \pi'_0, \pi'_1, \pi'_2 . \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell\pi_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!])\} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell\pi'_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}'\} . \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z} = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\mathsf{z}) \wedge \ell \notin \pi_1 \wedge \ell \notin \pi'_1 \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell, \ell\pi_2), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell, \ell\pi'_2))\}$

$\wr$def. $\in$ and if ℓ has multiple occurrences in $\pi'_1\ell\pi'_2$, we choose the first one, same for $\pi'_1\ell\pi'_2\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \bar{\pi}_0, \pi_1, \pi_2, \bar{\pi}_0{}', \pi'_1, \pi'_2 \,.\, \mathcal{B}[\![\mathsf{B}]\!]\varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell\pi_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!])\} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell\pi'_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \ell \notin \pi_1 \wedge \ell \notin \pi'_1 \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell,\ \ell\pi_2), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell,\ \ell\pi'_2))\}$

$\wr$letting $\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!] = \pi_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]$, $\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!] = \pi'_0\mathsf{at}[\![\mathsf{S}]\!] \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_t]\!]$ so that by def. (6.6) of ϱ, $\varrho(\bar{\pi}_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \varrho(\pi_0\mathsf{at}[\![\mathsf{S}]\!])$ and $\varrho(\bar{\pi}_0{}'\mathsf{at}[\![\mathsf{S}_t]\!]) = \varrho(\pi'_0\mathsf{at}[\![\mathsf{S}]\!])\wr$

$\subseteq \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0, \pi'_0 \,.\, \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) = \mathsf{tt} \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi_0{}'\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z})\} \cap \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \pi_0, \pi_1, \pi_2, \pi'_0, \pi'_1, \pi'_2 \,.\, \mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell\pi_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge \mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell\pi'_2 \in \widehat{\mathcal{S}}^*[\![\mathsf{S}_t]\!](\pi'_0\mathsf{at}[\![\mathsf{S}_t]\!]) \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}'\} \,.\, \varrho(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z} = \varrho(\pi_0{}'\mathsf{at}[\![\mathsf{S}_t]\!])\mathsf{z}) \wedge \ell \notin \pi_1 \wedge \ell \notin \pi'_1 \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\mathsf{at}[\![\mathsf{S}_t]\!]\pi_1\ell,\ \ell\pi_2), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0{}'\mathsf{at}[\![\mathsf{S}_t]\!]\pi'_1\ell,\ \ell\pi'_2))\}$ $\wr$def. $\exists$ and $\subseteq\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \mathcal{S}^*[\![\mathsf{S}_t]\!] \in \mathcal{D}(\ell)\langle \mathsf{x}', \mathsf{y}\rangle\}$ $\wr$letting $\rho = \varrho(\bar{\pi}_0)$, $\nu = \varrho(\bar{\pi}_0{}')(\mathsf{x}')$ and def. (47.19) of $\mathcal{D}\ell\langle \mathsf{x}', \mathsf{y}\rangle\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \{\mathcal{S}^*[\![\mathsf{S}_t]\!]\} \subseteq \mathcal{D}(\ell)\langle \mathsf{x}', \mathsf{y}\rangle\}$ $\wr$def. $\subseteq\wr$

$= \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \alpha^{\mathsf{d}}(\{\mathcal{S}^*[\![\mathsf{S}_t]\!]\})\,\ell$

$\wr$def. (47.25) of $\alpha^{\mathsf{d}}\wr$

$\subseteq \{\langle \mathsf{x}', \mathsf{y}\rangle \mid \exists \rho, \nu \,.\, \rho(\mathsf{x}') \neq \nu \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho = \mathsf{tt} \wedge \mathcal{B}[\![\mathsf{B}]\!]\rho[\mathsf{x}' \leftarrow \nu] = \mathsf{tt}\} \cap \mathcal{S}^{\mathsf{d}}[\![\mathsf{S}_t]\!]\,\ell$

$\wr$structural induction hypothesis$\wr$

$= \mathcal{S}^{\mathsf{d}}[\![\mathsf{S}_t]\!]\,\ell \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})$ $\wr$def. (47.48) of $\mathsf{nondet}\wr$

In words, the initial value of x' flows to the value of y at ℓ in the true branch S_t of the conditional `if (B)` S_t when there are at least two different values of x' for which B is true and x' flows to the value of y at ℓ in S_t.

$\subseteq \mathcal{S}^{\mathsf{d}}[\![\mathsf{S}_t]\!]\,\ell$

$\wr$A coarse over-approximation ignoring values *i.e.* that the conditional holds for only one value of $\mathsf{x}'\wr$ $\square$

Proof of (47.63) By Lemma 47.23, the Definition 47.28 of value dependency using the maximal traces semantics is equivalent to the definition of value dependency for finite prefix traces, as defined by (17.4). So the soundness of (47.63) follows from the following (3):

$$\left[\begin{array}{lcl} \alpha^{\mathsf{d}}(\mathcal{S}^{*}[\![\mathtt{S}]\!]) & = & \alpha^{\mathsf{d}}(\mathsf{lfp}^{\subseteq}\,\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]) \\ \dot{\subseteq}\ \ \mathsf{lfp}^{\dot{\subseteq}}\,\mathcal{F}^{\mathsf{diff}}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!] & = & \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\mathtt{S}]\!] \end{array}\right. \tag{3}$$

The proof of (3) is an application of Exercise 18.17. $\langle C,\ \sqsubseteq,\ \bot,\ \sqcup\rangle$ is the complete lattice $\langle\wp(\wp(\mathbb{T}^{+}\times\mathbb{T}^{+\infty})),\ \subseteq,\ \varnothing,\ \cup\rangle$. $\langle\mathcal{A},\ \preccurlyeq,\ 0,\ \curlyvee\rangle$ is the complete lattice $\langle\mathbb{P}^{\mathsf{d}},\ \subseteq^{\mathsf{d}},\ \bot^{\mathsf{d}},\ \cup^{\mathsf{d}}\rangle$. The Galois connection $\langle C,\ \sqsubseteq\rangle \xrightleftharpoons[\alpha]{\gamma} \langle\mathcal{A},\ \preccurlyeq\rangle$ is given by Lemma 47.26. The transformer f is (17.4). It preserves arbitrary non-empty unions so it is continuous. The transformer g is (47.63). It preserves arbitrary non-empty unions pointwise so it is pointwise continuous (*i.e.* for $\subseteq^{\mathsf{d}}$ and $\cup^{\mathsf{d}}$ defined pointwise). The main point of the proof is to check the semi-commutation condition

$$\alpha^{\mathsf{d}}\circ\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\quad\dot{\subseteq}\quad\mathcal{F}^{\mathsf{diff}}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\circ\alpha^{\mathsf{d}}\,. \tag{4}$$

By Exercise 18.17, we need to make the proof only for elements $X\in\mathcal{X}$ where $\mathcal{X}$ is chosen to be exactly the iterates of the transformer $\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]$ from $\varnothing$.

In practice, we have discovered $\mathcal{F}^{\mathsf{diff}}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]$ knowing $\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]$ and α^{d} by rewriting until getting a formula of the form $\mathcal{F}^{\mathsf{diff}}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\circ\alpha^{\mathsf{d}}$ and using $\dot{\subseteq}$-over-approximations to ignore values in the static analysis. By Exercise 18.17, we conclude that

$$\alpha^{\mathsf{d}}(\mathsf{lfp}^{\subseteq}\,\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!])\ \dot{\subseteq}\ \mathsf{lfp}^{\dot{\subseteq}}\,\mathcal{F}^{\mathsf{diff}}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\,.$$

The proof of semi-commutation (4) is by calculational design as follows. By def. (47.18) of diff, we do not have to compare futures of prefix traces where one is a prefix of the other.

$$\begin{array}{ll} \multicolumn{2}{l}{\alpha^{\mathsf{d}}(\{\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\,X\})\,\ell'} \\ =\ \{\langle\mathtt{x},\ \mathtt{y}\rangle\mid\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\,X\in\mathcal{D}(\ell')\langle\mathtt{x},\ \mathtt{y}\rangle\} & \text{(def. (47.25) of } \alpha^{\mathsf{d}}\text{)} \\ =\ \{\langle\mathtt{x},\ \mathtt{y}\rangle\mid\exists\langle\pi_0,\ \pi_1\rangle,\langle\pi'_0,\ \pi'_1\rangle\in\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\,X\ .\ (\forall\mathtt{z}\in\mathcal{V}\setminus\{\mathtt{x}\}\ .\ \varrho(\pi_0)\mathtt{z}=\varrho(\pi'_0)\mathtt{z})\ \wedge & \\ \quad \mathsf{diff}(\mathsf{seqval}[\![\mathtt{y}]\!]\ell'(\pi_0,\pi_1),\mathsf{seqval}[\![\mathtt{y}]\!]\ell'(\pi'_0,\pi'_1))\} & \text{(def. (47.19) of } \mathcal{D}^{\ell}\langle\mathtt{x},\ \mathtt{y}\rangle\text{)} \end{array}$$

$$\begin{array}{l} =\ \{\langle\mathtt{x},\ \mathtt{y}\rangle\mid\exists\langle\pi_0\ell,\ \ell\pi_1\rangle,\langle\pi'_0\ell,\ \ell\pi'_1\rangle\in\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\,X\ .\ (\forall\mathtt{z}\in\mathcal{V}\setminus\{\mathtt{x}\}\ . \\ \quad \varrho(\pi_0\ell)\mathtt{z}=\varrho(\pi'_0\ell)\mathtt{z})\wedge\mathsf{diff}(\mathsf{seqval}[\![\mathtt{y}]\!]\ell'(\pi_0\ell,\ell\pi_1),\mathsf{seqval}[\![\mathtt{y}]\!]\ell'(\pi'_0\ell,\ell\pi'_1))\} \\ \qquad\qquad \text{(since } \langle\pi_0\ell',\ \ell''\pi_1\rangle\notin\mathcal{F}^{*}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!](X) \text{ when } \ell'\neq\ell \text{ or } \ell''\neq\ell\text{)} \end{array} \tag{5}$$

There are three main cases depending on whether the dependency observation point ℓ' is **(1)** at the iteration (so $\ell'=\ell=\mathsf{at}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]$), **(2)** is in the loop body (so $\ell'\in\mathsf{in}[\![\mathtt{S}_b]\!]$), or **(3)** is after the iteration (so $\ell'=\mathsf{after}[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]$).

For each of these case, we have to consider all possible ways the traces $\ell\pi_1$ and $\ell\pi'_1$ in (5) can go through the dependency observation program point ℓ'. The definition of $\mathcal{F}^{*}$ below shows all possible choices **(A)**, **(B)**, or **(C)** of $\ell\pi_1$ and $\ell\pi'_1$ in (5). Notice that diff in (47.16) is commutative so $\langle\pi_0\ell,\ \ell\pi_1\rangle$ and $\langle\pi'_0\ell,\ \ell\pi'_1\rangle$ play symmetric rôles in (5) which reduces the number of cases to be considered.

$$\mathscr{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!](X) \triangleq \{\langle\pi_0\ell,\ \ell\rangle\} \qquad (A) \qquad (17.4)$$

$$\cup\,\{\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3\ell''\rangle \mid \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathscr{B}[\![\texttt{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathtt{tt} \qquad (B)$$

$$\wedge\ \langle\pi_0\ell\pi_2\ell \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!],\ \mathsf{at}[\![\texttt{S}_b]\!]\pi_3\ell''\rangle \in \mathscr{S}^*[\![\texttt{S}_b]\!]\}$$

$$\cup\,\{\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\neg(\texttt{B})} \mathsf{after}[\![\texttt{S}]\!]\rangle \mid \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathscr{B}[\![\texttt{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathtt{ff}\} \qquad (C)$$

The case (B) covers essentially 3 subcases depending of where is ℓ'' that is where the prefix observation $\mathsf{at}[\![\texttt{S}_b]\!]\pi_3\ell''$ of the execution of the body $\texttt{S}_b$ has terminated:

(Ba) within the loop body $\ell'' \in \mathsf{in}[\![\texttt{S}_b]\!]$;

(Bb) after the loop body $\ell'' = \mathsf{after}[\![\texttt{S}_b]\!] = \mathsf{at}[\![\texttt{S}]\!] = \ell$, because of the normal termination of the loop body, and thus at ℓ, just before the next iteration or the loop exit;

(Bc) after the loop $\ell'' = \mathsf{after}[\![\texttt{S}]\!]$ because of a **`break ;`** statement in the loop body $\texttt{S}_b$; □

— **(1)** If the dependency observation point ℓ' is at loop entry then $\ell' = \ell = \mathsf{at}[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]$. There are three subcases, depending on how $\ell' = \ell$ is reached $\ell\pi_1$ by (A), (B), or (C) of $\ell\pi_1$ and $\ell\pi'_1$ in (5).

— **(1–A)** In the first case $\ell\pi_1 = \ell$ so $\pi_1 = \ni$ in (A). We have $\mathsf{seqval}[\![\texttt{y}]\!]\ell'(\pi_0\ell, \ell) = \varrho(\pi_0\ell)\texttt{y}$ by (47.16). Whether $\ell\pi'_1$ is determined by (A), (B), or (C) we have in all cases that $\mathsf{seqval}[\![\texttt{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1) = \varrho(\pi'_0\ell) \mathbin{\hat{\cdot}} \sigma$ where σ is a possibly empty sequence of values of $\texttt{y}$ at $\ell' = \ell$. By def. (47.18) of diff, we dont't care about σ since $\mathsf{diff}(\mathsf{seqval}[\![\texttt{y}]\!]\ell'(\pi_0\ell, \ell\pi_1), \mathsf{seqval}[\![\texttt{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))$ is true if and only if $\varrho(\pi_0\ell)\texttt{y} \neq \varrho(\pi'_0\ell)$. In that case, we have

$$(5)$$

$$= \{\langle\texttt{x},\ \texttt{y}\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_1\rangle, \langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \mathscr{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]\ X\ .\ (\forall \texttt{z} \in \mathbb{V} \setminus \{\texttt{x}\}\ .\ \varrho(\pi_0\ell)\texttt{z} = \varrho(\pi'_0\ell)\texttt{z}) \wedge \varrho(\pi_0\ell)\texttt{y} \neq \varrho(\pi_0\ell)\texttt{y}\}$$

$$\subseteq \{\langle\texttt{x},\ \texttt{y}\rangle \mid \exists\pi_0\ell, \pi'_0\ell\ .\ (\forall \texttt{z} \in \mathbb{V} \setminus \{\texttt{x}\}\ .\ \varrho(\pi_0\ell)\texttt{z} = \varrho(\pi'_0\ell)\texttt{z}) \wedge (\varrho(\pi_0\ell)\texttt{y} \neq \varrho(\pi'_0\ell)\texttt{y})\} \qquad \text{(def. } \subseteq\text{)}$$

$$= \{\langle\texttt{x},\ \texttt{y}\rangle \mid \exists\rho, \nu\ .\ \rho(\texttt{y}) \neq \rho[\texttt{x} \leftarrow \nu](\texttt{y})\}$$

$$\text{(letting } \rho = \varrho(\pi_0\ell), \rho[\texttt{x} \leftarrow \nu] = \varrho(\pi'_0\ell) \text{ and Exercise 6.8)}$$

$$= \{\langle\texttt{x},\ \texttt{x}\rangle \mid \texttt{x} \in \mathbb{V}\} \qquad \text{(def. (19.10) of the environment assignment)}$$

$$= \mathbb{1}_{\mathbb{V}} \qquad \text{(def. identity relation on the set } \mathbb{V} \text{ of variables in Section 2.2.2)}$$

— **(1–Ba/Bc/C)** In this second case the trace $\ell\pi_1$ corresponds to one or more iterations of the loop followed by an execution of the loop body or a loop exit.

– In case (Ba), we have

$$\mathsf{seqval}[\![\texttt{y}]\!]\ell'(\pi_0\ell, \ell\pi_1)$$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'')$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$ $\wr$(B) with $\ell'' \in \mathsf{in}[\![\mathsf{S}_b]\!]$$\wr$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell)$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt}$

$\wr$def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ since $\langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$ with $\ell'' \in \mathsf{in}[\![\mathsf{S}_b]\!]$ so that ℓ cannot appear in the trace $\mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''$$\wr$

– In case (Bc), we have

$\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1)$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{break\text{-}to}[\![\mathsf{S}]\!])$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{break\text{-}to}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$
$\wr$(B) with $\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}]\!]$ and $\mathsf{break\text{-}to}[\![\mathsf{S}]\!] = \mathsf{after}[\![\mathsf{S}]\!]$$\wr$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell)$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt}$

$\wr$def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ since $\langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{break\text{-}to}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$ so that ℓ cannot appear in the trace $\mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{break\text{-}to}[\![\mathsf{S}]\!]$$\wr$

– In case (C), we have

$\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1)$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{ff}$ $\wr$(C)$\wr$

$= \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell)$ where $\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{ff}$ $\wr$def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$$\wr$

In all of these cases, the future observation $\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1)$ is the same so we can handle all cases (1–Ba/Bc/C) as follows:

(5)

$= \{\langle\mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_1\rangle, \langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \mathcal{F}^*[\![\mathtt{while}\ \ell\ (\mathtt{B})\ \mathtt{S}_b]\!]\, X\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))\}$

$\subseteq \{\langle\mathsf{x}, \mathsf{y}\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell\rangle \in X\ .\ \exists\langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \mathcal{F}^*[\![\mathtt{while}\ \ell\ (\mathtt{B})\ \mathtt{S}_b]\!]X\ .\ (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))\}$ (6)

$\wr$abstracting away the value of the conditions$\wr$

The possible choices for $\langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \mathcal{F}^*[\![\mathtt{while}\ \ell\ (\mathtt{B})\ \mathtt{S}_b]\!]\, X$ are given by (A), (B), and (C) and are considered below.

– **(1–Ba/Bc/C–A)** This case is the symmetric of **(1–A)**, and so has already bean considered.

– **(1–Ba/Bc/C–Ba/Bc/C)** In this case the above reasoning that we have done in **(1–Ba/Bc/C)** for the first trace $\ell\pi_1$ is also valid for the second trace $\ell\pi'_1$, and so we get

(6)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \,.\, \exists\langle \pi'_0\ell, \ell\pi'_1\rangle \in \mathcal{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]X \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))\}$

$\subseteq \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \,.\, \exists\langle \pi'_0\ell, \ell\pi'_2\ell\rangle \in X \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_2\ell))\}$

(abstracting away the value of the conditions)

$\subseteq \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in X \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0, \pi'_1))\}$

(letting $\pi_0 \leftarrow \pi_0\ell, \pi_1 \leftarrow \ell\pi_2\ell, \pi'_0 \leftarrow \pi'_0\ell, \pi'_1 \leftarrow \ell\pi'_2\ell$, and $\ell' = \ell$ in case **(1)**)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid X \in \{\Pi \in \wp(\mathbb{T}^+ \times \mathbb{T}^{+\infty}) \mid \exists\langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \Pi \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0, \pi'_1))\}\}$ (def. $\in$)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid X \in \mathcal{D}\ell\langle \mathsf{x}, \mathsf{y}\rangle\}$ (def. (47.19) of $\mathcal{D}\ell\langle \mathsf{x}', \mathsf{y}\rangle$)

$= \alpha^{\mathrm{d}}(\{X\})\ell$ (def. (47.25) of α^{d})

– **(1–Ba/Bc/C–Bb)** In this case we are in case **(1–Ba/Bc/C)** for the first prefix observation trace $\ell\pi_1$ corresponding to one or more iterations of the loop followed by an execution of the loop body or a loop exit and in case **Bb** for the second trace $\ell\pi'_1$ so that, after zero or more executions, the loop body has terminated normally at $\ell'' = \mathsf{after}[\![\mathsf{S}_b]\!] = \mathsf{at}[\![\mathsf{S}]\!] = \ell$ and the prefix observation stops there, just before the next iteration or the loop exit. We have

(6)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \,.\, \exists\langle \pi'_0\ell, \ell\pi'_1\rangle \in \mathcal{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]X \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell, \ell\pi'_1))\}$

(case **(1)** so $\ell' = \ell = \mathsf{at}[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]$)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \,.\, \exists\langle \pi'_0\ell, \ell\pi'_1\rangle \in \big\{\langle \pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \bigm| \langle \pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathsf{tt} \wedge \langle \pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \ell'' = \mathsf{after}[\![\mathsf{S}_b]\!] = \mathsf{at}[\![\mathsf{S}]\!] = \ell\big\} \,.\, (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell, \ell\pi'_1))\}$

(case **(Bb)** for $\ell\pi'_1$)

$= \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \,.\, \exists\langle \pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \,.\, \langle \pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathsf{tt} \wedge \langle \pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell))\}$

(def. $\in$ and $\ell'' = \ell$)

$= \{\langle x, y\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell\rangle \in X . \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle . \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathscr{B}[\![B]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathrm{tt} \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\forall z \in \mathbb{V}\setminus\{x\} . \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell))\}$
$\cup$
$\{\langle x, y\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell\rangle \in X . \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle . \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathscr{B}[\![B]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathrm{tt} \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\forall z \in \mathbb{V}\setminus\{x\} . \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell))\}$

$\wr$By def. (47.16) of $\mathrm{seqval}[\![y]\!]$ and (47.18) of diff, there is an instant of ℓ in $\ell\pi_2\ell$ and one in $\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell$ where the values of y while being the same before. So there are two possible cases whether this ℓ is in $\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]$ or in $\mathrm{at}[\![S_b]\!]\pi_3\ell$. So we have $\mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell)) = \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell)) \vee \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell))$$\wr$

$\subseteq \{\langle x, y\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell\rangle \in X . \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle . \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge (\forall z \in \mathbb{V}\setminus\{x\} . \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell))\}$
$\cup$
$\{\langle x, y\rangle \mid \exists\langle\pi_0\ell, \ell\pi''_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi'_3\ell\rangle . \langle\pi_0\ell, \ell\pi''_2\ell\rangle \in X \wedge \mathscr{B}[\![B]\!]\varrho(\pi_0\ell\pi''_2\ell) = \mathrm{tt} \wedge \langle\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle . \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathscr{B}[\![B]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathrm{tt} \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\forall z \in \mathbb{V}\setminus\{x\} . \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathrm{diff}(\mathrm{seqval}[\![y]\!]\ell(\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi''_3\ell), \mathrm{seqval}[\![y]\!]\ell(\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi_3\ell))\}$

$\wr$for the second term, we are in the case $\langle\pi_0\ell, \ell\pi_2\ell\rangle \in X$ with $\ell\pi_2\ell = \ell\pi_1$ corresponding to one or more iterations of the loop (so $\ell\pi_2\ell \neq \ell$ since otherwise we would be in case (**1-A**)), X is an iterate of $\mathscr{F}^*[\![$`while ℓ (B) S_b`$]\!]$, and so, by (17.4), can be written in the form $\ell\pi_2\ell = \ell\pi''_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!]\pi''_3\ell$ (where $\ell\pi''_2\ell$ may be reduced to ℓ for the first iteration) with $\ell\pi''_2\ell \in X$, $\mathscr{B}[\![B]\!]\varrho(\pi_0\ell\pi''_2\ell) = \mathrm{tt}$ and $\langle\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathrm{at}[\![S_b]\!], \mathrm{at}[\![S_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!]$. Moreover if the difference on y is in $\ell\pi''_2\ell$, the case is covered by the first term.$\wr$ (7)

$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell$
$\cup$

$\{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle\pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \,.\, \langle\pi_0\ell, \ell\pi''_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi''_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \,.\, \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge (\forall \mathsf{z} \in \mathcal{V}\setminus\{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell\pi''_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi''_3\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell))\}$

$\wr$ since $\varrho(\pi) = \varrho(\pi \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!])$ $\wr$

$= \alpha^{\mathrm{d}}(\{X\})\ell \cup \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\langle\pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \,.\, \langle\pi_0\ell, \ell\pi''_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi''_2\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \in \{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\} \wedge \exists\langle\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \,.\, \langle\pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\} \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}\} \,.\, \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell\pi''_2\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi''_3\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell\pi'_2\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell))\}$

$\wr$ def. $\in$, def. (47.18) of diff, and def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ with $\ell \neq \mathsf{at}[\![\mathsf{S}_b]\!]$ $\wr$

$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell \cup \{\langle \mathsf{x}, \mathsf{y}\rangle \mid \exists\pi_0\ell_0\pi_1\ell'\pi_2\ell\pi_3, \pi'_0\ell_0\pi'_1\ell'\pi'_2\ell\pi'_3 \,.\, \langle\pi_0\ell_0, \ell_0\pi_1\ell'\rangle \in X \wedge \langle\pi_0\ell_0\pi_1\ell', \ell'\pi_2\ell\pi_3\rangle \in \{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\} \wedge \langle\pi'_0\ell_0, \ell_0\pi'_1\ell'\rangle \in X \wedge \langle\pi'_0\ell_0\pi'_1\ell', \ell'\pi'_2\ell\pi'_3\rangle \in \{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\} \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}\} \,.\, \varrho(\pi_0\ell_0)\mathsf{z} = \varrho(\pi'_0\ell_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell_0\pi_1\ell'\pi_2\ell, \ell\pi_3), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell_0\pi'_1\ell'\pi'_2\ell, \ell\pi'_3))\}$

$\wr$ by letting $\pi_0\ell_0 \leftarrow \pi_0\ell$, $\ell_0\pi_1\ell' \leftarrow \ell\pi''_2\ell$, $\ell'\pi_2\ell \leftarrow \ell$, $\ell\pi_3 \leftarrow \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi''_3\ell$, and similarly for the second trace $\wr$

$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ell \,⨾\, \alpha^{\mathrm{d}}(\{\{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\}\})\ell)$

$\wr$ Lemma 47.59 with $\mathcal{S} \leftarrow X$ and $\mathcal{S}' \leftarrow \{\langle\pi_0\ell, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \mid \langle\pi_0\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi\rangle \in \{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\}$ $\wr$

$= \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ell \,⨾\, \alpha^{\mathrm{d}}(\{\{\langle\pi, \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\}\})\ell)$

$\wr$ def. (47.25) of α^{d}, (47.18) of diff, and (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ with $\ell \neq \ell$ $\wr$

$= \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ell \,⨾\, (\alpha^{\mathrm{d}}(\{\mathcal{S}^*[\![\mathsf{S}_b]\!]\})\ell \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})))$ $\wr$ Lemma 47.62 $\wr$

$= \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ell \,⨾\, (\alpha^{\mathrm{d}}(\{\mathcal{S}^{+\infty}[\![\mathsf{S}_b]\!]\})\ell) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B}))$ $\wr$ Lemma 47.23 $\wr$

$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ell \,⨾\, (\widehat{\overline{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\,\ell \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})))$ $\wr$ ind. hyp. (47.32), $⨾$ and $\rceil$ are $\subseteq$-increasing $\wr$

— **(1–Bb)** In this third and last case for (1), we have $\ell\pi_1 = \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell$ so the prefix observation ends after the normal termination of the loop body at $\mathsf{after}[\![\mathsf{S}_b]\!] = \mathsf{at}[\![\mathsf{S}]\!] = \ell$ (just before the next iteration or the loop exit).

The possible choices for $\langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \mathcal{F}^*[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathtt{S}_b]\!]\ X$ are given by **(A)**, **(B)**, and **(C)** and are considered below.

– **(1–Bb–A)** This case is the symmetric of **(1–A)**, and so has already been considered.

– **(1–Bb–Ba/Bc/C)** This case is the symmetric of **(1–Ba/Bc/C–Bb)**, and so has already been considered.

– **(1–Bb–Bb)** This is the case when the prefix observation traces $\langle\pi_0\ell,\ \ell\pi_1\rangle$ and $\langle\pi'_0\ell,\ \ell\pi'_1\rangle$ in (5) both end after the normal termination of the loop body at $\mathsf{after}[\![\mathsf{S}_b]\!] = \mathsf{at}[\![\mathsf{S}]\!] = \ell$ and so belong to $\{\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \mid \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\}$. In that case, we have

(5)

$$= \{\langle\mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_1\rangle, \langle\pi'_0\ell,\ \ell\pi'_1\rangle \in \{\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \mid \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\}\ .\ (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))\}$$

$\wr$case **(1–Bb–Bb)**$\wr$

$$= \{\langle\mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle\ .\ \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle\ .\ \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathsf{tt} \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\}\ .\ \varrho(\pi'_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell))\}$$

$\wr$def. $\in\wr$

$$\subseteq \{\langle\mathsf{x}, \mathsf{y}\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle\ .\ \langle\pi_0\ell, \ell\pi_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle\ .\ \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\}\ .\ \varrho(\pi'_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell))\}$$

$\wr$def. $\in\wr$

$$= \{\langle\mathsf{x}, \mathsf{y}\rangle \mid \exists\langle\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle\ .\ \langle\pi_0\ell, \ell\pi_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle\ .\ \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi)\} \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\}\ .\ \varrho(\pi'_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell))\}$$

$\wr$by def. (47.18) of diff, and def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ since in case **(1)**, $\ell' = \ell$ does not appear in $\xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3$ and the value of y is the same at ℓ after $\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell$ and at ℓ after $\pi_0\ell\pi_2\ell$. Same for $\pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell$. $\wr$

$\subseteq \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X, \langle \pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi'_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}[\![\mathsf{y}]\!]\ell(\pi'_0\ell, \ell\pi'_2\ell))\}$ ⦃def. $\subseteq$⦄

$\subseteq \alpha^{\mathsf{d}}(\{X\})\ell$ ⦃def. (47.25) of α^{d} ⦄

— Summing up for case (1) we get (5) $\subseteq \mathbb{1}_{\mathbb{V}} \cup \alpha^{\mathsf{d}}(\{X\})\ell \cup (\alpha^{\mathsf{d}}(\{X\})\ell \,\mathring{9}\, \widehat{\overleftarrow{\mathcal{S}}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell)\ \rceil\ \mathsf{nondet}(\mathsf{B}, \mathsf{B})$ which yields (47.63.a) of the form

$$⦇\ \ell' = \ell\ ?\ \mathbb{1}_{\mathbb{V}} \cup X(\ell) \cup \big(X(\ell) \,\mathring{9}\, ((\widehat{\overleftarrow{\mathcal{S}}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell)\ \rceil\ \mathsf{nondet}(\mathsf{B}, \mathsf{B}))\big) \,\mathring{\imath}\, \varnothing\ ⦈\,.$$

However, the term $X(\ell)$ does not appear in (47.63.a) since it can be simplified thanks to Exercise 15.8.

—— **(2)** Else, if the dependency observation point ℓ' on prefix traces is in the loop body S_b after zero or more loop iterations. So the two traces $\ell\pi_1$ and $\ell\pi'_1$ in (5) cannot be generated by (17.4.**A**). The case $\ell' = \ell = \mathsf{after}[\![\mathsf{S}_b]\!] = \mathsf{at}[\![\mathsf{S}]\!]$ has already been considered in case **(1)** (for subcases involving **(B)** and **(C)**). By def. (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]$ the case $\ell' = \mathsf{at}[\![\mathsf{S}_b]\!]$ is equivalent to $\ell' = \mathsf{at}[\![\mathsf{S}]\!]$ already considered in **(1)** since the evaluation of boolean expressions has no side effect so the value of variables y at $\mathsf{at}[\![\mathsf{S}_b]\!]$ and $\mathsf{at}[\![\mathsf{S}]\!]$ are the same. Similarly, the value of variables y before a **`break ;`** statement at labels in $\mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]$ that can escape the loop body S_b is the same as the value at $\mathsf{break\text{-}to}[\![\mathsf{S}_b]\!] = \mathsf{after}[\![\mathsf{S}]\!]$ and will be handled with case **(3)**.

It follows that in this case **(2)** we only have to consider the case $\ell' \in \mathsf{in}[\![\mathsf{S}_b]\!] \setminus (\{\mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{after}[\![\mathsf{S}_b]\!]\} \cup \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!])$ and the two traces $\ell\pi_1$ and $\ell\pi'_1$ in(5) are generated by **(B)** or **(C)**. There are three cases to consider.

— **(2–B–B)** The dependency observation point ℓ' on the two prefix observation traces $\ell\pi_1$ and $\ell\pi'_1$ in (5) is in the loop body S_b after zero or more loop iterations and the observation along these two traces stops in the loop body.

(5)

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0\ell,\ \ell\pi_1\rangle, \langle \pi'_0\ell,\ \ell\pi'_1\rangle \in \{\langle \pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \mid \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\}\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_1))\}$ ⦃case **2–B–B**⦄

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle\ .\ \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \exists\langle \pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell''\rangle\ .\ \langle \pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathsf{tt} \wedge \langle \pi'_0\ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi'_3\ell''))\}$ ⦃def. $\in$⦄

$$\subseteq \{\langle x,\ y\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \,.\, \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \,.\, \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge (\forall z \in \mathbb{V}\setminus\{x\} \,.\, \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket y\rrbracket\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''), \mathsf{seqval}\llbracket y\rrbracket\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''))\}$$

(def. $\in$)

$$\subseteq \{\langle x,\ y\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \,.\, \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \,.\, (\forall z \in \mathbb{V}\setminus\{x\} \,.\, \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket y\rrbracket\ell'(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}\llbracket y\rrbracket\ell'(\pi'_0\ell, \ell\pi'_2\ell))\}$$
$$\cup$$
$$\{\langle x,\ y\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \,.\, \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \,.\, \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge (\forall z \in \mathbb{V}\setminus\{x\} \,.\, \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket y\rrbracket\ell'(\pi_0\ell, \ell\pi_2\ell), \mathsf{seqval}\llbracket y\rrbracket\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''))\}$$
$$\cup$$
$$\{\langle x,\ y\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \,.\, \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \,.\, \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge (\forall z \in \mathbb{V}\setminus\{x\} \,.\, \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket y\rrbracket\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''), \mathsf{seqval}\llbracket y\rrbracket\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''))\}$$

(by def. (47.18) of diff and (47.16) of $\mathsf{seqval}\llbracket y\rrbracket\ell'$, there is an instance of ℓ' in both $\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''$ and $\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''$ before which the values of y at ℓ' and at which they differ. There are four cases (indeed 3 by symmetry), depending on whether the occurrence of ℓ'' is before or after the transition $\xrightarrow{B}$.)

$$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell' \cup$$
$$\{\langle x,\ y\rangle \mid \exists\langle\pi_0\ell,\ \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \,.\, \langle\pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \langle\pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge \exists\langle\pi'_0\ell,\ \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \,.\, \langle\pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket,\ \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''\rangle \in \{\langle\pi,\ \pi'\rangle \in \mathcal{S}^*\llbracket S_b\rrbracket \mid \mathcal{B}\llbracket B\rrbracket\varrho(\pi)\} \wedge (\forall z \in \mathbb{V}\setminus\{x\} \,.\, \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}\llbracket y\rrbracket\ell'(\pi_0\ell, \ell\pi_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi_3\ell''), \mathsf{seqval}\llbracket y\rrbracket\ell'(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}\llbracket S_b\rrbracket\pi'_3\ell''))\}$$

(For the second term where ℓ' occurs in $\ell\pi_2\ell$, the trace $\ell\pi_2\ell$ must have reached the loop body, and so, by the reasoning of (7), this second term is an instance of the third one.)

$$\subseteq \alpha^{\mathrm{d}}(\{X\})\ell' \cup \big(\alpha^{\mathrm{d}}(\{X\})\ell \mathbin{\fatsemi} ((\widehat{\mathcal{S}}^{\exists}_{\mathrm{diff}}\llbracket S_b\rrbracket\ \ell') \rceil \mathsf{nondet}(B, B))\big)$$

(by a reasoning similar to the one we did in case **(1–Ba/Bc/C–Bb)** from (7) on.)

— **(2–B–C/2–C–B)** The dependency observation point ℓ' on the two prefix observation traces $\ell\pi_1$ and $\ell\pi'_1$ in (5) is in the loop body S_b after zero or more loop iterations and the observation along these two traces stops in the loop body for one and at the loop exit for the other.

$$
\begin{aligned}
&(5)\\
=\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0\ell,\ \ell\pi_1\rangle \in \{\langle \pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \mid \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \\
& \mathsf{tt} \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\}\ .\ \exists\langle \pi'_0\ell,\ \ell\pi'_1\rangle \in \{\langle \pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\neg(\mathsf{B})} \\
& \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{ff}\}\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \\
& \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell,\ell\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell,\ell\pi'_1))\} \qquad \text{(case 2–B–C)}\\
\subseteq\ & \alpha^{\mathrm{d}}(\{X\})\ell' \cup \big(\alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨟} ((\widehat{\overset{\frown}{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell')\ \rceil\ \mathsf{nondet}(\mathsf{B},\mathsf{B}))\big)
\end{aligned}
$$

(This case is handled exactly as the previous one since the program point ℓ' where the change of value of variable y is observed is within the loop body so the loop must be entered in part $\ell\pi_2\ell$ of $\ell\pi_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]$ and the loop exit $\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]$ does not affect the variable y.)

— **(2–C–C)** The dependency observation point ℓ' on the two prefix observation traces $\ell\pi_1$ and $\ell\pi'_1$ in (5) is in the loop body S_b after zero or more loop iterations and the observation along these two traces stops at the loop exit.

$$
\begin{aligned}
&(5)\\
=\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0\ell,\ \ell\pi_1\rangle, \langle \pi'_0\ell,\ \ell\pi'_1\rangle \in \{\langle \pi_0\ell,\ \ell\pi_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in \\
& X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{ff}\}\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \\
& \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi_0\ell,\ell\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\ell'(\pi'_0\ell,\ell\pi'_1))\} \qquad \text{(case 2–C–C)}\\
\subseteq\ & \alpha^{\mathrm{d}}(\{X\})\ell' \cup \big(\alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨟} ((\widehat{\overset{\frown}{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell')\ \rceil\ \mathsf{nondet}(\mathsf{B},\mathsf{B}))\big)
\end{aligned}
$$

(This case is handled exactly as the two previous ones since, again, the program point ℓ' where the change of value of variable y is observed is within the loop body so the loop must be entered in part $\ell\pi_2\ell$ of $\ell\pi_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]$ and the loop exit $\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]$ does not affect the variable y. Similarly for the second trace $\ell\pi'_1$.)

— Summing up for case (2), we get $(5) \subseteq \alpha^{\mathrm{d}}(\{X\})\ell' \cup \big(\alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨟} ((\widehat{\overset{\frown}{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell')\ \rceil\ \mathsf{nondet}(\mathsf{B},\mathsf{B}))\big)$ which yields (47.63.b) of the form

$$
(\!|\ \ell' \in \mathsf{in}[\![\mathsf{S}_b]\!]\ ¿\ \big(X(\ell) \mathbin{⨟} ((\widehat{\overset{\frown}{\mathcal{S}}}{}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell')\ \rceil\ \mathsf{nondet}(\mathsf{B},\mathsf{B}))\big) \mathbin{:} \varnothing\ |\!).
$$

where the term $X(\ell')$ does not appear in (47.63.b) by the simplification following from Exercise 15.8.

— **(3)** Otherwise, the dependency observation point $\ell' = \mathsf{after}[\![\mathsf{S}]\!]$ on prefix traces is after the loop statement $\mathsf{S} = \mathtt{while}\ \ell\ \mathtt{(B)}\ \mathsf{S}_b$.

(5)

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_1\rangle, \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_1\rangle \in \mathcal{F}^*[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathsf{S}_b]\!]\ X\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^{\ell})\mathsf{z} = \varrho(\pi'_0{}^{\ell})\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_1))\}$

$\wr\ell' = \mathsf{after}[\![\mathsf{S}]\!]\int$

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_1\rangle, \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_1\rangle \in \{\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{ff}\} \cup \{\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\}\ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^{\ell})\mathsf{z} = \varrho(\pi'_0{}^{\ell})\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_1), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_1))\}$ (8)

$\wr$The only cases in (17.4) where $\ell' = \mathsf{after}[\![\mathsf{S}]\!]$ is reachable is either via **(C)** for normal termination after zero or more iterations or via **(B)** through a **`break ;`** in the loop body S_b during the first or later iteration$\int$

There are now three subcases, depending on whether the observation prefix traces ${}^{\ell}\pi_1$ and ${}^{\ell}\pi'_1$ are both from a normal exit, a both from a break, or one is from a break and the other from a normal exit.

— **(3–C–C)** This is the case when the observation prefix traces ${}^{\ell}\pi_1$ and ${}^{\ell}\pi'_1$ are both from a normal exit.

(8)

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle\ .\ \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{ff} \wedge \exists\langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle\ .\ \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell}) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^{\ell})\mathsf{z} = \varrho(\pi'_0{}^{\ell})\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]))\}$ $\wr$def. $\in$ and $\ell' = \mathsf{after}[\![\mathsf{S}]\!]\int$

$\subseteq \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle, \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{ff} \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell}) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^{\ell})\mathsf{z} = \varrho(\pi'_0{}^{\ell})\mathsf{z}) \wedge \varrho(\pi_0{}^{\ell}\pi_2{}^{\ell})\mathsf{y} \neq \varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell})\mathsf{y}\}$ (9)

$\wr X$ is an iterate of $\mathcal{F}^*[\![\mathtt{while}\ \ell\ \mathtt{(B)}\ \mathsf{S}_b]\!]$ so ${}^{\ell}\pi_2{}^{\ell}$ and ${}^{\ell}\pi'_2{}^{\ell}$ are iterates of the loop body. By definition of the labelling in Section 4.2, $\mathsf{after}[\![\mathsf{S}]\!]$ appears neither in ${}^{\ell}\pi_2{}^{\ell}$ nor in ${}^{\ell}\pi'_2{}^{\ell}$. It follows by def. (47.18) of diff and (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]\mathsf{after}[\![\mathsf{S}]\!]$ that $\mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])) = \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0{}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!])) = \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\ell)(\pi_0{}^{\ell}\pi_2{}^{\ell}, \ell), \mathsf{seqval}[\![\mathsf{y}]\!](\ell)(\pi'_0{}^{\ell}\pi'_2{}^{\ell}, \ell)) = \varrho(\pi_0{}^{\ell}\pi_2{}^{\ell})\mathsf{y} \neq \varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell})\mathsf{y}\int$

From there on, the development is very similar to the cases **(2.a)**, **(2.b)**, and **(2.c–d)** of the conditional with execution traces that may go through the true branch (here entering the loop) or the false branch (here not entering the iteration). There are four subcases (three by symmetry).

– **(3–C–C.a)** If none of the executions $\pi_0{}^\ell\pi_2{}^\ell$ and $\pi'_0{}^\ell\pi'_2{}^\ell$ enter the loop body since in both cases the condition B is false, we have $\ell\pi_2{}^\ell = \ell$ and $\ell\pi'_2{}^\ell = \ell$.

$$\begin{aligned}
&(9)\\
\subseteq\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0{}^\ell,\ \ell\rangle, \langle\pi'_0{}^\ell,\ \ell\rangle \in X \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell) = \mathrm{ff} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell) = \mathrm{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\\
&\varrho(\pi_0{}^\ell)\mathsf{z} = \varrho(\pi'_0{}^\ell)\mathsf{z}) \wedge \varrho(\pi_0{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell)\mathsf{y}\} \mathbin{]} \mathsf{nondet}(\neg\mathsf{B}, \neg\mathsf{B}) \qquad \text{(case (3–C–C.a))}\\
\subseteq\ & \mathbb{1}_{\mathbb{V}} \mathbin{]} \mathsf{nondet}(\neg\mathsf{B}, \neg\mathsf{B})
\end{aligned}$$

(since if $\mathsf{x} \notin \mathsf{nondet}(\neg\mathsf{B}, \neg\mathsf{B})$ then $\mathsf{x} \in \mathsf{det}(\neg\mathsf{B}, \neg\mathsf{B})$ so $\mathscr{B}[\![\neg\mathsf{B}]\!]\varrho(\pi_0{}^\ell)$ and $\mathscr{B}[\![\neg\mathsf{B}]\!]\varrho(\pi'_0{}^\ell)$ would imply $\varrho(\pi_0{}^\ell)\mathsf{x} = \varrho(\pi'_0{}^\ell)\mathsf{x}$. Therefore $\varrho(\pi_0{}^\ell) = \varrho(\pi'_0{}^\ell)$ in contradiction with $\varrho(\pi_0{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell)\mathsf{y}$.)

– **(3–C–C.b)** Else, if both executions $\pi_0{}^\ell\pi_2{}^\ell$ and $\pi'_0{}^\ell\pi'_2{}^\ell$ enter the loop body since in both cases the condition B is true, we have $\ell\pi_2{}^\ell \neq \ell$ and $\ell\pi'_2{}^\ell \neq \ell$

$$\begin{aligned}
&(9)\\
=\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0{}^\ell,\ \ell\pi_2{}^\ell\rangle, \langle\pi'_0{}^\ell,\ \ell\pi'_2{}^\ell\rangle \in X \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell\pi_2{}^\ell) = \mathrm{ff} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell\pi'_2{}^\ell) = \mathrm{ff} \wedge (\forall \mathsf{z} \in\\
&\mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^\ell)\mathsf{z} = \varrho(\pi'_0{}^\ell)\mathsf{z}) \wedge \varrho(\pi_0{}^\ell\pi_2{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell\pi'_2{}^\ell)\mathsf{y}\} \mathbin{]} \mathsf{nondet}(\mathsf{B}, \mathsf{B})
\end{aligned}$$

(case (3–C–C.b) and X belongs to the iterates of $\mathscr{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \mathsf{S}_b]\!]$ so this is possible only when $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell) = \mathrm{tt}$ and $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell) = \mathrm{tt}$ and def. (47.48) of nondet)

$$\begin{aligned}
\subseteq\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0{}^\ell,\ \ell\pi_2{}^\ell\rangle \in X\ .\ \exists\langle\pi'_0{}^\ell,\ \ell\pi'_2{}^\ell \xrightarrow{\ \mathsf{B}\ } \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^\ell\rangle\ .\ \langle\pi'_0{}^\ell,\ \ell\pi'_2{}^\ell\rangle \in X \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\\
&\varrho(\pi_0{}^\ell)\mathsf{z} = \varrho(\pi'_0{}^\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0{}^\ell, \ell\pi_2{}^\ell), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0{}^\ell, \ell\pi'_2{}^\ell))\}
\end{aligned}$$

(since $\varrho(\pi_0{}^\ell\pi_2{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell\pi'_2{}^\ell)\mathsf{y}$ implies $\mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi_0{}^\ell, \ell\pi_2{}^\ell), \mathsf{seqval}[\![\mathsf{y}]\!]^\ell(\pi'_0{}^\ell, \ell\pi'_2{}^\ell))$)

$$\subseteq\ \alpha^{\mathrm{d}}(\{X\})^\ell \qquad \text{(def. (47.25) of } \alpha^{\mathrm{d}}\text{)}$$

– **(3–C–C.c)** Otherwise, one execution enters the loop body (say $\pi_0{}^\ell\pi_2{}^\ell$) and the other does not (say $\pi'_0{}^\ell\pi'_2{}^\ell$), we have (the other case is symmetric) $\ell\pi_2{}^\ell \neq \ell$ and $\ell\pi'_2{}^\ell = \ell$. The calculation is similar to (2.c–d) for the simple conditional.

$$\begin{aligned}
&(9)\\
=\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0{}^\ell,\ \ell\pi_2{}^\ell\rangle, \langle\pi'_0{}^\ell,\ \ell\rangle \in X \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell) = \mathrm{tt} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell\pi_2{}^\ell) = \mathrm{ff} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell) =\\
&\mathrm{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^\ell)\mathsf{z} = \varrho(\pi'_0{}^\ell)\mathsf{z}) \wedge \varrho(\pi_0{}^\ell\pi_2{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell)\mathsf{y}\}
\end{aligned}$$

(case (3–C–C.c) and X is included in the iterates of $\mathscr{F}^*[\![\texttt{while}\ \ell\ \texttt{(B)}\ \mathsf{S}_b]\!]$ so this is possible only when $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell) = \mathrm{tt}$, $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell\pi_2{}^\ell) = \mathrm{ff}$, and $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell) = \mathrm{ff}$)

$$\begin{aligned}
=\ & \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists\langle\pi_0{}^\ell,\ \ell\pi_2{}^\ell\rangle, \langle\pi'_0{}^\ell,\ \ell\rangle \in X \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell) = \mathrm{tt} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi_0{}^\ell\pi_2{}^\ell) = \mathrm{ff} \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'_0{}^\ell) =\\
&\mathrm{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0{}^\ell)\mathsf{z} = \varrho(\pi'_0{}^\ell)\mathsf{z}) \wedge \varrho(\pi_0{}^\ell\pi_2{}^\ell)\mathsf{y} \neq \varrho(\pi'_0{}^\ell)\mathsf{y}\} \mathbin{]} \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})
\end{aligned}$$

$\wr$since, by def. (47.48) of nondet, if $\mathtt{x} \notin \mathsf{nondet}(\mathtt{B}, \neg\mathtt{B})$ then $\mathtt{x} \in \mathsf{det}(\mathtt{B}, \neg\mathtt{B})$ so by (47.48), $\mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell)$ and $\mathscr{B}[\![\neg\mathtt{B}]\!]\varrho(\pi'_0\ell)$ would imply $\varrho(\pi_0\ell)\mathtt{x} = \varrho(\pi'_0\ell)\mathtt{x}$ and therefore $\varrho(\pi_0\ell) = \varrho(\pi'_0\ell)$. X being included in the iterates of $\mathscr{F}^*[\![\mathtt{while}\ \ell\ (\mathtt{B})\ \mathtt{S}_b]\!]$ and, by Exercises 17.13 and 17.21, the language being deterministic, this would imply that $\ell\pi_2\ell = \ell$, in contradiction with $\mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell) = \mathtt{tt}$ and $\mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathtt{ff}$$\wr$

$= \{\langle \mathtt{x}, \mathtt{y}\rangle \mid \exists\langle \pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \,.\, \langle \pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in X \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell) = \mathtt{tt} \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell) = \mathtt{ff} \wedge \langle \pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!], \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![\mathtt{S}_b]\!] \wedge \exists\langle \pi'_0\ell, \ell\rangle \in X \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\ell) = \mathtt{ff} \wedge (\forall \mathtt{z} \in \mathbb{V}\setminus\{\mathtt{x}\} \,.\, \varrho(\pi_0\ell)\mathtt{z} = \varrho(\pi'_0\ell)\mathtt{z}) \wedge \varrho(\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell)\mathtt{y} \neq \varrho(\pi'_0\ell)\mathtt{y}\} \rceil \mathsf{nondet}(\mathtt{B}, \neg\mathtt{B})$

$\wr$by the argument (7) that if $\langle \pi_0\ell, \ell\pi_2\ell\rangle \in X$ corresponds to one or more iterations of the loop then it can be written in the form $\ell\pi_2\ell = \ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell$ (where $\ell\pi''_2\ell$ may be reduced to ℓ for the first iteration) with $\ell\pi''_2\ell \in X$, $\mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi''_2\ell) = \mathtt{tt}$ and $\langle \pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!], \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![\mathtt{S}_b]\!]$$\wr$

$\subseteq \{\langle \mathtt{x}, \mathtt{y}\rangle \mid \exists\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell, \pi'_0\ell \,.\, \langle \pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in X \wedge \langle \pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!], \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![\mathtt{S}_b]\!] \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell) = \mathtt{ff} \wedge \langle \pi'_0\ell, \ell\rangle \in X \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi''_2\ell) = \mathtt{tt} \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\ell) = \mathtt{ff} \wedge (\forall \mathtt{z} \in \mathbb{V}\setminus\{\mathtt{x}\} \,.\, \varrho(\pi_0\ell)\mathtt{z} = \varrho(\pi'_0\ell)\mathtt{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathtt{y}]\!]\mathsf{after}[\![\mathtt{S}]\!](\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!], \mathsf{after}[\![\mathtt{S}]\!]), \mathsf{seqval}[\![\mathtt{y}]\!]\mathsf{after}[\![\mathtt{S}]\!](\pi'_0\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!], \mathsf{after}[\![\mathtt{S}]\!]))\} \rceil \mathsf{nondet}(\mathtt{B}, \neg\mathtt{B})$

$\wr$def. (6.6) of ϱ, def. (47.16) of $\mathsf{seqval}[\![\mathtt{y}]\!]$ and program labelling so that $\mathsf{after}[\![\mathtt{S}]\!]$ does not appear in the trace (in particular $\ell \neq \mathsf{after}[\![\mathtt{S}]\!]$), and def. (47.18) of diff$\wr$

$= \{\langle \mathtt{x}, \mathtt{y}\rangle \mid \exists\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!], \pi'_0\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!] \,.\, \langle \pi_0\ell, \ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in X \wedge \langle \pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell, \ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!]\rangle \in \mathcal{S}' \wedge \langle \pi'_0\ell, \ell\rangle \in X \wedge \langle \pi'_0\ell, \ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!]\rangle \in \mathcal{S}' \wedge (\forall \mathtt{z} \in \mathbb{V}\setminus\{\mathtt{x}\} \,.\, \varrho(\pi_0\ell)\mathtt{z} = \varrho(\pi'_0\ell)\mathtt{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathtt{y}]\!]\mathsf{after}[\![\mathtt{S}]\!](\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!], \mathsf{after}[\![\mathtt{S}]\!]), \mathsf{seqval}[\![\mathtt{y}]\!]\mathsf{after}[\![\mathtt{S}]\!](\pi'_0\ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!], \mathsf{after}[\![\mathtt{S}]\!]))\} \rceil \mathsf{nondet}(\mathtt{B}, \neg\mathtt{B})$

$\wr$where $\mathcal{S}' = \{\langle \pi'_1\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell, \ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!]\rangle \mid \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_1\ell) = \mathtt{tt} \wedge \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell) = \mathtt{ff} \wedge \langle \pi'_1\ell \xrightarrow{\mathtt{B}} \mathsf{at}[\![\mathtt{S}_b]\!], \mathsf{at}[\![\mathtt{S}_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![\mathtt{S}_b]\!]\} \cup \{\langle \pi'_0\ell, \ell \xrightarrow{\neg\mathtt{B}} \mathsf{after}[\![\mathtt{S}]\!]\rangle \mid \mathscr{B}[\![\mathtt{B}]\!]\varrho(\pi'_0\ell) = \mathtt{ff}\}$$\wr$

$\subseteq (\alpha^{\mathrm{d}}(\{X\})\ \ell \mathbin{⨾} \alpha^{\mathrm{d}}(\{\mathcal{S}'\})\ \mathsf{after}[\![\mathtt{S}]\!]) \rceil \mathsf{nondet}(\mathtt{B}, \neg\mathtt{B})$

$\wr$Lemma 47.59 with $\ell_0 \leftarrow \ell$, $\ell' \leftarrow \ell$, and $\ell \leftarrow \mathsf{after}[\![\mathtt{S}]\!]$$\wr$

We have to calculate the second term

$$\alpha^{\mathrm{d}}(\{\mathcal{S}'\})\ \mathsf{after}[\![\mathtt{S}]\!] \tag{10}$$

$= \{\langle x, y\rangle \mid \mathcal{S}' \in \mathcal{D}(\mathsf{after}[\![S]\!])\langle x, y\rangle\}$ ⦃def. (47.25) of α^{d}⦄

$= \{\langle x, y\rangle \mid \exists\langle\pi_0, \pi_1\rangle, \langle\pi'_0, \pi'_1\rangle \in \mathcal{S}' \,.\, (\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi_0)z = \varrho(\pi'_0)z) \wedge \mathsf{diff}(\mathsf{seqval}[\![y]\!]\mathsf{after}[\![S]\!](\pi_0, \pi_1), \mathsf{seqval}[\![y]\!]\mathsf{after}[\![S]\!](\pi'_0, \pi'_1))\}$ ⦃def. (47.19) of $\mathcal{D}^{\ell}\langle x, y\rangle$⦄

$= \{\langle x, y\rangle \mid \exists\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell \xrightarrow{\neg B} \mathsf{after}[\![S]\!] \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_2\ell) = \mathsf{tt} \wedge \langle\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!]\}, \exists\pi'_0\ell \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_0\ell) = \mathsf{ff}\} \,.\, (\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)z = \varrho(\pi'_0)z) \wedge \mathsf{diff}(\mathsf{seqval}[\![y]\!]\mathsf{after}[\![S]\!](\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell, \ell \xrightarrow{\neg B} \mathsf{after}[\![S]\!]), \mathsf{seqval}[\![y]\!]\mathsf{after}[\![S]\!](\pi'_0\ell, \ell \xrightarrow{\neg B} \mathsf{after}[\![S]\!]))\}$

⦃def. $\mathcal{S}'$ and the other two combinations have already been considered in (**3–C–C.a**) and (**3–C–C.b**)⦄

$= \{\langle x, y\rangle \mid \exists\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell \xrightarrow{\neg B} \mathsf{after}[\![S]\!] \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_2\ell) = \mathsf{tt} \wedge \langle\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge \mathcal{B}[\![B]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell) = \mathsf{ff} \wedge \exists\pi'_0\ell \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_0\ell) = \mathsf{ff} \wedge (\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)z = \varrho(\pi'_0\ell)z) \wedge \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)y \neq \varrho(\pi'_0\ell)y)\}$

⦃def. (6.6) of ϱ, def. (47.16) of $\mathsf{seqval}[\![y]\!]$ and program labelling so that $\mathsf{after}[\![S]\!]$ does not appear in the trace (in particular $\ell \neq \mathsf{after}[\![S]\!]$), and def. (47.18) of diff⦄

$= \{\langle x, y\rangle \mid \exists\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell \xrightarrow{\neg B} \mathsf{after}[\![S]\!] \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_2\ell) = \mathsf{tt} \wedge \langle\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi'_3\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge \mathcal{B}[\![B]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell) = \mathsf{ff} \wedge \exists\pi'_0\ell \,.\, \mathcal{B}[\![B]\!]\varrho(\pi'_0\ell) = \mathsf{ff} \wedge (\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)z = \varrho(\pi'_0\ell)z) \wedge \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)y \neq \varrho(\pi'_0\ell)y)\} \rceil\, \mathsf{nondet}(\neg B, \neg B)$

⦃since if $x \notin \mathsf{nondet}(\neg B, \neg B)$ then $x \in \mathsf{det}(\neg B, \neg B)$ so by (47.48), $\mathcal{B}[\![\neg B]\!]\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)$, and $\mathcal{B}[\![\neg B]\!]\varrho(\pi'_0\ell)$, we would have $\varrho(\pi_0\ell\pi''_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell) = \varrho(\pi'_0\ell)$, which, with $\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)z = \varrho(\pi'_0\ell)z$, would imply $\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell) = \varrho(\pi'_0\ell)$, in contradiction with $\varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell)y \neq \varrho(\pi'_0\ell)y)$⦄

$\subseteq \{\langle x, y\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \,.\, (\forall z \in \mathcal{V}\setminus\{x\} \,.\, \varrho(\pi_0\mathsf{at}[\![S_b]\!])z = \varrho(\pi'_0\mathsf{at}[\![S_b]\!])z) \wedge \langle\pi_0\mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_1\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\varrho(\pi_0\mathsf{at}[\![S_b]\!]\pi_1\ell)y \neq \varrho(\pi'_0\mathsf{at}[\![S_b]\!])y\} \rceil\, \mathsf{nondet}(\neg B, \neg B)$

⦃letting $\pi_0\mathsf{at}[\![S_b]\!] \leftarrow \pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]$ with $\varrho(\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]) = \varrho(\pi'_2\ell)$, $\pi_0\mathsf{at}[\![S_b]\!] \leftarrow \pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell$, and $\pi_1\ell \leftarrow \pi'_3\ell$ ⦄

$= (\{\langle x, x\rangle \mid \exists\pi_0, \pi_1, \pi'_0 \,.\, (\forall z \in \mathcal{V}\setminus\{x\} \,.\, \varrho(\pi_0\mathsf{at}[\![S_b]\!])z = \varrho(\pi'_0\mathsf{at}[\![S_b]\!])z) \wedge \langle\pi_0\mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_1\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\varrho(\pi_0\mathsf{at}[\![S_b]\!]\pi_1\ell)x \neq \varrho(\pi'_0\mathsf{at}[\![S_b]\!])x\}$
$\cup \{\langle x, y\rangle \mid x \neq y \wedge \exists\pi_0, \pi_1, \pi'_0 \,.\, (\forall z \in \mathcal{V} \setminus \{x\} \,.\, \varrho(\pi_0\mathsf{at}[\![S_b]\!])z = \varrho(\pi'_0\mathsf{at}[\![S_b]\!])z) \wedge \langle\pi_0\mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_1\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\varrho(\pi_0\mathsf{at}[\![S_b]\!]\pi_1\ell)y \neq \varrho(\pi_0\mathsf{at}[\![S_b]\!])y\}) \rceil\, \mathsf{nondet}(\neg B, \neg B)$

⦃since when $x \neq y$, $\varrho(\pi'_0\mathsf{at}[\![S_b]\!])y = \varrho(\pi_0\mathsf{at}[\![S_b]\!])y$⦄

$= \{\langle x, y\rangle \mid \exists \pi_0, \pi_1, \pi'_0 \;.\; (\forall z \in \mathcal{V}\setminus\{x\} \;.\; \varrho(\pi_0 \mathsf{at}[\![S_b]\!])z = \varrho(\pi'_0 \mathsf{at}[\![S_b]\!])z) \wedge \langle \pi_0 \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_1\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\varrho(\pi_0 \mathsf{at}[\![S_b]\!]\pi_1\ell)y \neq \varrho(\pi_0 \mathsf{at}[\![S_b]\!])y\} \rceil \mathsf{nondet}(\neg B, \neg B)$ $\wr$grouping cases together$\wr$

$= \{\langle x, y\rangle \mid \exists \pi_0, \pi_1, \pi'_0 \;.\; (\forall z \in \mathcal{V}\setminus\{x\} \;.\; \varrho(\pi_0 \mathsf{at}[\![S_b]\!])z = \varrho(\pi'_0 \mathsf{at}[\![S_b]\!])z) \wedge \langle \pi_0 \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_1\ell\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\varrho(\pi_0 \mathsf{at}[\![S_b]\!]\pi_1\ell)y \neq \varrho(\pi_0 \mathsf{at}[\![S_b]\!])y\} \rceil \mathsf{nondet}(\neg B, \neg B)$

$\wr$letting $\rho = \varrho(\pi_0\ell)$, $\nu = \varrho(\pi'_0\ell)x$ so that $\forall z \in \mathcal{V} \setminus \{x\} \;.\; \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z$ implies $\varrho(\pi'_0\ell) = \rho[x \leftarrow \nu]$.$\wr$

$\subseteq (\{\langle x, x\rangle \mid x \in \mathcal{V}\} \cup \{\langle x, y\rangle \mid x \in \mathcal{V} \wedge y \in \mathsf{mod}[\![S_b]\!]\}) \rceil \mathsf{nondet}(\neg B, \neg B)$

$\wr$A coarse approximation is to consider the variables $y \neq x$ appearing to the left of an assignment in S_b, a necessary condition for y to be modified by the execution of S_b where the set $\mathsf{mod}[\![S]\!]$ of variables that may be modified by the execution of S is syntactically defined as in (47.50). $\wr$

$= \mathbb{1}_{\mathsf{nondet}(\neg B, \neg B)} \cup \mathsf{nondet}(\neg B, \neg B) \times \mathsf{mod}[\![S_b]\!]$ $\wr$def. $\rceil\wr$

– Summing up for all subcases of (3–C–C), we get (5) $\subseteq \mathbb{1}_{\mathsf{nondet}(\neg B, \neg B)} \cup \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\,\ell \,\fatsemi\, (\mathbb{1}_{\mathsf{nondet}(\neg B, \neg B)} \cup \mathsf{nondet}(\neg B, \neg B) \times \mathsf{mod}[\![S_b]\!])) \rceil \mathsf{nondet}(B, \neg B)$.

— **(3–B–B)** This is the case when the observation prefix traces $\ell\pi_1$ and $\ell\pi'_1$ are both from a `break ;` in the iteration body S_b.

(8)

$= \{\langle x, y\rangle \mid \exists \langle \pi_0\ell, \ell\pi_1\rangle, \langle \pi'_0\ell, \ell\pi'_1\rangle \in \{\langle \pi_0\ell, \ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \mid \langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![B]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathrm{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![S_b]\!] \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \in \mathcal{S}^*[\![S_b]\!]\} \;.\; (\forall z \in \mathcal{V} \setminus \{x\} \;.\; \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}[\![y]\!](\mathsf{after}[\![S]\!])(\pi_0\ell, \ell\pi_1), \mathsf{seqval}[\![y]\!](\mathsf{after}[\![S]\!])(\pi'_0\ell, \ell\pi'_1))\}$ $\wr$case **(3–B–B)**$\wr$

$= \{\langle x, y\rangle \mid \exists \pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi_3\ell'' \;.\; \langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![B]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathrm{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![S_b]\!] \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge \exists \pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell'' \;.\; \langle \pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![B]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathrm{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![S_b]\!] \wedge \langle \pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi'_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\forall z \in \mathcal{V} \setminus \{x\} \;.\; \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \mathsf{diff}(\mathsf{seqval}[\![y]\!](\mathsf{after}[\![S]\!])(\pi_0\ell, \ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]), \mathsf{seqval}[\![y]\!](\mathsf{after}[\![S]\!])(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]))\}$ $\wr$def. $\in\wr$

$= \{\langle x, y\rangle \mid \exists \pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi_3\ell'' \;.\; \langle \pi_0\ell, \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![B]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathrm{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![S_b]\!] \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge \exists \pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell'' \;.\; \langle \pi'_0\ell, \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![B]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathrm{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![S_b]\!] \wedge \langle \pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!], \mathsf{at}[\![S_b]\!]\pi'_3\ell'' \xrightarrow{\texttt{break}} \mathsf{after}[\![S]\!]\rangle \in \mathcal{S}^*[\![S_b]\!] \wedge (\forall z \in \mathcal{V} \setminus \{x\} \;.\; \varrho(\pi_0\ell)z = \varrho(\pi'_0\ell)z) \wedge \varrho(\pi_0\ell\pi_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi_3\ell'') \neq \varrho(\pi'_0\ell\pi'_2\ell \xrightarrow{B} \mathsf{at}[\![S_b]\!]\pi'_3\ell'')\}$

$\wr \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X$ and X contains only iterates of $\mathcal{F}^*[\![\texttt{while}\ \ell\ (\texttt{B})\ \texttt{S}_b]\!]$ so $\mathsf{after}[\![\texttt{S}]\!] \neq \ell$ cannot appear in ${}^{\ell}\pi_2{}^{\ell}$. Moreover, $\langle \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!],\ \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \in \mathcal{S}^*[\![\texttt{S}_b]\!]$ so, by def. Section 4.2 of program labelling, $\mathsf{after}[\![\texttt{S}]\!] \neq \mathsf{at}[\![\texttt{S}_b]\!]$ cannot appear in $\mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''}$. Therefore, by def. (6.6) of ϱ and (47.16) of $\mathsf{seqval}[\![\texttt{y}]\!]\ell$, $\mathsf{seqval}[\![\texttt{y}]\!](\mathsf{after}[\![\texttt{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]) = \varrho(\pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''})$. We conclude by def. (47.18) of $\mathsf{diff}\wr$

$$= \bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!]} \{\langle \texttt{x},\ \texttt{y}\rangle \mid \exists \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''}\ .\ \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{tt} \wedge \langle \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!], \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \in \mathcal{S}^*[\![\texttt{S}_b]\!] \wedge \exists \pi'_0{}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi'_3{}^{\ell''}\ .\ \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!] \wedge \langle \pi'_0{}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!], \mathsf{at}[\![\texttt{S}_b]\!]\pi'_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \in \mathcal{S}^*[\![\texttt{S}_b]\!] \wedge (\forall \texttt{z} \in \mathbb{V}\setminus\{\texttt{x}\}\ .\ \varrho(\pi_0{}^{\ell})\texttt{z} = \varrho(\pi'_0{}^{\ell})\texttt{z}) \wedge \varrho(\pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''}) \neq \varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi'_3{}^{\ell''})\}$$

$$\subseteq \bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!]} \alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨾} (\widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\texttt{S}_b]\!]\ \ell'' \rceil \mathsf{nondet}(\texttt{B}, \texttt{B}))$$

$\wr$by a reasoning similar to the one we did in case **(1–Ba/Bc/C–Bb)** from (7) on.$\wr$

$$= \alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨾} \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!]} \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\texttt{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\texttt{B}, \texttt{B})\Big) \qquad \wr ⨾ \text{ and } \rceil \text{ preserve arbitrary joins}\wr$$

— **(3–B–C)** This is the case when the observation prefix trace ${}^{\ell}\pi_1$ is from a normal exit of the iteration and ${}^{\ell}\pi'_1$ is from a **break ;** in the iteration body $\texttt{S}_b$. By symmetry of diff this also covers the inverse case.

(8)

$$= \{\langle \texttt{x},\ \texttt{y}\rangle \mid \exists \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_1\rangle \in \{\langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \mid \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!] \wedge \langle \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!], \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \in \mathcal{S}^*[\![\texttt{S}_b]\!]\}\ .\ \exists \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_1\rangle \in \{\langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\texttt{B})} \mathsf{after}[\![\texttt{S}]\!]\rangle \mid \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell}) = \mathsf{ff}\}\ .\ (\forall \texttt{z} \in \mathbb{V}\setminus\{\texttt{x}\}\ .\ \varrho(\pi_0{}^{\ell})\texttt{z} = \varrho(\pi'_0{}^{\ell})\texttt{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\texttt{y}]\!](\mathsf{after}[\![\texttt{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_1), \mathsf{seqval}[\![\texttt{y}]\!](\mathsf{after}[\![\texttt{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_1))\} \qquad \wr\text{case } \mathbf{(3\text{–}B\text{–}C)}\wr$$

$$= \{\langle \texttt{x},\ \texttt{y}\rangle \mid \exists \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''}\pi'_0{}^{\ell}\pi'_2{}^{\ell}\ .\ \langle \pi_0{}^{\ell},\ {}^{\ell}\pi_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi_0{}^{\ell}\pi_2{}^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\texttt{S}_b]\!] \wedge \langle \pi_0{}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!], \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]\rangle \in \mathcal{S}^*[\![\texttt{S}_b]\!] \wedge \langle \pi'_0{}^{\ell},\ {}^{\ell}\pi'_2{}^{\ell}\rangle \in X \wedge \mathcal{B}[\![\texttt{B}]\!]\varrho(\pi'_0{}^{\ell}\pi'_2{}^{\ell}) = \mathsf{ff} \wedge (\forall \texttt{z} \in \mathbb{V}\setminus\{\texttt{x}\}\ .\ \varrho(\pi_0{}^{\ell})\texttt{z} = \varrho(\pi'_0{}^{\ell})\texttt{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\texttt{y}]\!](\mathsf{after}[\![\texttt{S}]\!])(\pi_0{}^{\ell}, {}^{\ell}\pi_2{}^{\ell} \xrightarrow{\texttt{B}} \mathsf{at}[\![\texttt{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\texttt{break}} \mathsf{after}[\![\texttt{S}]\!]), \mathsf{seqval}[\![\texttt{y}]\!](\mathsf{after}[\![\texttt{S}]\!])(\pi'_0{}^{\ell}, {}^{\ell}\pi'_2{}^{\ell} \xrightarrow{\neg(\texttt{B})} \mathsf{after}[\![\texttt{S}]\!]))\} \qquad \wr\text{def. } \in\wr$$

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'_0\ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\ .\ \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi_0\ell\pi_2\ell) = \mathsf{tt} \wedge \langle \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \langle \pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi'_0\ell\pi'_2\ell) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0\ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!]))\}$

(∫$\langle \pi_0\ell,\ \ell\pi_2\ell\rangle, \langle \pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X$ and X contains only iterates of $\mathcal{F}^*[\![\mathtt{while}\ \ell\ (\mathtt{B})\ \mathsf{S}_b]\!]$ so $\mathsf{after}[\![\mathsf{S}]\!] \neq \ell$ can appear neither in $\ell\pi_2\ell$ nor in $\ell\pi'_2\ell$. Moreover, $\langle \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$ so, by def. Section 4.2 of program labelling, $\mathsf{after}[\![\mathsf{S}]\!] \neq \mathsf{at}[\![\mathsf{S}_b]\!]$ cannot appear in $\mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell''$. Therefore, by def. (6.6) of ϱ and (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]\ell$, $\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0\ell, \ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]) = \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!])$ and $\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0\ell, \ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]) = \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0\ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!])$.∫)

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'_0\ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\ .\ \langle \pi_0\ell,\ \ell\pi_2\ell\rangle \in X \wedge \langle \pi_0\ell\pi_2\ell,\ \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \{\langle \pi\ell,\ \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\ell) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\} \wedge \langle \pi'_0\ell,\ \ell\pi'_2\ell\rangle \in X \wedge \langle \pi'_0\ell\pi'_2\ell,\ \ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \{\langle \pi\ell,\ \ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\ell) = \mathsf{ff}\} \wedge (\forall \mathsf{z} \in \mathcal{V} \setminus \{\mathsf{x}\}\ .\ \varrho(\pi_0\ell)\mathsf{z} = \varrho(\pi'_0\ell)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0\ell\pi_2\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'_0\ell\pi'_2\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!], \mathsf{after}[\![\mathsf{S}]\!]))\}$ (∫def. $\in$∫)

$\subseteq \alpha^{\mathsf{d}}(\{X\})\ \ell\ ⨟\ \alpha^{\mathsf{d}}(\{\mathcal{S}'\})\ \mathsf{after}[\![\mathsf{S}]\!]$

(∫by Lemma 47.59 where $\mathcal{S}' = \{\langle \pi\ell,\ \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\ell) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]\} \cup \{\langle \pi\ell,\ \ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]\rangle \mid \mathcal{B}[\![\mathsf{B}]\!]\varrho(\pi\ell) = \mathsf{ff}\}$ with $\pi_0\ell_0 \leftarrow \pi_0\ell$, $\ell_0\pi_1\ell' \leftarrow \ell\pi_2\ell$, $\ell \leftarrow \mathsf{after}[\![\mathsf{S}]\!]$, $\ell'\pi_2\ell \leftarrow \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3\ell'' \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]$, $\ell\pi_3 \leftarrow \mathsf{after}[\![\mathsf{S}]\!]$ so $\pi_3 = \ni$, and $\pi'_0\ell_0 \leftarrow \pi'_0\ell$, $\ell_0\pi'_1\ell' \leftarrow \ell_0\pi'_2\ell$, $\ell'\pi'_2\ell \leftarrow \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]$, $\ell\pi'_3 \leftarrow \mathsf{after}[\![\mathsf{S}]\!]$ so $\pi'_3 = \ni$ ∫)

Similar to the calculation starting at (10), we have to calculate the second term

$\alpha^{\mathsf{d}}(\{\mathcal{S}'\})\ \mathsf{after}[\![\mathsf{S}]\!]$

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \mathcal{S}' \in \mathcal{D}(\mathsf{after}[\![\mathsf{S}]\!])\langle \mathsf{x},\ \mathsf{y}\rangle\}$ (∫def. (47.25) of α^{d}∫)

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \langle \pi_0, \pi_1\rangle, \langle \pi'_0, \pi'_1\rangle \in \mathcal{S}' \ .\ (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\} \ .\ \varrho(\pi_0)\mathsf{z} = \varrho(\pi'_0)\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\mathsf{after}[\![\mathsf{S}]\!](\pi_0, \pi_1), \mathsf{seqval}[\![\mathsf{y}]\!]\mathsf{after}[\![\mathsf{S}]\!](\pi'_0, \pi'_1))\}$ ≀def. (47.19) of $\mathcal{D}^{\ell}\langle \mathsf{x},\ \mathsf{y}\rangle$≀

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!] \ .\ \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'{\ell}) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\} \ .\ \varrho(\pi^{\ell})\mathsf{z} = \varrho(\pi'{\ell})\mathsf{z}) \wedge \mathsf{diff}(\mathsf{seqval}[\![\mathsf{y}]\!]\mathsf{after}[\![\mathsf{S}]\!](\pi^{\ell}, \ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]), \mathsf{seqval}[\![\mathsf{y}]\!]\mathsf{after}[\![\mathsf{S}]\!](\pi'{\ell}, \ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]))\}$

≀def. $\mathcal{S}'$ and the other two combinations have already been considered in (**3–B–B**) and (**2–C–C**)≀

$= \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!] \ .\ \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi^{\ell}) = \mathsf{tt} \wedge \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge \mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'{\ell}) = \mathsf{ff} \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\} \ .\ \varrho(\pi^{\ell})\mathsf{z} = \varrho(\pi'{\ell})\mathsf{z}) \wedge \varrho(\pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\}$

≀$\langle \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!],\ \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!]$ so, by def. Section 4.2 of program labelling, $\mathsf{after}[\![\mathsf{S}]\!] \neq \mathsf{at}[\![\mathsf{S}_b]\!]$ cannot appear in $\mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''}$. Therefore, by def. (6.6) of ϱ and (47.16) of $\mathsf{seqval}[\![\mathsf{y}]\!]\ell$, $\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi_0{\ell}, \ell\pi_2{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]) = \varrho(\pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''})$ and $\mathsf{seqval}[\![\mathsf{y}]\!](\mathsf{after}[\![\mathsf{S}]\!])(\pi'{\ell}, \ell\pi'_2{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!]) = \varrho(\pi'{\ell}\pi'_2{\ell})$. We conclude by def. (47.18) of diff≀

$\subseteq \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!] \ .\ \ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!] \wedge \langle \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge (\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\} \ .\ \varrho(\pi^{\ell})\mathsf{z} = \varrho(\pi'{\ell})\mathsf{z}) \wedge \varrho(\pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\} \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$

≀since if $\mathsf{x} \notin \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$ then $\mathsf{x} \in \mathsf{det}(\mathsf{B}, \neg\mathsf{B})$ so by (47.48), $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi^{\ell}) = \mathsf{tt}$ and $\mathscr{B}[\![\neg\mathsf{B}]\!]\varrho(\pi'{\ell}) = \mathsf{tt}$ imply $\varrho(\pi^{\ell})\mathsf{x} = \varrho(\pi'{\ell})\mathsf{x}$ which, together with $\forall \mathsf{z} \in \mathbb{V} \setminus \{\mathsf{x}\} \ .\ \varrho(\pi^{\ell})\mathsf{z} = \varrho(\pi'{\ell})\mathsf{z}$, implies that $\varrho(\pi^{\ell}) = \varrho(\pi'{\ell})$, in contradiction with $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi^{\ell}) = \mathsf{tt}$ and $\mathscr{B}[\![\mathsf{B}]\!]\varrho(\pi'{\ell}) = \mathsf{ff}$≀

$= \bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \exists \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!], \pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!] \ .\ \langle \pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!], \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]\rangle \in \mathcal{S}^*[\![\mathsf{S}_b]\!] \wedge (\forall \mathsf{z} \in \mathbb{V}\setminus\{\mathsf{x}\} \ .\ \varrho(\pi^{\ell})\mathsf{z} = \varrho(\pi'{\ell})\mathsf{z}) \wedge \varrho(\pi^{\ell} \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y} \neq \varrho(\pi'{\ell} \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y})\} \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$

≀def. ∪≀

$$\subseteq \bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} (\{\langle \mathsf{x},\ \mathsf{x}\rangle \mid \mathsf{x} \in \mathbb{V}\} \cup \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \mathsf{x} \in \mathbb{V} \wedge \mathsf{y} \in \mathsf{mod}[\![\mathsf{S}_b]\!]\}) \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B})$$

(since if $\mathsf{y} \neq \mathsf{x}$ then $\varrho(\pi^\ell)\mathsf{y} = \varrho(\pi'^\ell)\mathsf{y} = \varrho(\pi'^\ell \xrightarrow{\neg(\mathsf{B})} \mathsf{after}[\![\mathsf{S}]\!])\mathsf{y}$ so for the value of y to be different in $\varrho(\pi^\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''} \xrightarrow{\mathtt{break}} \mathsf{after}[\![\mathsf{S}]\!]) = \varrho(\pi^\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''}) = \varrho(\pi'^\ell \xrightarrow{\mathsf{B}} \mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''})$, y must be modified during the execution $\mathsf{at}[\![\mathsf{S}_b]\!]\pi_3{}^{\ell''}$ of S_b. A coarse approximation is to consider that variable y appears to the left of an assignment in S_b, a necessary condition for y to be modified by the execution of S_b where the set $\mathsf{mod}[\![\mathsf{S}]\!]$ of variables that may be modified by the execution of S is syntactically defined as in (47.50).)

$$(\mathbb{1}_{\mathbb{V}} \cup \{\langle \mathsf{x},\ \mathsf{y}\rangle \mid \mathsf{x} \in \mathbb{V} \wedge \mathsf{y} \in \mathsf{mod}[\![\mathsf{S}_b]\!]\}) \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \qquad \text{(def. identity relation } \mathbb{1} \text{ and } \cup\text{)}$$

$$= \mathbb{1}_{\mathsf{nondet}(\mathsf{B},\neg\mathsf{B})} \cup (\mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!]) \qquad \text{(def. } \rceil\text{)}$$

– Summing up for cases (**3–B–B**) and (**3–B–C**), we get

$(5) \subseteq \alpha^{\mathsf{d}}(\{X\})^\ell ⨾ \Big(\big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]^{\ell''}\big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \cup \mathbb{1}_{\mathsf{nondet}(\mathsf{B},\neg\mathsf{B})} \cup (\mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!])$.

— Summing up for all subcases of (3) for a dependency observation point $\ell' = \mathsf{after}[\![\mathsf{S}]\!]$, we would get a term (47.63.c) of the form

$$\begin{aligned} &(\!\![\ \ell' = \mathsf{after}[\![\mathsf{S}]\!]\ ⸮\ (\mathbb{1}_{\mathsf{nondet}(\neg\mathsf{B},\neg\mathsf{B})} \cup X(\ell) \cup \\ &\quad (X(\ell) ⨾ (\mathbb{1}_{\mathsf{nondet}(\neg\mathsf{B},\neg\mathsf{B})} \cup \mathsf{nondet}(\neg\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!])) \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \cup \\ &\qquad X(\ell) ⨾ \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \cup \\ &\qquad\quad \mathbb{1}_{\mathsf{nondet}(\mathsf{B},\neg\mathsf{B})} \cup (\mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!])) \,:\, \varnothing\ ]\!\!). \end{aligned} \tag{47.63.c$'$}$$

that can be simplified as follows (while loosing precision)

(5)

$$\subseteq \mathbb{1}_{\mathsf{nondet}(\neg\mathsf{B},\neg\mathsf{B})} \cup \alpha^{\mathsf{d}}(\{X\})^\ell \cup (\alpha^{\mathsf{d}}(\{X\})\ \ell ⨾ (\mathbb{1}_{\mathsf{nondet}(\neg\mathsf{B},\neg\mathsf{B})} \cup \mathsf{nondet}(\neg\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!])) \rceil \mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \cup \alpha^{\mathsf{d}}(\{X\})^\ell ⨾ \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \cup \mathbb{1}_{\mathsf{nondet}(\mathsf{B},\neg\mathsf{B})} \cup (\mathsf{nondet}(\mathsf{B}, \neg\mathsf{B}) \times \mathsf{mod}[\![\mathsf{S}_b]\!])$$

$$\subseteq \mathbb{1}_{\mathbb{V}} \cup \alpha^{\mathsf{d}}(\{X\})^\ell \cup (\alpha^{\mathsf{d}}(\{X\})\ \ell ⨾ (\mathbb{1}_{\mathbb{V}} \cup \mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])) \cup \alpha^{\mathsf{d}}(\{X\})^\ell ⨾ \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\mathcal{S}}^{\exists}_{\mathsf{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \cup \mathbb{1}_{\mathbb{V}} \cup (\mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])$$

(since $\mathsf{nondet}(\mathsf{B}_1, \mathsf{B}_2) \subseteq \mathbb{V}$ so $\mathbb{1}_{\mathsf{nondet}(\mathsf{B}_1,\mathsf{B}_2)} \subseteq \mathbb{1}_{\mathbb{V}}$ and def. $\rceil$)

$$\subseteq \mathbb{1}_{\mathbb{V}} \cup \alpha^{\mathrm{d}}(\{X\})\ell \cup (\alpha^{\mathrm{d}}(\{X\})\ \ell \mathbin{⨟} \mathbb{1}_{\mathbb{V}}) \cup (\alpha^{\mathrm{d}}(\{X\})\ \ell \mathbin{⨟} \mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!]) \cup \alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨟} \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\widehat{\mathcal{S}}}^{\exists}_{\mathrm{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \cup \mathbb{1}_{\mathbb{V}} \cup (\mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])$$

$$\text{(since ⨟ distributes over } \cup \text{)}$$

$$= \mathbb{1}_{\mathbb{V}} \cup \alpha^{\mathrm{d}}(\{X\})\ell \cup \big((\mathbb{1}_{\mathbb{V}} \cup \alpha^{\mathrm{d}}(\{X\})\ell) \mathbin{⨟} (\mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])\big) \cup \alpha^{\mathrm{d}}(\{X\})\ell \mathbin{⨟} \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\widehat{\mathcal{S}}}^{\exists}_{\mathrm{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big)$$

$$\text{(idempotency law for } \cup \text{ and ⨟ distributes over } \cup \text{)}$$

After simplification, we get a term (47.63.c) of the form

$$(\!| \ell' = \mathsf{after}[\![\mathsf{S}]\!] \ ? \ \mathbb{1}_{\mathbb{V}} \cup X(\ell) \cup \big((\mathbb{1}_{\mathbb{V}} \cup X(\ell)) \mathbin{⨟} (\mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])\big) \cup X(\ell) \mathbin{⨟} \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\widehat{\mathcal{S}}}^{\exists}_{\mathrm{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \ \text{⸬}\ \varnothing \,|\!).$$

For fixpoints X of $\mathcal{F}^{\mathrm{diff}}[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]$, we have $\mathbb{1}_{\mathbb{V}} \subseteq X(\ell)$ by (47.63.a) so that, by the chaotic iteration theorem [1, 2], $\mathbb{1}_{\mathbb{V}} \cup X(\ell)$ can be replaced by $X(\ell)$. We get a term (47.63.c) of the form

$$(\!| \ell' = \mathsf{after}[\![\mathsf{S}]\!] \ ? \ X(\ell) \cup \big(X(\ell \mathbin{⨟} (\mathbb{V} \times \mathsf{mod}[\![\mathsf{S}_b]\!])\big) \cup X(\ell) \mathbin{⨟} \Big(\Big(\bigcup_{\ell'' \in \mathsf{breaks\text{-}of}[\![\mathsf{S}_b]\!]} \widehat{\widehat{\mathcal{S}}}^{\exists}_{\mathrm{diff}}[\![\mathsf{S}_b]\!]\ \ell''\Big) \rceil \mathsf{nondet}(\mathsf{B}, \mathsf{B})\Big) \ \text{⸬}\ \varnothing \,|\!).$$

— Summing up for all cases (1), (2), and (3) for all dependency observation points, we conclude that

$$\forall \ell' \in \mathsf{labx}[\![\mathsf{S}]\!] \ .\ \alpha^{\mathrm{d}}(\{\mathcal{F}^{*}[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!](X)\})\ \ell' \subseteq \mathcal{F}^{\mathrm{diff}}[\![\texttt{while}\ \ell\ \texttt{(B)}\ \texttt{S}_b]\!]\ \alpha^{\mathrm{d}}(\{X\})\ \ell'$$

proving pointwise semi-commutation. □

5 Mathematical proofs of chapter 48

Proof of Lemma 48.63 By induction on the sequence of calls to unify. We proceed by by calculational design and case analysis on the structure of $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$ which can be a variable or a structured term and may belong to the domain of ϑ_0, or not.

- If $\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0) = \Omega^{\mathrm{r}}_{\mathrm{s}}$ in case (48.47.8) of an occur-check, we have $\gamma^{\mathrm{r}}_{\mathrm{s}}(\Omega^{\mathrm{r}}_{\mathrm{s}}) = \varnothing$ by (48.46). By the test (48.47.8), $\alpha \in \mathbb{vars}[\![\boldsymbol{\tau}_2]\!]$. If $\boldsymbol{\tau}_2 = \beta \in \mathbb{V}_{\mathfrak{t}}$ were a variable then the test $\alpha \in \mathbb{vars}[\![\boldsymbol{\tau}_2]\!]$ at (48.47.8) would be true only if $\alpha = \beta$ but this case is prevented by the test (48.47.7). By contradiction, $\boldsymbol{\tau}_2 \notin \mathbb{V}_{\mathfrak{t}}$ in case (48.47.8). It follows, by def. (48.51) of γ_{e} that $\gamma_{\mathrm{e}}(\boldsymbol{\tau}_1 \doteq \boldsymbol{\tau}_2) = \gamma_{\mathrm{e}}(\alpha \doteq \boldsymbol{\tau}_2) = \varnothing$ since otherwise, there would be some $\boldsymbol{\varrho}$ such that $\boldsymbol{\varrho}(\boldsymbol{\tau}_1) = \boldsymbol{\varrho}(f(\ldots\alpha\ldots))$ which would be an infinite object not in $\mathbf{P}^{\mathrm{v}}$, as shown in Lemma 48.9.

- By Lemma 48.58, unify does terminate so that, in case (48.47.6) with $\vartheta_n = \Omega^{\mathsf{r}}_{\mathsf{s}}$ there must be a series of recursive calls ending up in (48.47.8). So $\boldsymbol{\tau}_1$ or $\boldsymbol{\tau}_2$ has a recursive subterm which, again by Lemma 48.9, implies $\gamma^{\mathsf{r}}_{\mathsf{s}}(\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0)) = \gamma^{\mathsf{r}}_{\mathsf{s}}(\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0)) = \gamma^{\mathsf{r}}_{\mathsf{s}}(\Omega^{\mathsf{r}}_{\mathsf{s}}) = \varnothing$;

- In case (48.47.6) with $\vartheta_n \neq \Omega^{\mathsf{r}}_{\mathsf{s}}$, we have,

$$
\begin{aligned}
& \gamma_{\mathsf{e}}(\boldsymbol{\tau}_1 \doteq \boldsymbol{\tau}_2) \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0) \\
= \; & \gamma_{\mathsf{e}}(f(\boldsymbol{\tau}^1_1, \ldots, \boldsymbol{\tau}^n_1) \doteq g(\boldsymbol{\tau}^1_2, \ldots, \boldsymbol{\tau}^m_2)) \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0) && \wr \text{test (48.47.1) is } \mathsf{tt} \wr \\
= \; & \gamma_{\mathsf{e}}(f(\boldsymbol{\tau}^1_1, \ldots, \boldsymbol{\tau}^n_1) \doteq f(\boldsymbol{\tau}^1_2, \ldots, \boldsymbol{\tau}^n_2)) \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0) && \wr \text{test (48.47.2) is } \mathsf{ff} \wr \\
= \; & \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(f(\boldsymbol{\tau}^1_1, \ldots, \boldsymbol{\tau}^n_1)) = \boldsymbol{\varrho}(f(\boldsymbol{\tau}^1_2, \ldots, \boldsymbol{\tau}^n_2))\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0) && \wr \text{def. (48.51) of } \gamma_{\mathsf{e}} \wr \\
= \; & \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \bigwedge_{i=1}^{n} \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} && \wr \text{def. (48.7) of assignment application} \wr \\
= \; & \bigcap_{i=1}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0) && \wr \text{def. } \textstyle\bigcap \wr \\
= \; & (\{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^1_2)\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0)) \cap \bigcap_{2=1}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} \\
& && \wr \textstyle\bigcap \text{ is associative and commutative} \wr \\
= \; & (\gamma_{\mathsf{e}}(\boldsymbol{\tau}^1_i) \doteq \boldsymbol{\tau}^1_2) \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_0)) \cap \bigcap_{2=1}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} && \wr \text{def. (48.51)x of } \gamma_{\mathsf{e}} \wr \\
= \; & \mathsf{let}\ \vartheta_1 = \mathsf{unify}(\boldsymbol{\tau}^1_i, \boldsymbol{\tau}^1_2, \vartheta_0)\ \mathsf{in} \\
& \quad \bigcap_{2=1}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_1) && \wr \text{ind. hyp. and } \textstyle\bigcap \text{ commutative} \wr \\
= \; & \mathsf{let}\ \vartheta_1 = \mathsf{unify}((\boldsymbol{\tau}^1_i, \boldsymbol{\tau}^1_2, \vartheta_0)\ \mathsf{in} \\
& \quad \ldots \\
& \quad\quad \mathsf{let}\ \vartheta_j = \mathsf{unify}(\boldsymbol{\tau}^j_i, \boldsymbol{\tau}^j_2, \vartheta_{j-1})\ \mathsf{in} \\
& \quad\quad\quad \bigcap_{i=j+1}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_j) && \wr \text{recurrence hyp., } j < n \wr \\
= \; & \mathsf{let}\ \vartheta_1 = \mathsf{unify}(\boldsymbol{\tau}^1_i, \boldsymbol{\tau}^1_2, \vartheta_0)\ \mathsf{in} \\
& \quad \ldots \\
& \quad\quad \mathsf{let}\ \vartheta_j = \mathsf{unify}(\boldsymbol{\tau}^j_i, \boldsymbol{\tau}^j_2, \vartheta_{j-1})\ \mathsf{in} \\
& \quad\quad\quad \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^{j+1}_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^{j+1}_2)\} \cap \gamma^{\mathsf{r}}_{\mathsf{s}}(\vartheta_j) \cap \\
& \quad\quad\quad\quad \bigcap_{i=j+2}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^{\nu} \mid \boldsymbol{\varrho}(\boldsymbol{\tau}^1_i) = \boldsymbol{\varrho}(\boldsymbol{\tau}^i_2)\} && \wr \textstyle\bigcap \text{ is associative and commutative} \wr
\end{aligned}
$$

$$
\begin{array}{rll}
= & \mathsf{let}\ \vartheta_1 = \mathsf{unify}(\boldsymbol{\tau}_i^1, \boldsymbol{\tau}_2^1, \vartheta_0)\ \mathsf{in} & \\
& \quad \ldots & \\
& \quad\ \mathsf{let}\ \vartheta_j = \mathsf{unify}(\boldsymbol{\tau}_i^j, \boldsymbol{\tau}_2^j, \vartheta_{j-1})\ \mathsf{in} & \\
& \quad\quad \mathsf{let}\ \vartheta_{j+1} = \mathsf{unify}(\boldsymbol{\tau}_i^{j+1}, \boldsymbol{\tau}_2^{j+1}, \vartheta_j)\ \mathsf{in} & \\
& \quad\quad\quad \bigcap_{i=j+2}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\boldsymbol{\tau}_i^1) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2^i)\} \cap \gamma_s^r(\vartheta_{j+1}) & \text{(ind. hyp. and } \bigcap \text{ commutative)} \\
= & \mathsf{let}\ \vartheta_1 = \mathsf{unify}(\boldsymbol{\tau}_i^1, \boldsymbol{\tau}_2^1, \vartheta_0)\ \mathsf{in} & \\
& \quad \ldots & \\
& \quad\ \mathsf{let}\ \vartheta_j = \mathsf{unify}(\boldsymbol{\tau}_i^n, \boldsymbol{\tau}_2^n, \vartheta_{n-1})\ \mathsf{in} & \\
& \quad\quad \bigcap_{i=n+2}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\boldsymbol{\tau}_i^1) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2^i)\} \cap \gamma_s^r(\vartheta_n) & \text{(by recurrence when } j+1 = n\text{)} \\
= & \mathsf{let}\ \vartheta_1 = \mathsf{unify}(\boldsymbol{\tau}_i^1, \boldsymbol{\tau}_2^1, \vartheta_0)\ \mathsf{in} & \\
& \quad \ldots & \\
& \quad\ \mathsf{let}\ \vartheta_j = \mathsf{unify}(\boldsymbol{\tau}_i^n, \boldsymbol{\tau}_2^n, \vartheta_{n-1})\ \mathsf{in} & \\
& \quad\quad \gamma_s^r(\vartheta_n) & \\
& & \text{(since } \bigcap_{i=n+2}^{n} \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\boldsymbol{\tau}_i^1) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2^i)\} = \bigcap \varnothing = \mathbf{P}^\nu \text{ is the identity for } \cap \text{)}
\end{array}
$$

- In case (48.47.7), we have

$$
\begin{array}{rll}
& \gamma_e(\boldsymbol{\tau}_1 \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0) & \\
= & \gamma_e(\alpha \doteq \alpha) \cap \gamma_s^r(\vartheta_0) & \text{(} \alpha \in \mathbb{V}_t \text{ by test (48.47.7))} \\
= & \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\alpha)\} \cap \gamma_s^r(\vartheta_0) & \text{(def. (48.51) of } \gamma_e\text{)} \\
= & \mathbf{P}^\nu \cap \gamma_s^r(\vartheta_0) & \text{(since } \boldsymbol{\varrho} \in \mathbf{P}^\nu \triangleq \mathbb{V}_t \to \mathbf{T} \text{ by (48.6))} \\
= & \gamma_s^r(\vartheta_0) & \text{(} \mathbf{P}^\nu \text{ is the identity for } \cap \text{)} \\
= & \gamma_s^r(\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0)) & \text{(def. } \mathsf{unify} \text{ in case (48.47.7))}
\end{array}
$$

- In case (48.47.11), we have

$$
\begin{array}{rll}
& \gamma_e(\boldsymbol{\tau}_1 \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0) & \\
= & \gamma_e(\alpha \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0) &
\end{array}
$$

(where $\alpha \in \mathbb{V}_t$ by test (48.47.9), $\alpha \notin \mathsf{vars}[\![\boldsymbol{\tau}_2]\!]$ since test (48.47.8) is ff, $\alpha \notin \mathsf{dom}(\vartheta_0)$ by test (48.47.10), and $\boldsymbol{\tau}_2 \notin \mathbb{V}_t$ since test (48.47.1) is ff)

$$
\begin{array}{rll}
= & \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2)\} \cap \gamma_s^r(\vartheta_0) & \text{(def. (48.51) of } \gamma_e\text{)} \\
= & \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2)\} \cap \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t\ .\ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}(\vartheta_0(\beta))\} & \text{(def. (48.52) of } \gamma_s^r\text{)} \\
= & \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2) \wedge \forall \beta \in \mathbb{V}_t\ .\ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}(\vartheta_0(\beta))\} & \text{(def. } \cap\text{)} \\
= & \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t\ .\ \boldsymbol{\varrho}(\beta) = (\!| \beta = \alpha\ ?\ \boldsymbol{\varrho}(\vartheta_0(\beta)[\beta \in \mathsf{vars}[\![\boldsymbol{\tau}_2]\!] \leftarrow \boldsymbol{\tau}_2]) : \boldsymbol{\varrho}(\boldsymbol{\tau}_2[\alpha \leftarrow \vartheta_0(\beta)]) |\!)\} &
\end{array}
$$

$\wr$def. (48.7) of assignment application where $\boldsymbol{\varrho}(\alpha)$ is replaced by its equal $\boldsymbol{\varrho}(\boldsymbol{\tau}_2)$ and for $\beta \in \mathbb{V}_t \setminus \{\alpha\}$, $\boldsymbol{\varrho}(\beta)$ is replaced by its equal $\boldsymbol{\varrho}(\vartheta_0(\beta))\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = [\![\beta = \alpha \ ? \ \boldsymbol{\varrho}(\vartheta_0(\beta)[\beta \in \mathsf{vars}[\![\boldsymbol{\tau}_2]\!] \leftarrow \boldsymbol{\tau}_2]) \ \text{⸗} \ \boldsymbol{\varrho}(\{\langle\alpha, \boldsymbol{\tau}_2\rangle\}(\vartheta_0(\beta)))]\!]\}$

$\wr$by Exercise 48.60 where $\boldsymbol{\tau}' = \vartheta_0(\beta)\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = [\![\beta = \alpha \ ? \ \boldsymbol{\varrho}(\vartheta_0(\boldsymbol{\tau}_2)) \ \text{⸗} \ \boldsymbol{\varrho}(\{\langle\alpha, \boldsymbol{\tau}_2\rangle\}(\vartheta_0(\beta)))]\!]\}$ $\wr$by Exercise 48.62$\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}([\![\beta = \alpha \ ? \ \vartheta_0(\boldsymbol{\tau}_2) \ \text{⸗} \ (\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0)(\beta)]\!])\}$

$\wr$def. conditional and function composition $\circ\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}([\![\beta = \alpha \ ? \ (\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0)(\alpha) \ \text{⸗} \ (\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0)(\beta)]\!])\}$

$\wr$since $X \notin \mathsf{dom}(\vartheta_0)$ so $(\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0)(\alpha) = \{\langle\alpha, \boldsymbol{\tau}_2\rangle\}(\vartheta_0(\alpha)) = \{\langle\alpha, \boldsymbol{\tau}_2\rangle\}(\alpha) = \boldsymbol{\tau}_2\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}(\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0)(\beta)$ $\wr$def. conditional$\int$

$= \gamma_s^r\{\langle\alpha, \boldsymbol{\tau}_2\rangle\} \circ \vartheta_0$ $\wr$def. (48.52) of $\gamma_s^r\int$

$= \gamma_s^r(\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0))$ $\wr$(48.47.11)$\int$

- In case (48.47.12), we have $\boldsymbol{\tau}_1 = \alpha \in \mathsf{dom}(\vartheta_0)$ by tests (48.47.9) and (48.47.10) and $\boldsymbol{\tau}_2 \notin \mathbb{V}_t$ since test (48.47.1) is ff.

$\gamma_e(\boldsymbol{\tau}_1 \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0)$

$= \gamma_e(\alpha \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0)$ $\wr\boldsymbol{\tau}_1 = \alpha\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2) \wedge \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}(\vartheta_0(\beta))\}$

$\wr$def. (48.51) of γ_e, (48.52) of γ_s^r, and def. $\cap\int$

$= \{\boldsymbol{\varrho} \in \mathbf{P}^\nu \mid \boldsymbol{\varrho}(\vartheta_0(\alpha)) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2) \wedge \forall \beta \in \mathbb{V}_t \ . \ \boldsymbol{\varrho}(\beta) = \boldsymbol{\varrho}(\vartheta_0(\beta))\}$

$\wr\alpha \in \mathsf{dom}(\vartheta_0)$ so $\boldsymbol{\varrho}(\alpha) = \boldsymbol{\varrho}(\vartheta_0(\beta)) = \boldsymbol{\varrho}(\boldsymbol{\tau}_2)\int$

$= \gamma_e(\vartheta_0(\alpha) \doteq \boldsymbol{\tau}_2) \cap \gamma_s^r(\vartheta_0)$ $\wr$def. (48.51) of γ_e, (48.52) of γ_s^r, and def. $\cap\int$

$= \gamma_s^r(\mathsf{unify}(\vartheta_0(\alpha), \boldsymbol{\tau}_2, \vartheta_0))$ $\wr$ind. hyp. of Lemma 48.63$\int$

$= \gamma_s^r(\mathsf{unify}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \vartheta_0))$ $\wr$(48.47.12)$\int$

- In case (48.47.13) we are back to (48.47.11) or (48.47.12) by the symmetry argument of Remark 48.49. □

The following Lemma 11 shows that new entries are successively added to the table T_0.

Lemma 11 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0 \in \mathbf{T}^\nu$, if $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ is (recursively) called from the main call $\mathsf{lcg}(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0)$ and returns $\langle \boldsymbol{\tau}, T' \rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$, then

$$\begin{array}{ll} \text{preinvariant:} & \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \in \mathbf{T}^\nu \wedge T_0 \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu \\ \text{postinvariant:} & \boldsymbol{\tau} \in \mathbf{T}^\nu \wedge T' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu \wedge \mathsf{vars}[\![\boldsymbol{\tau}]\!] \subseteq \mathsf{dom}(T') \wedge \\ & \quad \forall \alpha \in \mathsf{dom}(T_0) \,.\, T_0(\alpha) = T'(\alpha) \end{array} \tag{12}$$ □

Proof of Lemma 11 By induction on the sequence of calls to lub and, for any given call, by recurrence to handle the recursive calls at (48.68.2), …, (48.68.4), and by case analysis on the conditional.

The first call at (48.68.12) satisfies the preinvariant of (48.39) since $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0 \in \mathbf{T}^\nu$ by hypothesis and $T_0 = \varnothing \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu$;

Assuming that an intermediate call to $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ satisfies the preinvariant (48.39), the proof that it satisfies the postinvariant (48.39) is by case analysis.

- In case (48.68.5), $\boldsymbol{\tau}_j \in \mathbf{T}^\nu$ by hypothesis on the intermediate call, so $\boldsymbol{\tau}_j^i \in \mathbf{T}^\nu$, $i = 1, \ldots, n$, $j = 1, 2$, by the test (48.68.1). Then we proceed by recurrence on the recursive calls.
  - For the basis $i = 0$, T_0 satisfies (48.39) by hypothesis on the intermediate call;
  - Assume, by recurrence hypothesis for $i \in [0, n[$, that $T_i \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu \wedge \forall \alpha \in \mathsf{dom}(T_0) \,.\, T_0(\alpha) = T_i(\alpha)$. Then, by induction on the sequence of calls to lub, $\boldsymbol{\tau}^{i+1} \in \mathbf{T}^\nu$ and $T_{i+1} \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu \wedge \mathsf{vars}[\![\boldsymbol{\tau}^{i+1}]\!] \subseteq \mathsf{dom}(T_{i+1}) \wedge \forall \alpha \in \mathsf{dom}(T_i) \,.\, T_i(\alpha) = T_{i+1}(\alpha)$. By transitivity, $\forall \alpha \in \mathsf{dom}(T_0) \,.\, T_0(\alpha) = T_{i+1}(\alpha)$. □

  By recurrence for $i = n$, $T' = T_n$ at (48.68.5) satisfies (48.39) since $\boldsymbol{\tau}^i \in \mathbf{T}^\nu$, $i = 1, \ldots, n$, implies $f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n) \in \mathbf{T}^\nu$ and $\mathsf{vars}[\![f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)]\!] = \bigcup_{i=1}^n \mathsf{vars}[\![\boldsymbol{\tau}^i]\!]$;
- The case (48.68.7) is trivial since $\beta \in \mathbf{T}^\nu$, $T' = T_0$, and $\beta \in \mathsf{dom}(T_0)$;
- In case (48.68.9), $T_0 \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu$ by hypothesis, $\beta \in \mathbf{T}^\nu$, and $\beta \in \mathbb{V}_{\mathfrak{t}} \setminus \mathsf{dom}(T_0)$ by the test (48.68.8) so $T' = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0] \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu$ and for all $\alpha \in \mathsf{dom}(T_0)$, $\alpha \neq \beta$ so $T'(\alpha) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0](\alpha) = T_0(\alpha)$. Moreover $\beta \in \mathsf{vars}[\![\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0]]\!] = \mathsf{vars}[\![T']\!]$. □

Remark Lemma 11 shows that T_0 can be declared as a variable local to lcg and global to lub, which would be unitialized to $\varnothing$ and updated by an assignment at (48.68.9).

For $T \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu \times \mathbf{T}^\nu$, let us define, when $\alpha \in \mathsf{dom}(T)$,

$$\begin{array}{rcl} \bar{\varsigma}_1(T)\alpha & \triangleq & \mathsf{let}\ \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle = T(\alpha)\ \mathsf{in}\ \boldsymbol{\tau}_1 \\ \bar{\varsigma}_2(T)\alpha & \triangleq & \mathsf{let}\ \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle = T(\alpha)\ \mathsf{in}\ \boldsymbol{\tau}_2 \end{array} \tag{13}$$

(which is undefined when $\alpha \notin \mathsf{dom}(T)$ in which case (48.30) applies, in particular when $T = \varnothing$).

The following Lemma 14 shows that table T_0 maintains two substitutions $\bar{\varsigma}_1(T)$ and $\bar{\varsigma}_1(T)$ which can be used to instantiate the term resulting from the call to the parameters.

Lemma 14 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \in \mathsf{T}^\nu$ and $T_0 \in \wp(\mathbb{V}_{\mathbb{t}} \times \mathsf{T}^\nu \times \mathsf{T}^\nu)$, if $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ is (recursively) called from the main call $\mathsf{lcg}(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0)$ and returns $\langle \boldsymbol{\tau}, T' \rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$, then

$$\bar{\varsigma}_1(T')\boldsymbol{\tau} \ = \ \boldsymbol{\tau}_1 \quad \text{and} \quad \bar{\varsigma}_2(T')\boldsymbol{\tau} \ = \ \boldsymbol{\tau}_2 \qquad (15)$$ □

Proof of Lemma 14 The preinvariant is tt. By induction on the sequence of calls to lub and, for any given call, by recurrence to handle the recursive calls at (48.68.2), …, (48.68.4), and by case analysis for the conditional.

- In case (48.68.5), by recurrence and induction on the sequence of recursive calls to leq, we have $\bar{\varsigma}_1(T_i)\boldsymbol{\tau}^i = \boldsymbol{\tau}_1^i$ and $\bar{\varsigma}_2(T_i)\boldsymbol{\tau}^i = \boldsymbol{\tau}_2^i$ for all $i \in [1,n]$. By the postinvariant of (48.39), we have $\forall \alpha \in \mathsf{dom}(T_i) \,.\, T_0(\alpha) = T_{i+1}(\alpha)$. It follows, by (13) that $\forall \alpha \in \mathbb{vars}[\![\boldsymbol{\tau}^i]\!] \subseteq \mathsf{dom}(T_i) \,.\, T_i(\alpha) = T_{i+1}(\alpha)$. Therefore, by (13), $\forall \alpha \in \mathbb{vars}[\![\boldsymbol{\tau}^i]\!] \,.\, \vartheta_j(T_{i+1})(\boldsymbol{\tau}^i) = \vartheta_j(T_i)(\boldsymbol{\tau}^i)$. It follows by (48.30) that $\vartheta_j(T_n)(f(\boldsymbol{\tau}^1, \boldsymbol{\tau}^2, \ldots, \boldsymbol{\tau}^n)) = f(\vartheta_j(T_n)(\boldsymbol{\tau}^1), \vartheta_j(T_n)(\boldsymbol{\tau}^2), \ldots, \vartheta_j(T_n)(\boldsymbol{\tau}^n)) = f(\vartheta_j(T_1)(\boldsymbol{\tau}^1), \vartheta_j(T_2)(\boldsymbol{\tau}^2), \ldots, \vartheta_j(T_n)(\boldsymbol{\tau}^n)) = f(\boldsymbol{\tau}_j^1, \ldots, \boldsymbol{\tau}_j^n) = \boldsymbol{\tau}_j$, $j = 1, 2$;
- In case (48.68.7), (15) directly follows from $\boldsymbol{\tau} = \beta$, $T' = T_0$, $\beta \in \mathsf{dom}(T_0)$, $T_0(\beta) = \langle \boldsymbol{\tau}_1, \ \boldsymbol{\tau}_2 \rangle$, and (13);
- In case (48.68.9), $\bar{\varsigma}_j(T')\boldsymbol{\tau} = \vartheta_j(\langle \boldsymbol{\tau}_1, \ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0])\beta = \mathsf{if}\ \beta \in \mathsf{dom}(T)\ \mathsf{then\ let}\ \langle \boldsymbol{\tau}_1', \ \boldsymbol{\tau}_2' \rangle = \langle \boldsymbol{\tau}_1, \ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0](\beta)\ \mathsf{in}\ \boldsymbol{\tau}_j'\ \mathsf{else}\ \alpha = \boldsymbol{\tau}_j$, $j = 1, 2$. □

$\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)$ computes an upper-bound of $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$.

Lemma 16 For all $\boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \in \mathsf{T}^\nu$, the lgc algorithm terminates with $[\boldsymbol{\tau}_1]_{\simeq^\nu} \preceq_{\simeq^\nu} [\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^\nu}$ and $[\boldsymbol{\tau}_2]_{\simeq^\nu} \preceq_{\simeq^\nu} [\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^\nu}$. □

Proof of Lemma 16 The termination proof of $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ is by structural induction on $\boldsymbol{\tau}_1$ (or $\boldsymbol{\tau}_2$). So the main call $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \varnothing)$ at (48.68.12) does terminate.

Lemma 16 follows by def. of the infimum $\overline{\varnothing}^\nu$ in cases (48.68.11).

Otherwise, at (48.68.12), $\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2) = \boldsymbol{\tau}$ where $\langle \boldsymbol{\tau}, \ T \rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \varnothing)$. By (48.42), $\bar{\varsigma}_j(T)\boldsymbol{\tau} = \boldsymbol{\tau}_j$, $j = 1, 2$. So by Exercise 48.16, $[\boldsymbol{\tau}_j]_{\simeq^\nu} \preceq_{\simeq^\nu} [\boldsymbol{\tau}]_{\simeq^\nu} = [\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^\nu}$. □

Let $[\boldsymbol{\tau}']_{\simeq^\nu}$ be an upper bound of $[\boldsymbol{\tau}_1]_{\simeq^\nu}$ and $[\boldsymbol{\tau}_2]_{\simeq^\nu}$ i.e. $\boldsymbol{\tau}_1 \preceq_{\simeq^\nu} \boldsymbol{\tau}'$ and $\boldsymbol{\tau}_2 \preceq_{\simeq^\nu} \boldsymbol{\tau}'$ so that, by Theorem 48.31, there exists substitutions ϑ_1 and ϑ_2 such that $\vartheta_1(\boldsymbol{\tau}') = \boldsymbol{\tau}_1$ and $\vartheta_2(\boldsymbol{\tau}') = \boldsymbol{\tau}_2$. We must prove that $[\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^\nu} \preceq_{\simeq^\nu} [\boldsymbol{\tau}']_{\simeq^\nu}$ that is, by Theorem 48.31, that there exist a substitution ϑ' such that $\vartheta'(\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)) = \boldsymbol{\tau}'$.

We modify the lub algorithm into lub' (which calls lub) as given in Figure 18 to construct this substitution ϑ' given any upper bound $\boldsymbol{\tau}'$.

Example 19 The assumption (17.13) prevents a call like $\mathsf{lub}'(f(a,b), f(b,a), \varnothing, f(\alpha,\alpha), \boldsymbol{\varepsilon}, \varnothing)$ where $f(\alpha,\alpha)$ is not an upper bound of $\{f(a,b), f(b,a)\}$. □

Example 20 For $\boldsymbol{\tau}_1 = f(g(a), g(g(a)), g(a), b, b)$, $\boldsymbol{\tau}_2 = f(g(b), g(h(b)), g(b), a, a)$ and $\boldsymbol{\tau}' = f(g(\alpha), \beta, g(\alpha), \gamma, U)$, we have

$\mathsf{lub}'(f(g(a), g(g(a)), g(a), b, b), f(g(b), g(h(b)), g(b), a, a), \varnothing, f(g(\alpha), \beta, g(\alpha), \gamma, U), \boldsymbol{\varepsilon})$
$\quad \mathsf{lub}'(g(a), g(b), \varnothing, g(\alpha), \boldsymbol{\varepsilon})$ (17.2b)
$\quad\quad \mathsf{lub}'(a, b, \varnothing, \alpha, \boldsymbol{\varepsilon})$ (17.2b)
$\quad\quad = \langle\beta,\ \{\langle\beta,\ \langle a,\ b\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle\}\rangle$ (17.9)
$\quad = \langle g(\beta),\ \{\langle\beta,\ \langle a,\ b\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle\}\rangle$ (17.5b)
$\quad \mathsf{lub}'(g(g(a)), g(h(b)), \{\langle\beta,\ \langle a,\ b\rangle\rangle\}, \beta, \{\langle\alpha,\ \beta\rangle\})$ (17.3b)
$\quad\quad \mathsf{lub}(g(a), h(b), \{\langle\beta,\ \langle a,\ b\rangle\rangle\})$ (17.2a)
$\quad\quad = \langle\gamma,\ \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}\rangle$
$\quad = \langle g(\gamma),\ \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\}\rangle$ (17.5a)
$\quad \mathsf{lub}'(g(a), g(b), \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}, g(\alpha), \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\})$
(17.4b)
$\quad\quad \mathsf{lub}'(a, b, \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}, \alpha, \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\})$ (17.6)
$\quad\quad = \langle\beta,\ \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\}\rangle$ (17.7)
$\quad = \langle g(\beta),\ \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\}\rangle$ (17.5b)
$\quad \mathsf{lub}'(b, a, \{\langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}, \gamma, \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle\})$ (17.8)
$\quad =\langle\alpha,\ \{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \alpha\rangle\}\rangle$
(17.9)
$\quad \mathsf{lub}'(b, a, \{\{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}, U, \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \alpha\rangle\})$
(17.8)
$\quad = \langle\alpha,\ \{\{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle, \langle U,\ \alpha\rangle\}\rangle$
$= \langle f(g(\beta), g(\gamma), g(\beta), \alpha, \alpha),\ \{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\},\ \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \alpha\rangle, \langle U,\ \alpha\rangle\}\rangle$ (17.5b)

so that $\boldsymbol{\tau} = f(g(\beta), g(\gamma), g(\beta), \alpha, \alpha)$, $T = \{\langle\alpha, \langle b, a\rangle\rangle, \langle\beta, \langle a, b\rangle\rangle, \langle\gamma, \langle g(a), h(b)\rangle\rangle\}$, and $\vartheta' = \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \alpha\rangle, \langle U,\ \alpha\rangle\}$. Let us check that

1. $\vartheta'(\boldsymbol{\tau}') = \{\langle\alpha,\ \beta\rangle, \langle\beta,\ g(\gamma)\rangle, \langle\gamma,\ \alpha\rangle, \langle U,\ \alpha\rangle\}(f(g(\alpha), \beta, g(\alpha), \gamma, U)) = f(g(\beta), g(\gamma), g(\beta), \alpha, \alpha) = \boldsymbol{\tau}$;
2. $\bar{\varsigma}_1(T) = \bar{\varsigma}_1(\{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}) = \{\langle\alpha,\ b\rangle, \langle\beta,\ a\rangle, \langle\gamma,\ g(a)\rangle\}$;
3. $\bar{\varsigma}_1(T)(\boldsymbol{\tau}) = \{\langle\alpha,\ b\rangle, \langle\beta,\ a\rangle, \langle\gamma,\ g(a)\rangle\}(f(g(\beta), g(\gamma), g(\beta), \alpha, \alpha)) = f(g(a), g(g(a)), g(a), b, b) = \boldsymbol{\tau}_1$;
4. $\bar{\varsigma}_2(T) = \bar{\varsigma}_2(\{\langle\alpha,\ \langle b,\ a\rangle\rangle, \langle\beta,\ \langle a,\ b\rangle\rangle, \langle\gamma,\ \langle g(a),\ h(b)\rangle\rangle\}) = \{\langle\alpha,\ a\rangle, \langle\beta,\ b\rangle, \langle\gamma,\ h(b)\rangle\}$;
5. $\bar{\varsigma}_2(T)(\boldsymbol{\tau}) = \{\langle\alpha,\ a\rangle, \langle\beta,\ b\rangle, \langle\gamma,\ h(b)\rangle\}(f(g(\beta), g(\gamma), g(\beta), \alpha, \alpha)) = f(g(b), g(h(b)), g(b), a, a) = \boldsymbol{\tau}_2$. □

We must show that lub' and lub compute the same result $\boldsymbol{\tau}$.

Lemma 21 For all $\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}, \boldsymbol{\tau}', \boldsymbol{\tau}'' \in \mathbf{T}^{\nu}, T_0, T, T'' \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^{\nu} \times \mathbf{T}^{\nu})$, and $\vartheta_0, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^{\nu}$, if $\langle \boldsymbol{\tau}, T, \vartheta' \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ and $\langle \boldsymbol{\tau}'', T'' \rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ then $\boldsymbol{\tau} = \boldsymbol{\tau}''$ and $T = T''$. □

Proof of Lemma 21 Any execution trace of $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ can be abstracted into an execution trace of $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ simply by ignoring the input ϑ_0, the resulting substitution ϑ', ignoring the program point (17.a) and mapping (17.2a), …, (17.5a) and (17.2b), …, (17.5b) to the program point (48.68.2), …, (48.68.5). The proof is by induction on the calls to lub and lub′ which are synchronous in the two traces. The point is that the result $\langle \boldsymbol{\tau}, T \rangle$ of a call $\langle \boldsymbol{\tau}, T, \vartheta' \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ does not depend during its computation on the parameters $\boldsymbol{\tau}'$, and ϑ_0. An exception is the test (17.a) but the two alternative yield the same result. (17.2a), …, (17.4a) is identical to (48.68.2), …, (48.68.4) while, by induction on the sequence of calls to lub′ (17.2b), …, (17.4b) is abstracted to that of (48.68.2), …, (48.68.4). It follows that $\langle \boldsymbol{\tau}, T \rangle$ at (48.68.12) is equal to $\langle \boldsymbol{\tau}, T \rangle$ at (17.14). □

The following Lemma 22 proves the well-typing of algorithm lub′.

Lemma 22 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_0', \boldsymbol{\tau}' \in \mathbf{T}^{\nu}$, $T_0 \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^{\nu} \times \mathbf{T}^{\nu})$, and $\vartheta_0, \vartheta_1, \vartheta_2 \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^{\nu}$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}_0', \varepsilon)$ with hypothesis $\vartheta_1(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$, then the case analysis in the definition of lub′ is complete (i.e., there is no missing case) and $\exists \gamma \in \mathbb{V}_{\mathfrak{t}} \mathrel{.} \boldsymbol{\tau}' = \gamma$ at (17.6) and (17.8). □

Proof of Lemma 22 Notice that Lemmata 11, 14, and 16 are valid for lub′ since they do not involve the extra parameters $\boldsymbol{\tau}'$, ϑ_0 or result ϑ'. The proof is by case analysis.

- For (17.1), the only possible cases for $\boldsymbol{\tau}'$ are (17.a) and (17.b), by definition (48.2) of terms with variables.
- For (17.6) and (17.8), the test (17.1) is false so, by the preinvariant of Lemma 11 and def. (48.2) of terms with variables, at least one $\boldsymbol{\tau}_j$, $j = 1, 2$ of $\boldsymbol{\tau}_1$ or $\boldsymbol{\tau}_2$ is a variable. Then $\boldsymbol{\tau}'$ must be a variable since otherwise $\boldsymbol{\tau}' = g(\boldsymbol{\tau}_1', \ldots, \boldsymbol{\tau}_m')$ so that it is impossible that $\vartheta_j(\boldsymbol{\tau}') = \boldsymbol{\tau}_j$ be a variable. □

The following Lemma 23 shows that variables recorded in T_0 are for non-matching subterms only.

Lemma 23 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \in \mathbf{T}^{\nu}$ and $T_0 \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^{\nu} \times \mathbf{T}^{\nu})$, if $\mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0)$ is (recursively) called from the main call $\mathsf{lub}(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing)$, then for all $\boldsymbol{\tau}_1', \boldsymbol{\tau}_1'^1, \ldots, \boldsymbol{\tau}_1'^n, \boldsymbol{\tau}_2', \boldsymbol{\tau}_2'^1, \ldots, \boldsymbol{\tau}_2'^n \in \mathbf{T}^{\nu}$,

$$\text{if } \exists f \in \mathbf{F}_n \mathrel{.} \boldsymbol{\tau}_1' = f(\boldsymbol{\tau}_1'^1, \ldots, \boldsymbol{\tau}_1'^n) \wedge \boldsymbol{\tau}_2' = f(\boldsymbol{\tau}_2'^1, \ldots, \boldsymbol{\tau}_2'^n) \text{ then } \forall \beta \in \mathsf{dom}(T_0) \mathrel{.} T_0(\beta) \neq \langle \boldsymbol{\tau}_2', \boldsymbol{\tau}_1' \rangle.$$

□

Proof of Lemma 23 Let us prove the contraposition, that is "if $\exists \beta \in \mathsf{dom}(T_0) \,.\, T_0(\beta) = \langle \boldsymbol{\tau}'_2,\ \boldsymbol{\tau}'_1 \rangle$ then $\forall f \in \mathbf{F}_n \,.\, \boldsymbol{\tau}'_1 \neq f({\boldsymbol{\tau}'_1}^1, \ldots, {\boldsymbol{\tau}'_1}^n) \vee \boldsymbol{\tau}'_2 \neq f({\boldsymbol{\tau}'_2}^1, \ldots, {\boldsymbol{\tau}'_2}^n)$".

The proof is by induction on the sequence of calls to lub and Lemma 23 is obviously true for the initial value of $T_0 = \varnothing$. Then observe that the only modification to the parameter T_0 in calls to lub is (48.68.9) for which (48.68.1) is false so that the returned T' is $\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0]$ with $\neg(\boldsymbol{\tau}_1 = f(\boldsymbol{\tau}_1^1, \ldots, \boldsymbol{\tau}_1^n) \wedge \boldsymbol{\tau}_2 = f(\boldsymbol{\tau}_2^1, \ldots, \boldsymbol{\tau}_2^n))$. This property is preserved by the recursive calls (17.2a) to (17.4a) for T_n returned at (17.5a) as well as for the unmodified T_0 returned at (17.7). By induction, Lemma 23 holds for all calls from the main call (17.14). $\square$

Lemma 24 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}'_0, \boldsymbol{\tau}, \boldsymbol{\tau}' \in \mathbf{T}^\nu$, $T_0, T \in \mathbb{V}_{\mathfrak{t}} \nrightarrow (\mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_1^0 \wedge \vartheta_2(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_2^0$ and returns $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle$, then

$$(\exists \beta \in \mathsf{dom}(T_0) \,.\, T_0(\beta) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle \wedge \boldsymbol{\tau}' = \gamma) \Rightarrow (\gamma \in \mathsf{dom}(\vartheta_0) \wedge \vartheta_0(\gamma) = \beta) \qquad \square$$

Proof of Lemma 24 We prove the stronger property that the following preinvariant and postinvariant do hold for any call $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$.

$$\begin{array}{ll} \text{preinvariant} & (\exists \beta \in \mathsf{dom}(T_0) \,.\, T_0(\beta) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle \wedge \boldsymbol{\tau}' = \gamma) \Rightarrow (\gamma \in \mathsf{dom}(\vartheta_0) \wedge \vartheta_0(\gamma) = \beta) \\ \text{postinvariant} & (\exists \beta \in \mathsf{dom}(T) \,.\, T(\beta) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle \wedge \boldsymbol{\tau}' = \gamma) \Rightarrow (\gamma \in \mathsf{dom}(\vartheta') \wedge \vartheta'(\gamma) = \beta) \end{array} \tag{25}$$

The proof is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

- For the basis, the preinvariant of (25) holds vacuously at the first call (17.14) since $T_0 = \varnothing$;
- For the induction step, we proceed by case analysis.
  - In case (17.5a), there is no recursive call to lub' and, by Lemma 23, the premiss of the postinvariant of (25) is ff so it does hold vacuously.
  - In case (17.5b), the first recursive call at (17.2a) satisfies the preinvariant because this preinvariant is assumed to hold for the intermediate call at (17).

    In case $n = 0$, this is also the postinvariant.

    Otherwise $n > 0$. Assume, by recurrence hypothesis, that the preinvariant holds before the call $\langle \boldsymbol{\tau}^i,\ T_i,\ \vartheta_i \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1^i, \boldsymbol{\tau}_2^n, T_{i-1}, \boldsymbol{\tau}'_i, \vartheta_{i-1})$. Then, by induction hypothesis on the sequence of calls to lub', the postinvariant (25) holds for T_i and ϑ_i, which is the preinvariant of the next recursive call, if any.

    It follows, by recurrence, that the postinvariant of (25) holds at (17.5b) for T_n and ϑ_n.
  - In case (17.7), we know by the test (17.6) and Lemma 22 that $\exists \beta \in \mathsf{dom}(T_0) \,.\, T_0(\beta) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle \wedge \boldsymbol{\tau}' = \gamma$ so by the preinvariant $\gamma \in \mathsf{dom}(\vartheta_0)$ and $\vartheta_0(\gamma) = \beta$. Since $T = T_0$ and $\vartheta' = \vartheta_0$, we have $\gamma \in \mathsf{dom}(\vartheta') \wedge \vartheta'(\gamma) = \beta$;

– In case (17.9), $\vartheta' = \beta[\gamma \leftarrow \vartheta_0]$, which implies the postinvariant (25). □

Let us prove the converse of Lemma 24.

Lemma 26 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_0', \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}_0', \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$ and returns $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle$, then

$$\forall \beta, \gamma \in \mathbb{V}_{\mathfrak{t}} \,.\, (\gamma \in \mathsf{dom}(\vartheta_0) \wedge \vartheta_0(\gamma) = \beta) \Rightarrow (\beta \in \mathsf{dom}(T_0)). \qquad \square$$

Proof of Lemma 26 We prove the stronger property that the following preinvariant and postinvariant do hold for any call $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$.

$$\begin{array}{ll} \text{preinvariant} & \forall \beta, \gamma \in \mathbb{V}_{\mathfrak{t}} \,.\, (\gamma \in \mathsf{dom}(\vartheta_0) \wedge \vartheta_0(\gamma) = \beta) \Rightarrow (\beta \in \mathsf{dom}(T_0)) \\ \text{postinvariant} & \forall \beta, \gamma \in \mathbb{V}_{\mathfrak{t}} \,.\, (\gamma \in \mathsf{dom}(\vartheta') \wedge \vartheta'(\gamma) = \beta) \Rightarrow (\beta \in \mathsf{dom}(T)) \end{array} \tag{27}$$

The proof is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

- For the basis, $\vartheta_0 = \boldsymbol{\varepsilon}$ so $\mathsf{dom}(\vartheta_0) = \varnothing$ so the preinvariant (27) holds vacuously;
- The induction step is by case analysis.
  - In case (17.5a), there is no recursive call to lub' and $\vartheta' = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0]$. So if $\alpha \in \mathsf{dom}(\vartheta') \setminus \{\gamma\}$ then the postinvariant follows from the preinvariant. For $\gamma \in \mathsf{dom}(\vartheta')$, we have $\vartheta'(\gamma) = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n) \notin \mathbb{V}_{\mathfrak{t}}$ so that the postondition holds vacuously;
  - In case (17.5b), the preinvariant of the first recursive call (17.2a) holds by the preinvariant of (27) on the main call (17). Assuming the preinvariant holds for a following recursive call, the postinvariant holds by induction on the sequence of calls to lub', which is also the preinvariant of the next call. By recurrence the postinvariant of (27) holds for $\vartheta' = \vartheta_n$ and $T = T_n$ after the last call at (17.5b);
  - In case (17.7), we have $\gamma \in \mathsf{dom}(\vartheta') \wedge \vartheta'(\gamma) = \beta$ so the preinvariant (27) on the intermediate call trivially implies the postinvariant;
  - In case (17.9), $T = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0]$ and $\vartheta' = \beta[\gamma \leftarrow \vartheta_0]$.
    If $\alpha \in \mathsf{dom}(\vartheta') \setminus \{\gamma\}$ and $\vartheta'(\alpha) = \beta'$ then $\alpha \in \mathsf{dom}(\vartheta_0)$ and $\vartheta_0(\alpha) = \beta'$ then, by the preinvariant on the intermediate call, $\beta' \in \mathsf{dom}(T_0) = \mathsf{dom}(T)$.
    Otherwise, for $\gamma \in \mathsf{dom}(\vartheta')$, we have $\vartheta'(\gamma) = \beta[\gamma \leftarrow \vartheta_0](\gamma) = \beta$ with $\beta \in \mathsf{dom}(\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0]) = \mathsf{dom}(T)$. □

The next Lemma 28 shows how the term variables are used.

Lemma 28 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_0', \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_t \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1^0, \vartheta_2^0, \vartheta' \in \mathbb{V}_t \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}_0', \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$ and returns $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle$, then

$$\begin{array}{ll} \text{preinvariant} & \mathsf{vars}[\![\vartheta_0(\mathbb{V}_t)]\!] \subseteq \mathsf{dom}(T_0) \\ \text{postinvariant} & \mathsf{vars}[\![\vartheta'(\mathbb{V}_t)]\!] \subseteq \mathsf{dom}(T) \end{array} \tag{29}$$

(where $\vartheta_0(S) = \{\vartheta_0(\alpha) \mid \alpha \in S\}$ and $\mathsf{vars}[\![S]\!] = \bigcup\{\mathsf{vars}[\![\boldsymbol{\tau}]\!] \mid \boldsymbol{\tau} \in S\}$.) □

Proof of Lemma 28 The proof is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

- For the first call at (17.14), $\vartheta_0 = \boldsymbol{\varepsilon}$ so $\mathsf{vars}[\![\vartheta_0(\mathbb{V}_t)]\!] = \mathsf{vars}[\![\varnothing]\!] = \varnothing \subseteq \mathsf{dom}(T_0)$;
- Otherwise the preinvariant of (29) holds for T_0 and ϑ_0 at the first recursive call (17.2b). Assume, by induction hypothesis, that $\mathsf{vars}[\![\vartheta_{i-1}(\mathbb{V}_t)]\!] \subseteq \mathsf{dom}(T_{i-1})$ before the i^{th} call (17.2b),…, (17.4b), $i \in [1, n]$. By induction hypothesis on the sequence of calls to lub', we have $\mathsf{vars}[\![\vartheta_i(\mathbb{V}_t)]\!] \subseteq \mathsf{dom}(T_i)$ after that call, which is also the preinvariant of the next call, if any. By recurrence, $\mathsf{vars}[\![\vartheta'(\mathbb{V}_t)]\!] = \mathsf{vars}[\![\vartheta_n(\mathbb{V}_t)]\!] \subseteq \mathsf{dom}(T_n) = \mathsf{dom}(T)$ in case the call (17) to lub' terminates at (17.5b);
- If lub' terminates at (17.5a), there are two cases.
  - $\mathsf{vars}[\![\vartheta'(\{\gamma\})]\!] = \mathsf{vars}[\![f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0](\{\gamma\})]\!] = \mathsf{vars}[\![f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)]\!] = \bigcup_{i=1}^n \mathsf{vars}[\![\boldsymbol{\tau}^i]\!]$. By Lemma 11 and 21, we have $\mathsf{vars}[\![\boldsymbol{\tau}^i]\!] \subseteq \mathsf{dom}(T_i)$, $i = 1, \ldots, n$ and $\mathsf{dom}(T_i) \subseteq \mathsf{dom}(T_n)$ so that $\bigcup_{i=1}^n \mathsf{vars}[\![\boldsymbol{\tau}^i]\!] \subseteq \bigcup_{i-1}^n \mathsf{dom}(T_i) \subseteq \mathsf{dom}(T_n) = \mathsf{dom}(T)$;
  - $\mathsf{vars}[\![\vartheta'(\mathbb{V}_t \setminus \{\gamma\})]\!] = \mathsf{vars}[\![f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0](\mathbb{V}_t \setminus \{\gamma\})]\!] = \mathsf{vars}[\![\vartheta_0(\mathbb{V}_t \setminus \{\gamma\})]\!] \subseteq \mathsf{vars}[\![\vartheta_0(\mathbb{V}_t)]\!]$ which, by the preinvariant (29), is included in $\mathsf{dom}(T_0)$. By Lemma 11 and 21, $\mathsf{dom}(T_{i=1}) \subseteq \mathsf{dom}(T_i)$, $i = 1, \ldots, n$ so that, by transitivity, $\mathsf{dom}(T_0) \subseteq \mathsf{dom}(T_n) = \mathsf{dom}(T)$. Therefore $\mathsf{vars}[\![\vartheta'(\mathbb{V}_t \setminus \{\gamma\})]\!] \subseteq \mathsf{dom}(T)$;
  - Since $\vartheta'(\mathbb{V}_t) = \vartheta'(\{\gamma\}) \cup \vartheta'(\mathbb{V}_t \setminus \{\gamma\})$, we conclude that $\mathsf{vars}[\![\vartheta'(\mathbb{V}_t)]\!] = \mathsf{vars}[\![\vartheta'(\{\gamma\}) \cup \vartheta'(\mathbb{V}_t \setminus \{\gamma\})]\!] = \mathsf{vars}[\![\vartheta'(\{\gamma\})]\!] \cup \mathsf{vars}[\![\vartheta'(\mathbb{V}_t \setminus \{\gamma\})]\!] \subseteq \mathsf{dom}(\vartheta') \cup \mathsf{dom}(\vartheta') = \mathsf{dom}(\vartheta')$; □
- If lub' terminates at (17.7) then the postinvariant directly follows from the preinvariant of (29) since $T = T_0$ and $\vartheta' = \vartheta_0$;
- Finally, if lub' terminates at (17.9), there are two subcases.
  - We have $\mathsf{vars}[\![\vartheta'(\{\gamma\})]\!] = \mathsf{vars}[\![\beta[\gamma \leftarrow \vartheta_0](\{\gamma\})]\!] = \mathsf{vars}[\![\{\beta\}]\!] = \{\beta\} \subseteq \mathsf{dom}(\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0]) = \mathsf{dom}(T)$;

– Moreover $\mathsf{vars}[\![\vartheta'(\mathbb{V}_{\mathfrak{t}}\setminus\{\gamma\})]\!] = \mathsf{vars}[\![\beta[\gamma \leftarrow \vartheta_0](\mathbb{V}_{\mathfrak{t}}\setminus\{\gamma\})]\!] = \mathsf{vars}[\![\vartheta_0(\mathbb{V}_{\mathfrak{t}}\setminus\{\gamma\})]\!] \subseteq \mathsf{vars}[\![\vartheta_0(\mathbb{V}_{\mathfrak{t}})]\!] \subseteq \mathsf{dom}(T_0)$, by the preinvariant of (29). But $\mathsf{dom}(T_0) \subseteq \mathsf{dom}(T_0) \cup \{\beta\} = \mathsf{dom}(\langle\boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2\rangle[\beta \leftarrow T_0]) = \mathsf{dom}(T)$, proving the postinvariant of vars-codom-substitution0 by transitivity;

– We conclude since vars preserves joins. □

The following series of lemmata aims at proving that the substitution built by lub' is the one allowing us to prove that lub returns the least common generalization.

Lemma 30 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_0', \boldsymbol{\tau}' \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1^0, \vartheta_2^0, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}_0', \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$ and returns $\langle\boldsymbol{\tau},\ T,\ \vartheta'\rangle$, then

$$\vartheta_1^0(\boldsymbol{\tau}') = \boldsymbol{\tau}_1 \wedge \vartheta_2^0(\boldsymbol{\tau}') = \boldsymbol{\tau}_2. \tag{31}$$ □

Proof of Lemma 30 For the first call at (17.14), (31) holds by the hypothesis $\vartheta_1^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$ on the actual parameters. Assume that $\vartheta_j^0(\boldsymbol{\tau}') = \boldsymbol{\tau}_j$, $j = 1, 2$ before an intermediate call (17). Then (31) holds before the recursive calls (17.2b), …, (17.4b) since the induction hypothesis $\vartheta_j^0(\boldsymbol{\tau}') = \boldsymbol{\tau}_j$, $\boldsymbol{\tau}' = f(\boldsymbol{\tau}_1', \ldots, \boldsymbol{\tau}_n')$ by the test (17.a) which is false, $\boldsymbol{\tau}_j = f(\boldsymbol{\tau}_j^1, \ldots, \boldsymbol{\tau}_j^n)$ by the test (17.1) which is true, and (48.30) imply that $\vartheta_j^0(\boldsymbol{\tau}') = \vartheta_j^0(f(\boldsymbol{\tau}_1', \ldots, \boldsymbol{\tau}_n')) = f(\vartheta_j^0(\boldsymbol{\tau}_1'), \ldots, \vartheta_j^0(\boldsymbol{\tau}_n')) = f(\boldsymbol{\tau}_j^1, \ldots, \boldsymbol{\tau}_j^n) = \boldsymbol{\tau}_j$ and therefore $\vartheta_j^0(\boldsymbol{\tau}_i') = \boldsymbol{\tau}_j^i$, $j = 1, \ldots, n$. We conclude by induction on the sequence of calls to lub'. □

Lemma 32 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}_0', \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1^0, \vartheta_2^0, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}_0', \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_1^0 \wedge \vartheta_2^0(\boldsymbol{\tau}_0') = \boldsymbol{\tau}_2^0$ and returns $\langle\boldsymbol{\tau},\ T,\ \vartheta'\rangle$, then

$$\begin{array}{ll} \text{preinvariant} & \forall j = 1,2\ .\ \forall \alpha \in \mathsf{dom}(\vartheta_0)\ .\ \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_0)(\vartheta_0(\alpha)) \\ \text{postinvariant} & \forall j = 1,2\ .\ \forall \alpha \in \mathsf{dom}(\vartheta')\ .\ \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T)(\vartheta'(\alpha)) \wedge \bar{\varsigma}_j(T)(\boldsymbol{\tau}) = \boldsymbol{\tau}_j \end{array} \tag{33}$$ □

Proof of Lemma 32 Notice again that Lemma 11, 14, and 16 are valid for lub' since they do not involve the extra parameters $\boldsymbol{\tau}', \vartheta_0$, or result ϑ'. It follows, by Lemma 14, that the postinvariant of (33) satisfies $\bar{\varsigma}_j(T)(\boldsymbol{\tau}) = \boldsymbol{\tau}_j$, $j = 1, 2$. The proof of (33) is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

- For the basis, the preinvariant (33) holds vacuously for the main call (17.14) since $\vartheta_0 = \boldsymbol{\varepsilon}$ so $\mathsf{dom}(\vartheta_0) = \varnothing$;

- Assume that the preinvariant (33) holds before any intermediate call (17) of lub'. We must show that it holds before all recursive calls (17.2b), …, (17.4b).

By hypothesis on the intermediate call, we have $\forall j = 1, 2 \;.\; \forall \alpha \in \mathsf{dom}(\vartheta') \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_0)(\vartheta'(\alpha))$ at the first recursive call (17.2b).

Assume that $\forall j = 1, 2 \;.\; \forall \alpha \in \mathsf{dom}(\vartheta_{i-1}) \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_{i-1})(\vartheta_{i-1}(\alpha))$ before the i^{th} recursive call. By induction on the sequence of calls to lub', the postinvariant of (33) holds. Therefore we have $\forall j = 1, 2 \;.\; \forall \alpha \in \mathsf{dom}(\vartheta_i) \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_i)(\vartheta_i(\alpha))$ before the $i + 1^{\text{th}}$ call. By recurrence, all recursive calls do satisfy (33).

We must also show that the intermediate call satisfies the postinvariant of (33). We proceed by cases.

- In case (17.5b), we have $T = T_n$ and ϑ_n which satisfy the postinvariant of (33), as shown above.
- In case (17.5a), the postinvariant is $\forall j = 1, 2 \;.\; \forall \alpha \in \mathsf{dom}(f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0]) \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_n)(f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0](\alpha))$.
  - If $\alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\}$, we must show that $\vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_n)(\vartheta_0(\alpha))$.
    By Lemma 11, $\forall \alpha \in \mathsf{dom}(T_{i-1}) \;.\; T_{i-1}(\alpha) = T_i(\alpha)$, $i = 1, \dots, n$ so that, by transitivity, $\forall \alpha \in \mathsf{dom}(T_0) \;.\; T_0(\alpha) = T_n(\alpha)$. Therefore, by (13), for all $\beta \in \mathsf{dom}(T_0)$, $\bar{\varsigma}_j(T_0)\beta \triangleq \mathsf{let}\ \langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle = T_0(\beta)\ \mathsf{in}\ \boldsymbol{\tau}_j = \mathsf{let}\ \langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle = T_n(\beta)\ \mathsf{in}\ \boldsymbol{\tau}_j = \bar{\varsigma}_j(T_n)\beta$. By Lemma 28, $\mathsf{vars}[\![\vartheta_0(\mathbb{V}_{t})]\!] \subseteq \mathsf{dom}(T_0)$ so, in particular, $\forall \alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\} \;.\; \mathsf{vars}[\![\vartheta_0(\alpha)]\!] \subseteq \mathsf{dom}(T_0)$. This implies that $\forall \alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\} \;.\; \forall \beta \in \mathsf{vars}[\![\vartheta_0(\alpha)]\!] \;.\; \bar{\varsigma}_j(T_0)\beta = \bar{\varsigma}_j(T_n)\beta$. By (48.30) and (48.30), we infer that $\forall \alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\} \;.\; \bar{\varsigma}_j(T_0)\boxtimes_{\Theta}(\boxtimes) = \bar{\varsigma}_j(T_n)\boxtimes_{\Theta}(\boxtimes)$. By the preinvariant of (33), we have $\forall \alpha \in \mathsf{dom}(\vartheta_0) \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_0)(\vartheta_0(\alpha))$. Therefore, by transitivity, $\vartheta_j^0(\alpha) = \bar{\varsigma}_j(T_n)(\vartheta_0(\alpha))$.
  - Otherwise $\alpha = \gamma$, in which case we must show that $\vartheta_j^0(\gamma) = \bar{\varsigma}_j(T_n)(f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n))$. By Lemma 30, (48.42) of Lemma 48.40, and (17.5a), we have $\vartheta_j^0(\gamma) = \vartheta_j^0(\boldsymbol{\tau}') = \boldsymbol{\tau}_j = \bar{\varsigma}_j(T)(\boldsymbol{\tau}) = \bar{\varsigma}_j(T)(f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n))$.
- In case (17.7), the postinvariant of (31) immediately follows from the preinvariant since $T = T_0$ and $\vartheta' = \vartheta_0$;
- In case (17.9), we must show that $\forall j = 1, 2 \;.\; \forall \alpha \in \mathsf{dom}(\beta[\gamma \leftarrow \vartheta_0]) \;.\; \vartheta_j^0(\alpha) = \bar{\varsigma}_j(\langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0])(\beta[\gamma \leftarrow \vartheta_0](\alpha))$. There are two cases.
  - If $\alpha = \gamma$ then we must prove that $\vartheta_j^0(\gamma) = \bar{\varsigma}_j(\langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0])(\beta)$, that is, by (13), $\vartheta_j^0(\gamma) = \boldsymbol{\tau}_j$. It is not possible that $\gamma \in \mathsf{dom}(\vartheta_0)$ since otherwise, we would have $\forall \beta \in \mathsf{dom}(T_0) \;.\; T_0(\beta) \neq \langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle$ since the test (17.6) is $\mathtt{ff}$ and $\boldsymbol{\tau}' = \gamma \in \mathbb{V}_{t}$ by Lemma 22, which is in contradiction with (the contrapositive of) Lemma 26. Therefore $\vartheta_0(\gamma) = \gamma$ by (48.30). It follows that we have to prove that $\vartheta_j^0(\vartheta_0(\gamma)) = \boldsymbol{\tau}_j$, which directly follows from the preinvariant of (31);
  - Otherwise, $\alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\}$ and we must show that $\vartheta_j^0(\alpha) = \bar{\varsigma}_j(\langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle[\beta \leftarrow T_0])(\vartheta_0(\alpha))$. The test (17.8) implies $\beta \notin \mathsf{dom}(T_0)$ and so $\beta \notin \mathsf{vars}[\![\vartheta_0(\alpha)]\!]$ since $\mathsf{vars}[\![\vartheta_0(\mathbb{V}_{t})]\!] \subseteq \mathsf{dom}(T_0)$ by (29) of Lemma 28. Therefore, by (13), $\forall \gamma \in \mathsf{vars}[\![\vartheta_0(\alpha)]\!] \;.\; \bar{\varsigma}_j(T_0)(\gamma) =$

$\bar{\varsigma}_j(\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2\rangle[\beta \leftarrow T_0])(\gamma)$. It follows, by (48.30) and (48.30), that $\bar{\varsigma}_j(T_0)(\vartheta_0(\alpha)) = \bar{\varsigma}_j(\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2\rangle[\beta \leftarrow T_0])(\vartheta_0(\alpha))$. We conclude, by the preinvariant (31) and transitivity that $\bar{\varsigma}_j(\langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2\rangle[\beta \leftarrow T_0])(\vartheta_0(\alpha)) = \vartheta^0_j(\alpha)$. □ □

Lemma 34 For all $\boldsymbol{\tau}^0_1, \boldsymbol{\tau}^0_2, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}'_0, \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}^0_1, \boldsymbol{\tau}^0_2, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}^0_1 \wedge \vartheta_2(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}^0_2$ and returns $\langle \boldsymbol{\tau},\ T,\ \vartheta'\rangle$, then the following postinvariant holds after the call.

$$\mathsf{dom}(\vartheta') = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![\boldsymbol{\tau}']\!] \tag{35}$$ □

Proof of Lemma 34 The proof of (35) is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

Consider any intermediate call $\langle \boldsymbol{\tau}, T, \vartheta'\rangle = \mathsf{lub}'(\boldsymbol{\tau}^0_1, \boldsymbol{\tau}^0_2, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$. We proceed by case analysis of the returned values $\langle \boldsymbol{\tau},\ T,\ \vartheta'\rangle$.

- In case (17.5a), we have $\mathsf{dom}(\vartheta') = \mathsf{dom}(f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0]) = \mathsf{dom}(\vartheta_0) \cup \{\gamma\} = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![\boldsymbol{\tau}']\!]$ since $\vartheta' = \gamma$ by the test (17.a);
- In case (17.5b), we have $\mathsf{dom}(\vartheta_i) = \mathsf{dom}(\vartheta_{i-1}) \cup \mathbb{vars}[\![\boldsymbol{\tau}^i]\!]$, $i = 1, \ldots, n$, by induction hypothesis on the sequence of calls to lub'. It follows that $\mathsf{dom}(\vartheta') = \mathsf{dom}(\vartheta_n) = \mathsf{dom}(\vartheta_0) \cup \bigcup_{i=1}^n \mathbb{vars}[\![\boldsymbol{\tau}^i]\!] = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)]\!] = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![\boldsymbol{\tau}']\!]$;
- In case (17.7), we have $\vartheta' = \beta[\gamma \leftarrow \vartheta_0]$ so $\mathsf{dom}(\vartheta') = \mathsf{dom}(\vartheta_0) \cup \{\gamma\} = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![\boldsymbol{\tau}']\!]$ since $\boldsymbol{\tau}' = \gamma$ by Lemma 22;
- Finally, in case (17.9), $\mathsf{dom}(\vartheta') = \mathsf{dom}(\beta[\gamma \leftarrow \vartheta_0]) = \mathsf{dom}(\vartheta_0) \cup \{\gamma\} = \mathsf{dom}(\vartheta_0) \cup \mathbb{vars}[\![\boldsymbol{\tau}']\!]$ since $\boldsymbol{\tau}' = \gamma$ by Lemma 22. □ □

Lemma 36 For all $\boldsymbol{\tau}^0_1, \boldsymbol{\tau}^0_2, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}'^0, \boldsymbol{\tau}^{n-1}, \boldsymbol{\tau}^n, \boldsymbol{\tau}^{m-1}.\boldsymbol{\tau}^m \in \mathbf{T}^\nu$, $T_n, T_m \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, consider any computation trace for the main call $\mathsf{lub}'(\boldsymbol{\tau}^0_1, \boldsymbol{\tau}^0_2, \varnothing, \boldsymbol{\tau}'^0, \boldsymbol{\varepsilon}, \varnothing)$ at (17.14) with hypothesis $\vartheta_1(\boldsymbol{\tau}'^0) = \boldsymbol{\tau}^0_1 \wedge \vartheta_2(\boldsymbol{\tau}'^0) = \boldsymbol{\tau}^0_2$. Assume that in this computation trace, a call $\langle \boldsymbol{\tau}^k,\ T_k\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{k-1})$ is followed by a later call $\langle \boldsymbol{\tau}^m,\ T_m\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{m-1})$ with the same parameters $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$. Then $\boldsymbol{\tau}^k = \boldsymbol{\tau}^m$.

By Lemma 21, this also holds for calls to lub' independently of the other two parameters. □

Proof of Lemma 36 By (12) in Lemma 11, Lemma 21, (17.2a), …, (17.4a), and (17.2b), …, (17.4b) and recurrence, the successive calls of lub and lub' in the trace have parameters T_i and result T_{i+1}

with increasing domains and preservation of the previous values so that $\forall\alpha \in \mathsf{dom}(T_k)\ .\ T_k(\alpha) = T_m(\alpha)$.

To prove that $\boldsymbol{\tau}^k = \boldsymbol{\tau}^m$, we consider the calls $\langle\boldsymbol{\tau}^k, T_k\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{k-1})$ and the later $\langle\boldsymbol{\tau}^m, T_m\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{m-1})$ to lub (by Lemma 21, the reasoning is the same for lub'). The only possible executions are the following.

- If one execution follows the true branch of (48.68.1), so does the other since they have the same parameters. By recurrence and induction on the sequence of calls for (48.68.2), …, (48.68.4) with $\forall\alpha \in \mathsf{dom}(T_{i-1})\ .\ T_{i-1}(\alpha) = T_i(\alpha)$, $i = 1, \ldots, n$, we have $\boldsymbol{\tau}^k = f(\boldsymbol{\tau}^{1^k}, \ldots, \boldsymbol{\tau}^{n^k}) = f(\boldsymbol{\tau}^{1^m}, \ldots, \boldsymbol{\tau}^{nm}) = \boldsymbol{\tau}^m$;
- If both calls go through (48.68.7) then obviously $\boldsymbol{\tau}^k = \boldsymbol{\tau}^m = \beta$;
- Both calls cannot go through (48.68.9) since the first ones (which is $\langle\boldsymbol{\tau}^k, T_k\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{k-1})$) that goes through (48.68.9) will add β to the $\mathsf{dom}(T_k) \subseteq \mathsf{dom}(T_{m-1})$;
- If $\langle\boldsymbol{\tau}^k, T_k\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{k-1})$ goes through (48.68.9) then the call $\langle\boldsymbol{\tau}^m, T_m\rangle = \mathsf{lub}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_{m-1})$ must go through (48.68.7) since $\mathsf{dom}(T_k) \subseteq \mathsf{dom}(T_{m-1})$ with $\beta \in \mathsf{dom}(T_{m-1})$ so that $\boldsymbol{\tau}^k = \boldsymbol{\tau}^m = \beta$. □ □

Lemma 37 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}'_0, \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_1^0 \wedge \vartheta_2(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_2^0$ and returns $\langle\boldsymbol{\tau}, T, \vartheta'\rangle$, then the following postinvariant holds after the call.

$$\forall\alpha \in \mathsf{dom}(\vartheta_0)\ .\ \vartheta_0(\alpha) = \vartheta'(\alpha) \tag{38}$$ □

Proof of Lemma 37 The proof of (35) is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

Consider any intermediate call $\langle\boldsymbol{\tau}, T, \vartheta'\rangle = \mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$. We proceed by case analysis of the returned values $\langle\boldsymbol{\tau}, T, \vartheta'\rangle$.

- In case (17.5a), we have $\forall\alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\}\ .\ \vartheta_0(\alpha) = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0](\alpha) = \vartheta'(\alpha)$.

  It may also be that $\gamma \in \mathsf{dom}(\vartheta_0)$. Since the main call starts with $\boldsymbol{\varepsilon}$ and by (35) the domain of ϑ_0 grows along the calls, there must be a previous call that added γ to $\mathsf{dom}(\vartheta_0)$. At that previous call, say $\mathsf{lub}'(\boldsymbol{\tau}_1^k, \boldsymbol{\tau}_2^k, T_0^k, \boldsymbol{\tau}'^k, \vartheta_0^k)$, we had $\boldsymbol{\tau}'^k = \gamma$ since (17.5a) and (17.9) are the two only cases where the domain of ϑ_0^k is extending with γ. By the initial hypothesis and (31) of Lemma 30, $\vartheta_j^0(\boldsymbol{\tau}'^k) = \vartheta_j^0(\gamma) = \boldsymbol{\tau}_j^k$. At the current call $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ where $\boldsymbol{\tau}'_0 = \gamma$, we also have, by the initial hypothesis and (31) of Lemma 30, that $\vartheta_j^0(\boldsymbol{\tau}') = \vartheta_j^0(\gamma) = \boldsymbol{\tau}_j$. By transitivity $\boldsymbol{\tau}_j^k = \boldsymbol{\tau}_j$. So the current and previous calls had the same first two parameters. It follows, by Lemma 36, that they have the same results. This implies that necessarily, $\vartheta_0(\gamma) = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)$.

- In case (17.5b), we have $\forall \alpha \in \mathsf{dom}(\vartheta_{i-1})\ .\ \vartheta_{i=1}(\alpha) = \vartheta_i(\alpha), i = 1, \ldots, n$, by induction hypothesis on the sequence of calls to lub'. It follows, by transitivity, that $\forall \alpha \in \mathsf{dom}(\vartheta_0)\ .\ \vartheta_0(\alpha) = \vartheta_n(\alpha) = \vartheta'(\alpha)$;

- In case (17.7), for all $\alpha \in \mathsf{dom}(\vartheta_0) \setminus \{\gamma\}$, we have $\vartheta_0(\alpha) = \beta[\gamma \leftarrow \vartheta_0](\alpha) = \vartheta'(\alpha)$. We may also have $\gamma \in \mathsf{dom}(\vartheta_0)$, in which case the test (17.6), Lemma 22, and Lemma 24 imply that $\vartheta_0(\gamma) = \beta$ so $\vartheta_0(\gamma) = \beta = \beta[\gamma \leftarrow \vartheta_0](\gamma) = \vartheta'(\gamma)$;

- Finally, in case (17.9), it is not possible that $\gamma \in \mathsf{dom}(\vartheta_0)$ since otherwise, we would have $\forall \beta \in \mathsf{dom}(T_0)\ .\ T_0(\beta) \neq \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle$ since the test (17.6) is ff and $\boldsymbol{\tau}' = \gamma \in \mathbb{V}_{\mathfrak{t}}$ by Lemma 22, which is in contradiction with (the contrapositive of) Lemma 26. It follows that $\forall \alpha \in \mathsf{dom}(\vartheta_0)\ .\ \vartheta_0(\alpha) = \beta[\gamma \leftarrow \vartheta_0](\alpha) = \vartheta'(\alpha)$ since $\alpha \neq \gamma$. □ □

Lemma 39 For all $\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \boldsymbol{\tau}'_0, \boldsymbol{\tau}', \boldsymbol{\tau} \in \mathbf{T}^\nu$, $T_0, T \in \wp(\mathbb{V}_{\mathfrak{t}} \times \mathbf{T}^\nu \times \mathbf{T}^\nu)$, and $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta' \in \mathbb{V}_{\mathfrak{t}} \nrightarrow \mathbf{T}^\nu$, if $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0)$ is (recursively) called from the main call $\mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$ with hypothesis $\vartheta_1(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_1^0 \wedge \vartheta_2(\boldsymbol{\tau}'_0) = \boldsymbol{\tau}_2^0$ and returns $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle$, then the following postinvariant holds after the call.

$$\vartheta'(\boldsymbol{\tau}') = \boldsymbol{\tau} \tag{40}$$ □

Proof of Lemma 39 The proof of (40) is by induction on the sequence of calls to lub' and, for any given call, by recurrence to handle the recursive calls at (17.2b), (17.3b),…, (17.4b), and by case analysis for the conditional.

Consider any intermediate call $\langle \boldsymbol{\tau}, T, \vartheta' \rangle = \mathsf{lub}'(\boldsymbol{\tau}_1^0, \boldsymbol{\tau}_2^0, \varnothing, \boldsymbol{\tau}'_0, \boldsymbol{\varepsilon})$. We proceed by case analysis of the returned values $\langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle$.

- In case (17.5a), we have $\vartheta'(\boldsymbol{\tau}') = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0](\gamma) = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n) = \boldsymbol{\tau}$;

- In case (17.5b), we handle (17.2b), …, (17.4b) by recurrence.

  - For the basis at (17.2b), we have $\mathsf{dom}(\vartheta_1) = \mathsf{dom}(\vartheta_0) \cup \mathsf{vars}[\![\boldsymbol{\tau}'_1]\!]$ by (35) of Lemma 34, and $\vartheta_1(\boldsymbol{\tau}'_1) = \boldsymbol{\tau}^1$, by induction on the sequence of calls to lub';
  - Assume, by recurrence hypothesis, that for the i^{th} call (17.2b), …, (17.4b), $i \in [1, n[$, we have

$$\begin{gathered}\mathsf{dom}(\vartheta_i) = \mathsf{dom}(\vartheta_0) \cup \bigcup_{j=1}^{i} \mathsf{vars}[\![\boldsymbol{\tau}'_j]\!] \wedge \\ \forall j \in [1, i]\ .\ \forall \alpha \in \mathsf{dom}(\vartheta_j)\ .\ \vartheta_i(\alpha) = \vartheta_j(\alpha) \wedge \\ \forall j \in [1, i]\ .\ \vartheta_i(\boldsymbol{\tau}'_j) = \vartheta_j(\boldsymbol{\tau}'_j) = \boldsymbol{\tau}^j\end{gathered} \tag{41}$$

  - At the next $i + 1^{\text{th}}$ call, we have

    1. By (35) of Lemma 34 and recurrence hyp. (41), $\mathsf{dom}(\vartheta_{i+1}) = \mathsf{dom}(\vartheta_i) \cup \mathsf{vars}[\![\boldsymbol{\tau}'_{i+1}]\!] = \mathsf{dom}(\vartheta_0) \cup \bigcup_{j=1}^{i} \mathsf{vars}[\![\boldsymbol{\tau}'_j]\!] \cup \mathsf{vars}[\![\boldsymbol{\tau}'_{i+1}]\!] = \mathsf{dom}(\vartheta_0) \cup \bigcup_{j=1}^{i+1} \mathsf{vars}[\![\boldsymbol{\tau}'_j]\!]$;

2. By (38) of Lemma 37, we have $\forall \alpha \in \mathsf{dom}(\vartheta_i) \;.\; \vartheta_i(\alpha) = \vartheta_{i+1}(\alpha)$ so that by recurrence hyp. (41), $\forall j \in [1, i+1] \;.\; \forall \alpha \in \mathsf{dom}(\vartheta_j) \;.\; \vartheta_{i+1}(\alpha) = \vartheta_i(\alpha) = \vartheta_j(\alpha)$
3. By (1)., $\forall j \in [1, i+1] \;.\; \mathsf{vars}[\![\boldsymbol{\tau}'_j]\!] \subseteq \mathsf{dom}(\vartheta_j) \subseteq \mathsf{dom}(\vartheta_{i+1})$ and by (2)., $\forall \alpha \in \mathsf{dom}(\vartheta_j) \;.\; \vartheta_{i+1}(\alpha) = \vartheta_j(\alpha)$ so that, by (48.30) and (48.30), $\forall j \in [1, i] \;.\; \vartheta_{i+1}(\boldsymbol{\tau}'_j) = \vartheta_i(\boldsymbol{\tau}'_j) = \vartheta_j(\boldsymbol{\tau}'_j) = \boldsymbol{\tau}^j$. Moreover, $\vartheta_{i+1}(\boldsymbol{\tau}'_{i+1}) = \boldsymbol{\tau}^{i+1}$, by induction on the sequence of calls to lub'. Grouping all cases $j \in [1, i]$ and $j = i+1$ together, we have $\forall j \in [1, i+1] \;.\; \vartheta_{i+1}(\boldsymbol{\tau}'_j) = \vartheta_j(\boldsymbol{\tau}'_j) = \boldsymbol{\tau}^j$. □

By recurrence, (41) holds for $i = n$. Therefore $\vartheta'(\boldsymbol{\tau}') = \vartheta_n(f(\boldsymbol{\tau}'_1, \ldots, \boldsymbol{\tau}'_n)) = f(\vartheta_n(\boldsymbol{\tau}'_1), \ldots, \vartheta_n(\boldsymbol{\tau}'_n)) = f(\boldsymbol{\tau}^1, \ldots, \boldsymbol{\tau}^n) = \boldsymbol{\tau}$.

- In case (17.7), we have $\exists \beta \in \mathsf{dom}(T_0) \;.\; T_0(\beta) = \langle \boldsymbol{\tau}_1, \boldsymbol{\tau}_2 \rangle \wedge \boldsymbol{\tau}' = \gamma$ so that by Lemma 24, we have $\gamma \in \mathsf{dom}(\vartheta_0) \wedge \vartheta_0(\gamma) = \beta$. It follows that $\vartheta'(\boldsymbol{\tau}') = \vartheta_0(\gamma) = \beta = \boldsymbol{\tau}$.
- Finally, in case (17.9), by (17.9) and Lemma 22, we have $\vartheta'(\boldsymbol{\tau}') = \beta[\gamma \leftarrow \vartheta_0](\gamma) = \beta = \boldsymbol{\tau}$. □

Proof of Theorem 48.72 By Lemma 16, $[\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^v}$ is a $\preceq_{\simeq^v}$-upper-bound of $[\boldsymbol{\tau}_1]_{\simeq^v}$ and $[\boldsymbol{\tau}_2]_{\simeq^v}$. By Lemma 21, so is $[\mathsf{lgc}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)]_{\simeq^v}$.

Now if $[\boldsymbol{\tau}']_{\simeq^v}$ is any $\preceq_{\simeq^v}$-upper-bound of $[\boldsymbol{\tau}_1]_{\simeq^v}$ and $[\boldsymbol{\tau}_2]_{\simeq^v}$ then by Exercise 48.16, $\exists \vartheta_1, \vartheta_2 \;.\; \vartheta_1(\boldsymbol{\tau}') = \boldsymbol{\tau}_1 \wedge \vartheta_2(\boldsymbol{\tau}') = \boldsymbol{\tau}_2$, which is the precondition (17.13). It follows that the call to $\mathsf{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \varnothing, \boldsymbol{\tau}', \boldsymbol{\varepsilon}, \varnothing)$ terminates (by Lemma 16 and 21) and returns $\langle \mathsf{lgc}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2),\; T,\; \vartheta' \rangle$ such that $\vartheta'(\boldsymbol{\tau}') = \mathsf{lgc}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)$ (by (40) of Lemma 39). By Exercise 48.16, this means that $\mathsf{lgc}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2) \preceq_{\simeq^v} [\boldsymbol{\tau}']_{\simeq^v}$. This proves by Lemma 21 that $\mathsf{lgc}(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2)$ is the $\preceq_{\simeq^v}$-least upper-bound of $[\boldsymbol{\tau}_1]_{\simeq^v}$ and $[\boldsymbol{\tau}_2]_{\simeq^v}$. □

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$$
\begin{array}{ll}
\text{let rec lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, T_0, \boldsymbol{\tau}', \vartheta_0) = & (17) \\
\quad \text{if } \boldsymbol{\tau}_1 = f(\boldsymbol{\tau}_1^1, \dots, \boldsymbol{\tau}_1^n) \wedge \boldsymbol{\tau}_2 = f(\boldsymbol{\tau}_2^1, \dots, \boldsymbol{\tau}_2^n) \text{ then} & (1) \\
\quad\quad \text{if } \boldsymbol{\tau}' = \gamma \in \mathbb{V}_{\mathfrak{t}} \text{ then} & (a) \\
\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^1,\ T_1 \rangle = \text{lub}(\boldsymbol{\tau}_1^1, \boldsymbol{\tau}_2^1, T_0) \text{ in} & (2a) \\
\quad\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^2,\ T_2 \rangle = \text{lub}(\boldsymbol{\tau}_1^2, \boldsymbol{\tau}_2^2, T_1) \text{ in} & (3a) \\
\quad\quad\quad\quad\quad \dots & \dots \\
\quad\quad\quad\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^n,\ T_n \rangle = \text{lub}(\boldsymbol{\tau}_1^n, \boldsymbol{\tau}_2^n, T_{n-1}) \text{ in} & (4a) \\
\quad\quad\quad\quad\quad\quad\quad \langle f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n),\ T_n,\ f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n)[\gamma \leftarrow \vartheta_0] \rangle & (5a) \\
\quad\quad \text{else /* } \boldsymbol{\tau}' = f(\boldsymbol{\tau}_1', \dots, \boldsymbol{\tau}_n') \text{ */} & (b) \\
\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^1,\ T_1,\ \vartheta_1 \rangle = \text{lub}'(\boldsymbol{\tau}_1^1, \boldsymbol{\tau}_2^1, T_0, \boldsymbol{\tau}_1', \vartheta_0) \text{ in} & (2b) \\
\quad\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^2,\ T_2,\ \vartheta_2 \rangle = \text{lub}'(\boldsymbol{\tau}_1^2, \boldsymbol{\tau}_2^2, T_1, \boldsymbol{\tau}_2', \vartheta_1) \text{ in} & (3b) \\
\quad\quad\quad\quad\quad \dots & \dots \\
\quad\quad\quad\quad\quad\quad \text{let } \langle \boldsymbol{\tau}^n,\ T_n,\ \vartheta_n \rangle = \text{lub}'(\boldsymbol{\tau}_1^n, \boldsymbol{\tau}_2^n, T_{n-1}, \boldsymbol{\tau}_n', \vartheta_{n-1}) \text{ in} & (4b) \\
\quad\quad\quad\quad\quad\quad\quad \langle f(\boldsymbol{\tau}^1, \dots, \boldsymbol{\tau}^n),\ T_n,\ \vartheta_n \rangle & (5b) \\
\quad \text{elsif } \exists \beta \in \text{dom}(T_0)\ .\ T_0(\beta) = \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle \text{ then} \quad \text{/* } \boldsymbol{\tau}' = \gamma \in \mathbb{V}_{\mathfrak{t}} \text{ */} & (6) \\
\quad\quad \langle \beta,\ T_0,\ \vartheta_0 \rangle & (7) \\
\quad \text{else let } \beta \in \mathbb{V}_{\mathfrak{t}} \setminus \text{dom}(T_0) \text{ in} \quad \text{/* } \boldsymbol{\tau}' = \gamma \in \mathbb{V}_{\mathfrak{t}} \text{ */} & (8) \\
\quad\quad \langle \beta,\ \langle \boldsymbol{\tau}_1,\ \boldsymbol{\tau}_2 \rangle [\beta \leftarrow T_0],\ \beta[\gamma \leftarrow \vartheta_0] \rangle & (9) \\
\text{let lcg}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2) = & (10) \\
\quad \text{if } \boldsymbol{\tau}_1 = \overline{\varnothing}^{\nu} \text{ then } \boldsymbol{\tau}_2 & (11) \\
\quad \text{elsif } \boldsymbol{\tau}_2 = \overline{\varnothing}^{\nu} \text{ then } \boldsymbol{\tau}_1 & (12) \\
\quad \text{else} \quad \text{/* assume } \exists \vartheta_1, \vartheta_2\ .\ \vartheta_1(\boldsymbol{\tau}') = \boldsymbol{\tau}_1 \wedge \vartheta_2(\boldsymbol{\tau}') = \boldsymbol{\tau}_2 \text{ */} & (13) \\
\quad\quad\quad \text{let } \langle \boldsymbol{\tau},\ T,\ \vartheta' \rangle = \text{lub}'(\boldsymbol{\tau}_1, \boldsymbol{\tau}_2, \varnothing, \boldsymbol{\tau}', \boldsymbol{\varepsilon}, \varnothing) \text{ in } \boldsymbol{\tau} \quad \text{/* } \vartheta'(\boldsymbol{\tau}') = \boldsymbol{\tau} \text{ */} & (14)
\end{array}
$$

Figure 18: The modified least upper bound algorithm