J C b O i (2015) 29:308 329
DOI 10.1007/ 10878-014-9779-0

A structural transformation from p-π to MSVL

Ling Luo · Zhenhua Duan · Cong Tian · Xiaobing Wang

P b i hed i e: 7 A g 2014

Abstract Thi a e e a c a a f ai a ach f -π ce e MSVL g . T hi e d, cha e a d c ica i i i e a e de ed i MSVL. F he, ba ed he e de i i , a i g f c- i $\mathcal{F}$ hich a f b ded -π ce e i MSVL g i f ai ed. M e e, he de f he a f ai i ed. B he a f ai , -π ca ide echa i de i , a e a d if c e i e-de e de e b ea f he ech i e f MSVL. Fi a , a ca e d i gi e i a e h he a f ai ca be ed i ac ice.

Keywords R ce a geb a · Te a gic · π-ca c · MSVL · Ve i ca i

1 Introduction

R ce a geb a i a ef f ai f de ibi g a d a a i g c ica i g a d c e . F i g CCS (Mi 1980), CSP (H a e 1985) a d ACP (Be g a a d K 1985) a i d f a ia i f ce a geb a ha e bee ed f diffe e e . E ecia i h he de e e f e e c i g ech gie , π-ca c (Mi 1999; Mi e a . 1992; Sa gi gi a d

L. L · Z. D a (✉) · C. Tia · X. Wa g
ICTT a d ISN Lab, Xidia U i i , Xi'a 710071, Pe e' Re b ic f Chi a
ai : hhd a @ ai . idia .ed .c

L. L
ai : i g @ . idia .ed .c

C. Tia
ai : c ia @ ai . idia .ed .c

X. Wa g
ai : b a g@ ai . idia .ed .c

Wa a 2002) i ch a aia i ide ed i ac ice e e he c ec e bi e . H e a , i π-ca c , he e d ai f a aci a d he e ide ce i e f a a a a e a e a e i acc . Th ,i i c e ie f de i i e-de e de . -π (L a d D a 2012) i a e e i f π-ca c f ecif i g i e-de e de a ec bi e . A h gh -π ide e f a geb aic a ache ecif a d a a e c c e i e-de e de , i i ea a if he e a a ica h ea f de chec i g.

O he h ha d, jec i a gic (PTL) (D a e a . 1994; D a 1996, 2006) i a ef a f de a ibi g e e ce f a i i be ee a e i eac i e a d ff ab da echa f a i ca i . MSVL (D a e a . 2008b; Ya g e a 2010; Ya g a d D a 2008), a e ec ab e b e f PTL, i a de i g ai a d a i ca i a g age. The i de , a ai a a d a a ic a ic ha e bee a ica i e iga ed hich ide e e , i i e a d c e ie ce f a a ica f a a i ca i . M e , a i e e a f MSVL ha bee de e ed a d i ca i h e de de i g i ai a d a i ca i . Si ce MSVL i ef f de i g a d a if i g c c e i e-de e de , i i c e ie e e -π.

The ef e, i hi a e a e i a ed i e iga e h a f -π ce e i MSVL , ha e ca a e ad a age f ech i e f MSVL a if a ie f i e-de e de de ed b -π. T hi e d e e e a i g f c i $\mathcal{F}$ hich ide a c a a ai f -π ce e i c e di g MSVL . The c ib i f hi a a i h ee-f d: (1) e i ed he a i g f c i $\mathcal{F}$ a d de i i f cha e a d c ica i i i e gi e i a ab ac c f e ce a a (L a d D a 2013), a d ed a he ; (2) e i e iga ed he c i e c be ee i a ea i g a d e c c e c ; (3) e ed he d e f he a f ai .

The e f he a a i ga i ed a f . The a a d a ic f -π i b ie i d ced i Sec . 2. I Sec . 3, he a a d a ic f MSVL a e i d ced; f he , he cha e a d c ica i i i e a e f a de ed. Sec i 4 i de ed he c a a f ai f -π ce e MSVL . I Sec . 5, he d e f he a f ai i ed. A ca e d i gi e i Sec . 6. Fi a , c c i a e d a i Sec . 7.

2 p-π

-π i a e e i f π-ca c i c de i a a aci e e . Le $\mathcal{N}$ be a i iec ab e e f e , PR a c ab e e f i i , a d $\mathbb{N}$ he e f - ega i e i ega . The a f -π ce e i gi e be .

$$\pi ::= x(y) \mid \overline{x}\langle y\rangle \mid \tau \mid I_p \mid skip \mid \varepsilon$$
$$P ::= 0 \mid \pi \cdot P \mid P_1 + P_2 \mid P_1|P_2 \mid [a_1 = a_2]P \mid \nu a\ P \mid A\langle a_1, \ldots, a_n\rangle$$

he e x, y, a, a d a_i (i i a i ega 1 $n \in \mathbb{N}$) a e e a gi g $\mathcal{N}$.

The aci e π fa i ca eg ie : i a a e aci e a d i a a e. A i a a e aci e e e e ei he e di g (de ed b $\overline{x}\langle y\rangle$)

ecei i g (de ed b $x(y)$) e age, e ec i g a i e τ a i i ε. A i a aci e e e ei he I_p={$p_1 \wedge skip, \ldots, p_k \wedge skip$} $skip$. He e $p_i \in PR(1 \le i \le k$ a d $i \in \mathbb{N})$, a d $skip$ i a ecia i i dica i g a i e i . F c e ie ce e e $\tilde{p}_i$ e e e $p_i \wedge skip$ a d $\overline{x}$ (x) de e $\overline{x}\langle\rangle$ ($x()$). N e ha $\overline{x}\langle\rangle$ ($x()$) ea a aci e i h e age.

A ce (ce e e i) ca be a ce 0, a aci e g a ded ce $\pi \cdot P$, a i f ce e $P_1 + P_2$, a a e i i f ce e $P_1|P_2$, a ch c e $[a_1{=}a_2]P$, a e ici c e $\nu a\ P$, a ce i a ce $A\langle a_1, \ldots, a_n\rangle$. $[a_1{=}a_2]P$ i dica e ha P i e ec ed if $a_1{=}a_2$. $\nu a\ P$ beha e a P e ce ha he ica i he b d e a i f - bidde . A i $A\langle a_1, \ldots, a_n\rangle$ i a ce ide i de ed b $A(x_1, \ldots, x_n) \stackrel{\text{def}}{=} P_A$ a d $A\langle a_1, \ldots, a_n\rangle$={$\overrightarrow{a}/\overrightarrow{x}$}$P_A$, he e $\overrightarrow{a}$ a d $\overrightarrow{x}$ a e he ec f $a_1, \ldots, a_n$ a d $x_1, \ldots, x_n$, e ec i e . The e f e i a ce $n(P)$ c i f b d e $bn(P)$ a d ee e $fn(P)$. N e , a a, a ea i g i (a) $\nu a\ P$ a e b d e . O he a e ee e . The abb e ia i ab $skip$ a d $await$ a e de ed a f .

Skip_0 $\quad skip^0 \stackrel{\text{def}}{=} \varepsilon$

Skip_n $\quad skip^n \stackrel{\text{def}}{=} skip \cdot skip^{n-1} (n \ge 1)$

Await_d $\; await(P) \stackrel{\text{def}}{=} \varepsilon \cdot P + skip \cdot P + \cdots + skip^n \cdot P (n \ge 0)$

he e $n \in \mathbb{N}$. The d i ed ce $await(P)$ i ed ea i e ch , - ica i . He e P i $await(P)$ i a e di g (ecei i g) e g a ded ce .

Definition 1 The c a c g e ce he e f -π ce e $\mathcal{P}$ i de ed b he i ee e a i be .

$$
\begin{array}{ll}
\text{S1}\ \ P|0 \ \equiv\ P & \text{S2}\ \ \nu x P \ \equiv\ \nu y\{y/x\}P \text{ if } y \notin fn(P) \\
\text{S3}\ \ P + Q \ \equiv\ Q + P & \text{S4}\ \ x(y) \cdot P \ \equiv\ x(z) \cdot \{z/y\}P \text{ if } z \notin fn((y)P) \\
\text{S5}\ \ P|Q \ \equiv\ Q|P & \text{S6}\ \ (P|Q)|R \ \equiv\ P|(Q|R) \\
\text{S7}\ \ \nu x\, 0 \ \equiv\ 0 & \text{S8}\ \ \nu x\, (P|Q) \ \equiv\ P|\nu x\, Q, \text{ if } x \notin fn(P) \\
\text{S9}\ \ \nu xy\, P \ \equiv\ \nu yx\, P & \text{S10}\ \ [x = y]P \ \equiv\ 0, \text{ if } x \ne y \\
\text{S11}\ \ \varepsilon \cdot P \ \equiv\ P & \text{S12}\ \ skip \cdot P + skip \cdot Q \ \equiv\ skip \cdot (P + Q) \\
\text{S13}\ \ P + 0 \ \equiv\ P & \text{S14}\ \ A\langle a_1, \ldots, a_n\rangle \equiv \{\overrightarrow{a}/\overrightarrow{x}\}P_A \text{ if } A(x_1, \ldots, x_n) \stackrel{\text{def}}{=} P_A \\
\text{S15}\ \ \nu x\, \overline{x}\langle y\rangle \cdot P \equiv 0 & \text{S16}\ \ P + (Q + R) \ \equiv\ (P + Q) + R
\end{array}
$$

The e ec i f -π ce e c i f age : e f i a a e aci e e a d he he e f i a aci e e a d he e ec i f a i a aci e i a ed a e a i a i h e i e i . F he a i a e , he b ab e aci i gi e a f :

$$
\begin{aligned}
\pi_o \ &::= \bar{x}\langle y\rangle \mid x(z) \mid \bar{x}(z) \mid \tau \mid I_p \mid skip \\
\pi_c \ &::= \bar{x}\langle y\rangle \mid x(z) \mid \bar{x}(z) \mid \tau \\
\pi_t \ &::= I_p \mid skip
\end{aligned}
$$

$$\text{Tau:}\frac{}{\tau\cdot P\xrightarrow{\tau}P}\qquad \text{In:}\frac{}{x(z)\cdot P\xrightarrow{x(w)}\{w/z\}P}(w\notin fn((z)P))$$

$$\text{Out:}\frac{}{\bar{x}\langle y\rangle\cdot P\xrightarrow{\bar{x}\langle y\rangle}P}\qquad \text{Par:}\frac{P_1\xrightarrow{\pi_c}P_1'}{P_1|P_2\xrightarrow{\pi_c}P_1'|P_2}(bn(\pi_c)\cap fn(P_2)=\emptyset)$$

$$\text{Sum:}\frac{P_1\xrightarrow{\pi_c}P_1'}{P_1+P_2\xrightarrow{\pi_c}P_1'}\qquad \text{Close:}\frac{P_1\xrightarrow{\bar{x}(y)}P_1'\ \ P_2\xrightarrow{x(y)}P_2'}{P_1|P_2\xrightarrow{\tau}\nu y\,(P_1'|P_2')}$$

$$\text{Com:}\frac{P_1\xrightarrow{\bar{x}\langle y\rangle}P_1'\ \ P_2\xrightarrow{x(z)}P_2'}{P_1|P_2\xrightarrow{\tau}P_1'|\{y/z\}P_2'}\qquad \text{Mat:}\frac{P\xrightarrow{\pi_o}P'}{[a_1=a_2]P\xrightarrow{\pi_o}P'}(a_1=a_2)$$

$$\text{Open:}\frac{P\xrightarrow{\bar{x}\langle y\rangle}P'}{\nu y\,P\xrightarrow{\bar{x}(z)}\{z/y\}P'}\quad(x\neq y,z\notin fn(\nu yP'))$$

$$\text{Res:}\frac{P\xrightarrow{\pi_o}P'}{\nu xP\xrightarrow{\pi_o}\nu xP'}(x\notin n(\pi_o))\qquad \text{Ide:}\frac{\{\overrightarrow{a}/\overrightarrow{x}\}P_A\xrightarrow{\pi_o}P'}{A\langle\overrightarrow{a}\rangle\xrightarrow{\pi_o}P'}(A(\overrightarrow{x})\stackrel{\text{def}}{=}P_A)$$

$$\text{Act}_t:\frac{}{\pi_t\cdot P\xrightarrow{\pi_t}P}\qquad \text{Sum}_{t_1}:\frac{P_1\xrightarrow{skip}P_1'\ \ P_2\xrightarrow{skip}P_2'}{P_1+P_2\xrightarrow{skip}P_1'+P_2'}$$

$$\text{Act}_\varepsilon:\frac{P\xrightarrow{\pi_c}P'}{\varepsilon\cdot P\xrightarrow{\pi_c}P'}\qquad \text{Await:}\frac{\varepsilon\cdot P+skip\cdot await(P)\xrightarrow{\pi_o}P'}{await(P)\xrightarrow{\pi_o}P'}$$

$$\text{Com}_{idle}:\frac{P_1\xrightarrow{\pi_t}P_1'\ \ P_2\equiv 0}{P_1|P_2\xrightarrow{\pi_t}P_1'}\qquad \text{Sum}_{t_2}:\frac{P_1\xrightarrow{\pi_t}P_1'}{P_1+P_2\xrightarrow{\pi_t}P_1'}(P_1+P_2\not\xrightarrow{skip})$$

$$\text{Com}_t:\frac{P_1\xrightarrow{\pi_{t_1}}P_1'\ \ P_2\xrightarrow{\pi_{t_2}}P_2'}{P_1|P_2\xrightarrow{\pi_{t_1}\cup\pi_{t_2}}P_1'|P_2'}(\pi_{t_1}\cap\pi_{t_2}-skip=\emptyset,P_1|P_2\not\xrightarrow{\tau})$$

Fig. 1 O a i a a ic f -π

w he e x a d y a e f ee e i $fn(\pi_o)$ $fn(\pi_c)$. z i a b d e i $bn(\pi_o)$ $bn(\pi_c)$. He e, $\overline{x}(z)$ i de ed b $\nu z\,\overline{x}\langle z\rangle$.

A i [12], a a i i i he f f $P\xrightarrow{\pi_o}Q$ i ea ha P ca e e i Q af e f i g ac i π_o. I Fig. 1, *late* a i a a ic f -π i de ed.

Definition 2 F a -π ce P, he LTS (Labe ed T a i i S) f P i a ai $(\mathcal{P},\mathcal{T})$, i w hich $\mathcal{P}$ i he e f -π ce e a d $\mathcal{T}$ i he e f a i i . $\mathcal{P}$ a d $\mathcal{T}$ a e de ed a f w :

1. $P\in\mathcal{P}$;
2. F a $Q\in\mathcal{P}$, if $Q\xrightarrow{\pi_o}Q'$, he $Q'\in\mathcal{P}$, $(Q,\pi_o,Q')\in\mathcal{T}$. F c e ie ce w e e LTS$_P$ de e he LTS d ced f ce P.

3 Framed temporal logic programming language MSVL

O de i g gic i R jec i T a L gic (PTL) a d MSVL i a e ec ab e b e f PTL. MSVL c i f e e i a d e . The a i e ice e i *e* a d b ea e e i *b* f MSVL a e i d c i e de ed a f w :

$$e ::= c|v|v_p|\&x| * v_p|\bigcirc x|\circleddash x|e_0 op e_1 \qquad (op ::= +|-|*|/)$$
$$b ::= \mathsf{true}|\mathsf{false}|\neg b|b_0 \wedge b_1|e_0 = e_1|e_0 < e_1$$

w he e c i a c a , v a da a a iab e, v_p a i a iab e a d x de e a da a a iab e a i a iab e. & i a i e efe e ce a d $*$ a i de efe e ce. $\bigcirc$ ea *next* a d $\circleddash$ *previous*. A d ic a iab e x i aid be ed i prog if frame(x) lbf(x) i c ai ed i prog.

A ed i MSVL ca be a i ed b he i ee e a e be w . $p_1, \ldots, p_m, p$ a d q a e ge a ed .

T i a i :	ε	Ba ic a ig e :	$x = e$
P i a a ig e :	$*v_p = e$	S a e e:	lbf(x)
I a a e:	frame(x)	C j c i :	$p \wedge q$
Se ec i :	$p \vee q$	Ne e :	$\bigcirc p$
A a e :	$\Box p$	C di i a e :	if b then p else q
E i e ia a i ca i :	$\exists x : p(x)$	Se e ia e :	p ; q
Pa a e :	$p \parallel q$	Whi e e :	while b do p
S ch i ed ica i :	await(b)	R jec i :	$(p_1, \ldots, p_m)$ prj q

ε i he i a i e . The ba ic a ig e $x = e$ ea ha he a e f a iab e x i e a he a e f e e i e. Si i a , $*v_p = e$ i he a ig e a cia ed w i h he i . The i a ig e $x := e$ i de ed a $x := e \stackrel{\text{def}}{=} skip \wedge \bigcirc x = e$. The *next* e $\bigcirc p$ ea ha p h d a he edia e cce a e. $\Box p$ ie ha p h d i a a e w . The e e ia e p ; q ig i e ha p h d he c e a e i e i i f e a w hich i i a e a d q w i a e ec i g ha i .

The a e e lbf(x) a d i a a e frame(x) i i e i g ech i e. The i g a i de ed b frame a d frame(x) ea ha *variable x always keeps its old value over an interval if no assignment to x is encountered*. T gi e i de ii , a e w a ig e i a i ed a $x \Leftarrow e \stackrel{\text{def}}{=} x = e \wedge p_x$, w he e p_x i a ic i i c ec ed w i h a iab e x a d ca be ed f he e . The he a ig e ag i a i ed a : af(x) $\stackrel{\text{def}}{=} p_x$. Th , lbf($x$) a d frame($x$) ca be de ed a lbf($x$) $\stackrel{\text{def}}{=} \neg$af($x$) $\rightarrow \exists a : (\circleddash x = a \wedge x = a)$ a d frame(x) $\stackrel{\text{def}}{=} \Box$(more $\rightarrow \bigcirc$ lbf(x)) e ec i e w he e a i a a ic a iab e.

The c di i a e if b then p else q e a a e b; if b i true, he p i e ec ed, he w i e q i e ec ed. The i a i while b do p a w ce p be e ea ed e ec ed a ie (i ie) be i e a g a he c di i b i a i ed a he begi i g f each e ec i . The e ec i e $p \vee q$ e e ha p q w i be e ec ed. The c j c i e $p \wedge q$ dec a e ha he ce e p a d q a e e ec ed c e ha i g a he a e a d a iab e d i g he a e ec i . The a a e c c i $p \parallel q$, h w a he c e a i a . The di i g i hed diffe e ce be w ee $p \parallel q$ a d $p \wedge q$ i ha he a w b h p a d q be ab e ecif he w i a w hi e he a e d e . E.g., len(2) $\parallel$ len(3) h d b len(2) $\wedge$ len(3) i b i false. The a e await(b) i ed ch i e ica i be ee a a e ce e .

R jec i $(p_1, \ldots, p_m)$ prj q c ai ha q i e ec ed i a a e ih $p_1, \ldots, p_m$ a a i a b ai ed b a i g he e d i f he i a hich p'_i $(1 \leq i \leq m)$ a e e ec ed. The c c i he ce e $p_1, \ldots, p_m, q$ be a . The e i e ia a i ca i e $\exists x : p(x)$ i e d hide he a iab e x i hi he ce p. We e a e i e h d ed ce hi i d f . C ide a f a $\exists x : p(x)$ i h a b d e x. The e i e ia a i ca i $(\exists x)$ i ed $\exists x : p(x)$ b ai a e i a e f a $p(y)$ i h a f ee a iab e y b e i g x a y, i.e., $\exists x : p(x) \equiv p(y)$.

I he f i g e b ie i d ce he a i a a ic f MSVL (Ya g a d D a 2008). The ed c i ce f MSVL i di ided i ha e : e f a e ed c i a d he h f i a ed c i .

F b ai i g he a e f a iab e i a a e e e $s_i[(m, \dot{p}_x)/x]$ a x a a $(m, \dot{p}_x)$ i h h a iab e bei g cha ged a a e s_i. He e, $\dot{p}_x$ de e a i e ag p_x $\neg p_x$ a d m i a a e i D. F h , f c e ie ce e e $s_i[w]$ ea ha a a iab e a d i i a ea i g i a e w a c e a e s_i a e i a ia ed i h hei a e . The e a e e f c g a i , e f e e i a d he h f . A c g a i i de ed i f a ad e $\mathbb{C} = (p, \sigma_{i-1}, s_i, i)$ h e p i a f ed MSVL , $\sigma_{i-1} = \langle s_0, \ldots, s_{i-1}\rangle (i > 1)$ de hich ec d i f a i f a a e , s_i he c e a e a hich p i bei g e ec ed a d i a c a f c i g he b f a e i σ_{i-1}. F h , f i = 0, e $\sigma_{-1} = \epsilon$ be a e e ce. Th , he i i ia c g a i i $\mathbb{C}_0 = (p, \epsilon, s_0, 0)$. Whe a i i abe a d ai ab e, i a c g a i a i e a $\mathbb{C}_f = (\text{true}, \sigma, \varnothing, |\sigma| + 1)$. Si i a , he c g a i f a ih e ice e i e a d b ea e e i b a e $(e, \sigma_{i-1}, s_i, i)$ a d $(b, \sigma_{i-1}, s_i, i)$ e ec i e . The e a e e f e a i a he e f c g a i , e f c g a i . . a a e, a d he h f c g a i i h diff e a e . F c g a i i hi a a e, he a i $\rightarrowtail$ i ed h ea f c g a i i h diff e a e , $\rightarrow$ i ed.

Le CS be he e f a c g a i . The h a ii e a i acc di g $\rightarrowtail$ a d $\rightarrow$ a e gi e a f .

$$
\begin{array}{ll}
\overset{0}{\rightarrowtail} : \{(\mathbb{C}, \mathbb{C}) \mid \mathbb{C} \in CS\} & \overset{0}{\rightarrow} : \{(\mathbb{C}, \mathbb{C}') \mid \mathbb{C}, \mathbb{C}' \in CS \text{ a d } \mathbb{C} \overset{*}{\rightarrowtail} \mathbb{C}'\} \\
\overset{i+1}{\rightarrowtail} : \{(\mathbb{C}_1, \mathbb{C}_2) \mid \mathbb{C}_1, \mathbb{C}_2 \in CS \text{ a d } \exists \mathbb{C}' \in CS, & \overset{i+1}{\rightarrow} : \{(\mathbb{C}_1, \mathbb{C}_2) \mid \mathbb{C}_1, \mathbb{C}_2 \in CS \text{ a d } \exists \mathbb{C}' \in CS, \\
\qquad \mathbb{C}_1 \overset{i}{\rightarrowtail} \mathbb{C}' \text{ a d } \mathbb{C}' \rightarrowtail \mathbb{C}_2, i \geq 0\} & \qquad \mathbb{C}_1 \overset{i}{\rightarrow} \mathbb{C}' \text{ a d } \mathbb{C}' \rightarrow \mathbb{C}_2, i \geq 0\} \\
\overset{+}{\rightarrowtail} : \bigcup_{i>0} \overset{i}{\rightarrowtail} & \overset{+}{\rightarrow} : \bigcup_{i>0} \overset{i}{\rightarrow} \\
\overset{*}{\rightarrowtail} : \overset{0}{\rightarrowtail} \cup \overset{+}{\rightarrowtail} & \overset{*}{\rightarrow} : \overset{0}{\rightarrow} \cup \overset{+}{\rightarrow}
\end{array}
$$

U a e e CS$_q$ de e he e f he c g a i d ced he MSVL q. The e a ai e fe e i , a ii e i hi a a e a d i a a ii e i de ed i (Ya g a d D a 2008).

The e a e ig i ca i d f ica i de be ee c c e ce e : b ha ed a iab e a d b cha e . I MSVL, ch a ica i i ba ed ha ed a iab e he ea , i π-ca c , i b cha e . F h e f a ai , he cha e a d ica i i i e a e de ed i MSVL.T de bi i , a cha e h d be ca ab e f bei g a ed a e age. T hi e d, he cha e i a i ed a a i efe i g a i e. The cha e a d ica i i i e a e eci ed i De i i 3.

Definition 3

$$
\begin{aligned}
&C_x && \stackrel{\text{def}}{=} \&X\\
&X && \stackrel{\text{def}}{=} (w, r, v_p)\\
&i\ e(C_x) && \stackrel{\text{def}}{=} \Pi_1(*C_x) = \text{true}\\
&ead(C_x) && \stackrel{\text{def}}{=} \Pi_2(*C_x) = \text{true}\\
&e\ d(C_x, C_y) && \stackrel{\text{def}}{=} i\ e(C_x) \wedge \Pi_3(*C_x) = C_y \wedge \varepsilon\\
&ecei\ e(C_x, C_y) && \stackrel{\text{def}}{=} ead(C_x) \wedge C_y = \Pi_3(*C_x) \wedge \varepsilon\\
&ai\_\ e\ d(C_x, C_y) && \stackrel{\text{def}}{=} i\ e(C_x) \wedge await(ead(C_x)); (\Pi_3(*C_x) = C_y \wedge \varepsilon)\\
&ai\_ecei\ e(C_x, C_y) && \stackrel{\text{def}}{=} ead(C_x) \wedge await(i\ e(C_x)); (C_y = \Pi_3(*C_x) \wedge \varepsilon)
\end{aligned}
$$

he e w a d r a e b ea a iab e dec a i g ea he cha e C_x i ai i g f e di g e age ecei i g e age. v_p i a cha e a iab e e e e i g he e age be e b C_x . He e, X i a i e c ec ed i h cha e C_x a d ca be ed f he e . R jec i f c i $\Pi_i (1 \leq i \leq 3)$ i de ed b ai a e f he i e , e.g., $\Pi_1(X) = \Pi_1(w, r, v_p) = w$. $i\ e(C_x)$ de e a e d ac i cc i g ia cha e C_x a d $ead(C_x)$ a ecei e ac i cc i g ia cha e C_x. ica i ca be ch a ch - . $e\ d(C_x, C_y)$ e e e a a ch e di g i i e, $ecei\ e(C_x, C_y)$ a a ch ecei i g i i e $ai\_\ e\ d(C_x, C_y)$ a ch e di g i i e a d $ai\_ecei\ e(C_x, C_y)$ a ch ecei i g i i e. A ch e d- i g a d ecei i g i e ec e i i g eadi g i a a e hi e ch e di g a d ecei i g i ai f e ac i i a .

4 Transformation from p-π to MSVL

A h gh -π a d MSVL de ibe c c e eac i e f e a i dif- fe e a e ca h ha each b ded -π ce ca be a ed i a MSVL b he a i g f c i $\mathcal{F}$: {*bounded p-π process*} $\rightarrow$ {MSVL*program*} hich i de ed a f . $\mathcal{F}(P)$ a P b he i d c- i i c e . The de i i f b ded -π ce i gi e be .

Definition 4 Le P be a -π ce . P i b ded iff f each ce ide i $A(x_1, \ldots, x_n) \stackrel{\text{def}}{=} P_A$ i h ec i e ca i P, he e i a ce P'_A i he f $\pi_1^s + \cdots + \pi_i^s + \pi_1'^s \cdot A\langle x_1, \ldots, x_n\rangle + \cdots + \pi_m'^s \cdot A\langle x_1, \ldots, x_n\rangle$ ch ha $A(x_1, \ldots, x_n) \equiv P'_A$ he e, π_j^s $(1 \leq j \leq i)$ a d $\pi_k'^s$ $(1 \leq k \leq m)$ de e $\pi_{j_1} \cdot \pi_{j_2} \cdot \cdots \cdot \pi_{j_{nj}}$ a d $\pi_{k_1} \cdot \pi_{k_2} \cdot \ldots \cdot \pi_{k_{nk}}$, e ec i e .

F ea f di c i w e c ida e a d i i . Acc di g he e f e $n(P)$ a d i i PR_P a ea i g i a -π ce P, he e f cha e $CH_{\mathcal{F}(P)}$ a d i i a (b ea) a iab e $V_{\mathcal{F}(P)}$ f he c e di g MSVL a e b ai ed. F i a ce, if $n(P)=\{a, b, c\}$ a d $PR_P=\{p_1, p_2, p_3\}$, w e ha e, $CH_{\mathcal{F}(P)} = \{C_a, C_b, C_c\}$ a d $V_{\mathcal{F}(P)} = \{x_{p_1}, x_{p_2}, x_{p_3}\}$. The c a a - f ai e f ce e a e f a i ed be w .

4.1 E ce

$$\mathcal{F}(0) \stackrel{\text{def}}{=} \varepsilon$$

E ce ea d i g hi g, i ca a a ba a ed ε i MSVL.

4.2 O ac i e

$$\mathcal{F}(\bar{x}\langle y\rangle \cdot P) \stackrel{\text{def}}{=} e\ d(C_x, C_y); \mathcal{F}(P)$$

O ac i e g a ded ce $\bar{x}\langle y\rangle \cdot P$ ea i e d y h gh x a d he beha e a P. Si ce $\bar{x}\langle y\rangle$ i a i a a e ac i e w i h w ai i g f i a , he ce ca be a ed $e\ d(C_x, C_y); \mathcal{F}(P)$, w he e $e\ d(C_x, C_y)$ i a a ch e di g. C_x a d C_y a e he c e di g MSVL cha e f x a d y.

4.3 I ac i e

$$\mathcal{F}(x(y) \cdot P) \stackrel{\text{def}}{=} \exists C_y : (\mathsf{frame}(C_y) \wedge (\ ecei\ e(C_x, C_y); \mathcal{F}(P)))$$

I ac i e g a ded ce $x(y) \cdot P$ i dica e i w i acce z f x a d he beha e a $\{z/y\}P$. He e, i ce y i a b d e a d w i be b i ed a , i h d be a a ed a ca cha e. The ef e, he e i a i $\exists$ i h gh i . F ha , $\mathsf{frame}(C_y)$ g a a ee ha he cha e C_y a w a ee i d a e(efe he d cha e i a ce) a a i a if a ig e C_y i e c ed. Wha acc a e ha e i ha C_y w i be a ig ed he e age e b cha e C_x. We a e he e age i C_z ha C_y w i efe he e cha e i a ce a C_z. A a g $\bar{x}\langle y\rangle, x(y)$ i a a ed i a a ch ecei i g.

4.4 A w ai

$$\mathcal{F}(await(\bar{x}\langle y\rangle \cdot P)) \stackrel{\text{def}}{=} w\ ai\_\ e\ d(C_x, C_y); \mathcal{F}(P)$$
$$\mathcal{F}(await(x(y) \cdot P)) \stackrel{\text{def}}{=} \exists C_y : (\mathsf{frame}(C_y) \wedge (w\ ai\_\ ecei\ e(C_x, C_y); \mathcal{F}(P)))$$

F de i ed ce $await(P)$, w he e P i a e di g (ecei i g) e g a ded ce , i ce he c ica i i ch , i a f ai i e - ch e di g a d ecei i g. E ce f he diffe e c ica i de , he a f ai f $await\,(\bar{x}\langle y\rangle\cdot P)$ a d $await(x(y)\cdot P)$ a e i ia h e f $\bar{x}\langle y\rangle\cdot P$ a d $x(y)\cdot P$, e ec i e .

4.5 I a ac i e

$$\mathcal{F}(\tau\cdot P)\stackrel{\text{def}}{=}p_I\wedge\varepsilon;\mathcal{F}(P)$$

I a ac i e g aded ce $\tau\cdot P$ f a i a ac i τ a d he beha e a P. I ca a ed $p_I\wedge\varepsilon;\mathcal{F}(P)$ i hich p_I i a ecia i i ed a ife he h a i a ac i a e ace.

4.6 R ac i e

$$\mathcal{F}(I_p\cdot P)\stackrel{\text{def}}{=}x_{p_1}=\mathsf{true}\ \wedge\cdots\wedge x_{p_n}=\mathsf{true}\wedge skip;\mathcal{F}(P)$$

h e $I_p=\{\tilde{p}_1,\ldots,\tilde{p}_n\}$. The ac i e g aded ce $I_p\cdot P$ a i e $p_i(1\le i\le n)$ i he e i a d he beha e a P. I i i e , i ca be a ed x_{p_1}=true $\wedge\cdots\wedge x_{p_n}$=true $\wedge\,skip;\mathcal{F}(P)$. H e, $x_{p_1},\ldots,$ a d x_{p_n} a e he c e di g b ea a iab e f $p_1,\ldots,$ a d p_n, e ec i e .

4.7 T e i ac i e

$$\mathcal{F}(skip\cdot P)\stackrel{\text{def}}{=}skip;\mathcal{F}(P)$$

T e i ac i e g aded ce $skip\cdot P$ dec e ha i i id e i he e i a d he beha e a P. I a f ai i aigh f a d.

4.8 E ac i e

$$\mathcal{F}(\varepsilon\cdot P)\stackrel{\text{def}}{=}\varepsilon;\mathcal{F}(P)$$

F ac i e g aded ce $\varepsilon\cdot P$, i i e ec e a a ii a d he beha e a P. S i a $skip\cdot P$, i i di ec a a ed i $\varepsilon;\mathcal{F}(P)$.

4.9 N de i i ic ch ice

$$\mathcal{F}(P_1+P_2)\stackrel{\text{def}}{=}\mathcal{F}(P_1)\vee\mathcal{F}(P_2)$$

S c e P_1+P_2 h ha P_1 a d P_2 i ceed de i a e , ha i ca a a bee e ed b a di j ci e .

4.10 Pa a e

$$\mathcal{F}(P_1 \mid P_2) \stackrel{\text{def}}{=} \mathcal{F}(P_1) \,||\, \mathcal{F}(P_2)$$

Pa a e i i c e $P_1 \mid P_2$ a ife ha P_1 a d P_2 e ec e i a a e a d i di ec be a ed i a a a e e .

4.11 Ma ch

$$\mathcal{F}([a_1 = a_2]P) \stackrel{\text{def}}{=} \texttt{if}\ C_{a_1} = C_{a_2}\ \texttt{then}\ \mathcal{F}(P)\ \texttt{else}\ \varepsilon$$

Ma ch c e $[a_1 = a_2]P$ e ha if a_1 a d a_2 a e he e e, he ce i beha e a P, e e i i a 0. I a a i i de ed ba ed he c di i a e .

4.12 Re ic i

$$\mathcal{F}(\nu a\ P) \stackrel{\text{def}}{=} \exists C_a : (\mathsf{frame}(C_a) \wedge \mathcal{F}(P))$$

Re ic i c e $\nu a\ P$ ea ha he ce i beha e a P e ce ha he ica i b d e a i f bidde . a i a ed ca cha e C_a ha e ic i c e $\nu a\ P$ ca be de ed ab e he e frame i ed a i he a a i f he i ac i e g a ded c e.

4.13 R ce i a ce

F ce i a ce $A\langle a_1, \ldots, a_n \rangle$ e a e ha $A(x_1, \ldots, x_n)$ i de ed b P_A, ha $A\langle a_1, \ldots, a_n \rangle = \{\overrightarrow{a}/\overrightarrow{x}\}P_A$. T a ce i a ce e a he be .

Theorem 1 *Let process* $A(x_1, \ldots, x_n) \stackrel{\text{def}}{=} P_A$ *and* $A\langle a_1, \ldots, a_n \rangle = \{\overrightarrow{a}/\overrightarrow{x}\}P_A$. *If* A *is recursively called in* P_A *and there is a* P'_A *in the form of* $\pi_1^s + \cdots + \pi_i^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n \rangle + \cdots . + \pi_m^{'s} \cdot A\langle x_1, \ldots, x_n \rangle$ *such that* $A(x_1, \ldots, x_n) \equiv P'_A$, *where,* π_j^s $(1 \le j \le i)$ *and* $\pi_k^{'s}$ $(1 \le k \le m)$ *denote* $\pi_{j_1} \cdot \cdots \cdot \pi_{j_{nj}}$, $\pi_{k_1} \cdot \cdots \cdot \pi_{k_{nk}}$, *respectively, then, there exists the least fixed point* $L_{fix}\langle a_1, \ldots, a_n \rangle$ *of* $A\langle a_1, \ldots, a_n \rangle$ *such that* $A\langle a_1, \ldots, a_n \rangle = L_{fix}\langle a_1, \ldots, a_n \rangle$.

Proof The he ca be ed b i g Ta i' ed- i he (Ta i 1955) a d Sc ' ed- i i d ci (Wi e 1993). □

F ab e, f he e de i i $A(x_1, \ldots, x_n) = \pi_1^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n \rangle$, he ea ed i f $A\langle a_1, \ldots, a_n \rangle$ i $\{\overrightarrow{a}/\overrightarrow{x}\}\pi_1^{'s*} \cdot \pi_1^s$. H e , i ac ice, he i a i e be f e i de i i ic. The ef e, a $A\langle a_1, \ldots, a_n \rangle$ i

MSVL e ca ecif a abi a i ege N a be fi ai i e c he ec i . F $A(x_1, \ldots, x_n)=\pi_1^s + \cdots + \pi_i^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n\rangle + \cdots . + \pi_m^{'s} \cdot A\langle x_1, \ldots, x_n\rangle$, he a f ai i i a. Si ce a ce i a ce ca be de ed i h ec i e ca i -π, i a f ai i be di ided i h ee ca e :

1. Wi h ec i e ca i he de i i f A:

$$\mathcal{F}(A\langle a_1, \ldots, a_n\rangle) \stackrel{\text{def}}{=} \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(P_A)$$

   F hi i d f ce i a ce, i i be di ec a a ed b b i i . $\overrightarrow{C_a}$ a d $\overrightarrow{C_x}$ a e he c e di g MSVL cha e ec f $\overrightarrow{a}$ a d $\overrightarrow{x}$. He e e e a b i i e h d $\{\overrightarrow{C_a}/\overrightarrow{C_x}\}$ b i e $\overrightarrow{C_a}$ f $\overrightarrow{C_x}$ ha each C_x i be b i ed b C_a i hi he b d c e f C_{x_i} $(1 \le i \le n)$ i $\mathcal{F}(P_A)$.

2. Wi h ec i e ca i A a d $A(x_1, \ldots, x_n) \equiv \pi_1^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n\rangle$:

$$
\begin{aligned}
\mathcal{F}(A\langle a_1, \ldots, a_n\rangle) \stackrel{\text{def}}{=} \; & j := 0; \\
& \mathcal{F}(A_{-1}\langle a_1, \ldots, a_n\rangle) := \varepsilon; \\
& \mathcal{F}(A_0\langle a_1, \ldots, a_n\rangle) := \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s); \\
& \texttt{while}\ (j < N) \\
& \texttt{do}\ (j := j + 1; \\
& \mathcal{F}(A_j\langle a_1, \ldots, a_n\rangle) := \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s) \\
& \vee(\{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^{'s}); \mathcal{F}(A_{j-1}\langle a_1, \ldots, a_n\rangle))))
\end{aligned}
$$

   Wh e N i a c a i ege . F hi i d ce i a ce, b The 1, a ea ed i ca be b ai ed. I ac ice, a ec i ced e ge a a bi a gi e i e i ai e f $A\langle a_1, \ldots, a_n\rangle$. F ce i a ce i h ec i e ca i he de i i f A a d $A(x_1, \ldots, x_n) = \pi_1^s + \cdots + \pi_i^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n\rangle + \cdots . + \pi_m^{'s} \cdot A\langle x_1, \ldots, x_n\rangle$, he c e di g MSVL ca be b ai ed i he a .

3. Wi h ec i e ca i he de i i f A b A i i he a ed i The 1: F hi i d ce ide i , i beha i a be c e ge ha e ca di ec a f he i MSVL.

Acc di g he a f ai $\mathcal{F}$, e i e iga e he c i e c be ee i ea i g a d e c c e c . I -π he e ec i de f i a a e aci e e i a a e c e i i i ea i de ha ea i MSVL he a a e e $f_1||f_2$ i ed ced i e c c e de. B he f i g f , i i b ai ed ha he i d f c e echa i a e c i e i f he a f ai . The e ec i f -π ce e ie age : e f i a a e aci e e a d he h f i a aci e e . C i cide a , he ed c i f MSVL i di ided i ha e : e f a e ed c i a d he h f i a ed c i . We i h he f i g fac : (1) he e ec i f i a a e aci e e i c i e i h he a e ed c i ; (2) he e ec i f i a aci e e i i ed i h he i a ed c i .

(1) F he e ec i fi a a e ac i e e , ha e a e h ee ib e c - di i : (a) ica i g f ee e ; (b) ica i g b d e ; (c) i a ica i . The f i h e ec he h ee c di i i gi e a f .

(a) ica i g f ee e Le $P_1 = \bar{x}\langle y\rangle \cdot P_1'$ a d $P_2 = x(z) \cdot P_2'$ e ha e,

$$\dfrac{\dfrac{}{\bar{x}\langle y\rangle \cdot P_1' \xrightarrow{\bar{x}\langle y\rangle} P_1'}(\text{b O }) \quad \dfrac{}{x(z) \cdot P_2' \xrightarrow{x(w)} \{w/z\}P_2'}(\text{b I })}{P_1|P_2 \xrightarrow{\tau} P_1'|\{y/w\}\{w/z\}P_2'}(\text{b C }).$$

F $\mathcal{F}(P_1|P_2)$ e ha e,

$$\begin{aligned}
\mathcal{F}(P_1|P_2) &\equiv \mathcal{F}(\bar{x}\langle y\rangle \cdot P_1'|x(z) \cdot P_2') \\
&\equiv \mathcal{F}(\bar{x}\langle y\rangle \cdot P_1')||\mathcal{F}(x(z) \cdot P_2') \\
&\equiv (\ e\ \ d(C_x, C_y); \mathcal{F}(P_1'))||\exists C_z : (\mathsf{frame}(C_z) \wedge (\ ecei\ \ e(C_x, C_z); \mathcal{F}(P_2'))) \\
&\overset{C}{\equiv} (\ e\ \ d(C_x, C_y); \mathcal{F}(P_1'))||\mathsf{frame}(C_w) \wedge (\ ecei\ \ e(C_x, C_w); \{C_w/C_z\}\mathcal{F}(P_2')) \\
&\equiv \mathsf{frame}(C_w) \wedge ((\ e\ \ d(C_x, C_y); \mathcal{F}(P_1'))||(\ ecei\ \ e(C_x, C_w); \{C_w/C_z\}\mathcal{F}(P_2'))) \\
&\equiv^* \mathsf{frame}(C_w) \wedge (\Pi_1(*C_x) = \mathsf{true} \wedge \Pi_2(*C_x) = \mathsf{true} \wedge C_w = C_y \wedge \varepsilon \wedge (\mathcal{F}(P_1') \\
&\qquad ||\{C_w/C_z\}\mathcal{F}(P_2'))).
\end{aligned}$$

F c he b ai ed f a, i ce $\Pi_1(*C_x) = \mathsf{true} \wedge \Pi_2(*C_x) = \mathsf{true} \wedge C_w = C_y \wedge \varepsilon$ i a a e f a, i.e. i h a a a i he f a, ica i g f ee e i c i e i h he a e ed c i .

(b) ica i g b d e Le $P_1 = \nu y\, \bar{x}\langle y\rangle \cdot P_1'$ a d $P_2 = x(z) \cdot P_2'$, i i b ai ed,

$$\dfrac{\dfrac{\dfrac{}{\bar{x}\langle y\rangle \cdot P_1' \xrightarrow{\bar{x}\langle y\rangle} P_1'}(\text{b O })}{\nu y\, \bar{x}\langle y\rangle \cdot P_1' \xrightarrow{\bar{x}(w)} \{w/y\}P_1'}(\text{b O e }) \quad \dfrac{}{x(z) \cdot P_2' \xrightarrow{x(u)} \{u/z\}P_2'}(\text{b I })}{\nu y\, \bar{x}\langle y\rangle \cdot P_1'|x(z) \cdot P_2' \xrightarrow{\tau} \nu w\, (\{w/y\}P_1'|\{w/u\}\{u/z\}P_2')}(\text{b C e}).$$

F $\mathcal{F}(P_1|P_2)$ e ha e,

$$\begin{aligned}
\mathcal{F}(P_1|P_2) &\equiv \mathcal{F}(\nu y\, \bar{x}\langle y\rangle \cdot P_1'|x(z) \cdot P_2') \\
&\equiv \mathcal{F}(\nu y\, \bar{x}\langle y\rangle \cdot P_1')||\mathcal{F}(x(z) \cdot P_2') \\
&\equiv \exists C_y : (\mathsf{frame}(C_y) \wedge \mathcal{F}(\bar{x}\langle y\rangle \cdot P_1'))||\mathcal{F}(x(z) \cdot P_2') \\
&\equiv \exists C_y : (\mathsf{frame}(C_y) \wedge (\ e\ \ d(C_x, C_y); \mathcal{F}(P_1')))||\exists C_z : (\mathsf{frame}(C_z) \wedge \\
&\qquad (\ ecei\ \ e(C_x, C_z); \mathcal{F}(P_2'))) \\
&\overset{C}{\equiv} (\mathsf{frame}(C_w) \wedge (\ e\ \ d(C_x, C_w); \{C_w/C_y\}\mathcal{F}(P_1')))||\exists C_z : (\mathsf{frame}(C_z) \\
&\qquad \wedge (\ ecei\ \ e(C_x, C_z); \mathcal{F}(P_2')))
\end{aligned}$$

$$\overset{C,}{\equiv} \textsf{frame}(C_w) \wedge (\;e\;\; d(C_x, C_w); \{C_w/C_y\}\mathcal{F}(P_1'))||\textsf{frame}(C_u) \wedge$$
$$(\text{ecei}\;\; e(C_x, C_u); \{C_u/C_z\}\mathcal{F}(P_2'))$$
$$\equiv \textsf{frame}(C_w) \wedge \textsf{frame}(C_u) \wedge (\;e\;\; d(C_x, C_w); \{C_w/C_y\}\mathcal{F}(P_1'))||$$
$$(\text{ecei}\;\; e(C_x, C_u); \{C_u/C_z\}\mathcal{F}(P_2'))$$
$$\equiv^* \textsf{frame}(C_w) \wedge \textsf{frame}(C_u) \wedge (\Pi_1(*C_x) = \textsf{true} \wedge \Pi_2(*C_x) = \textsf{true}$$
$$\wedge\;\; C_u = C_w \wedge \varepsilon \wedge (\{C_w/C_y\}\mathcal{F}(P_1')||\{C_u/C_z\}\mathcal{F}(P_2'))$$

Si i a , i ce $\Pi_1(*C_x) = \textsf{true} \wedge \Pi_2(*C_x) = \textsf{true} \wedge C_u = C_w \wedge \varepsilon$ i a a e f , a, c , ica i g b , d e i c i e w i h he a e ed c i .

(c) i a c , ica i F $\tau \cdot P$, w e ha e,

$$\frac{}{\tau \cdot P \xrightarrow{\tau} P}(\text{b Ta }).$$

F $\mathcal{F}(\tau \cdot P)$, i i b ai ed, $\mathcal{F}(\tau \cdot P) \equiv p_I \wedge \varepsilon; \mathcal{F}(P)$.

Ob i , $p_I \wedge \varepsilon$ i a a e f , a. The ef e, i a c , ica i i c i e w i h he a e ed c i .

(2) F he e ec i f i a ac i e e , e $P_1 = \pi_{t_1} \cdot P_1'$ a d $P_2 = \pi_{t_2} \cdot P_2'$, w e ha e,

$$\frac{}{P_1 \xrightarrow{\pi_{t_1}} P_1'}(\text{b Ac }_t),\quad \frac{}{P_2 \xrightarrow{\pi_{t_2}} P_2'}(\text{b Ac }_t)$$
$$\frac{}{P_1|P_2 \xrightarrow{\pi_{t_1} \cup \pi_{t_2}} P_1'|P_2'}(\text{b C }_t).$$

We a e $\pi_{t_1} = \{\tilde{p}_1, \tilde{p}_2\}$ a d $\pi_{t_2} = \{\tilde{p}_3, \tilde{p}_4\}$. F $\mathcal{F}(P_1|P_2)$, w e ha e,

$$\begin{aligned}\mathcal{F}(P_1|P_2) &\equiv \mathcal{F}(\{\tilde{p}_1, \tilde{p}_2\} \cdot P_1'|\{\tilde{p}_3, \tilde{p}_4\} \cdot P_2')\\ &\equiv \mathcal{F}(\{\tilde{p}_1, \tilde{p}_2\} \cdot P_1')||\mathcal{F}(\{\tilde{p}_3, \tilde{p}_4\} \cdot P_2')\\ &\equiv (x_{p_1}{=}\textsf{true} \wedge x_{p_2}{=}\textsf{true} \wedge skip; \mathcal{F}(P_1'))||(x_{p_3}{=}\textsf{true} \wedge x_{p_4}{=}\textsf{true} \wedge skip;\\ &\quad \mathcal{F}(P_2'))\\ &\equiv^* x_{p_1}{=}\textsf{true} \wedge x_{p_2}{=}\textsf{true} \wedge x_{p_3}{=}\textsf{true} \wedge x_{p_4}{=}\textsf{true} \wedge \bigcirc(\mathcal{F}(P_1')||\mathcal{F}(P_2'))\end{aligned}$$

B he a f a i $\mathcal{F}$ a d he c e di g a ic e , i a e ce , e f MSVL, he b ai ed f , a i f he f $q_c \wedge \bigcirc q_f$. Thi ea he ed c i f he f , a eed e he e a e a d i a a i i , e a e e , ed w w i h he ed c i ce . The e ec i f ce e w i h *skip* i i a. Th , he e ec i fi a ac i e e i c i e w i h he i a ed c i .

He e w e di c w ice e a ed he a f a i .

(1) The a ia i f he i i e e .

I MSVL, he i i e e f a a e de ed a f w w i h 1=highe a d 7=w e :

Table 1 C e de ce be ee a

I -π	I MSVL
.	;
ν	$\exists$
$+$	$\vee$
$\vert$	$\vert\vert$

Table 2 C e de ce be ee a geb aic a

I -π	I MSVL
$\nu x\ P \equiv \nu y\ \{y/x\}P$	$\exists x : f(x) \equiv \exists y : f(y)$
$P + Q \equiv Q + P$	$f_1 \vee f_2 \equiv f_2 \vee f_1$
$P \vert Q \equiv Q \vert P$	$P \vert\vert Q \equiv Q \vert\vert P$
$(P\vert Q)\vert R \equiv P\vert(Q\vert R)$	$(P\vert\vert Q)\vert\vert R \equiv P\vert\vert(Q\vert\vert R)$
$\nu x\ 0 \equiv 0$	$\exists x : \varepsilon \equiv \varepsilon$
$\nu xy\ P \equiv \nu yx\ P$	$\exists x : \exists y : f(x, y) \equiv \exists y : \exists x : f(x, y)$

$$1:\ \neg \quad 2:\ \bigcirc, \Box, \Diamond, \odot, +, * \quad 3:\ \exists, \forall \quad 4:\ =$$
$$5:\ \vee, \wedge \quad 6:\ \rightarrow, \leftrightarrow \quad 7:\ ;\ ,\ \mathsf{prj}$$

I -π, e ed a i ($\pi\cdot$, νa a d $[a_1 = a_2]$) ha e i i a i $+$ a d i i $\vert$.

B he a a i $\mathcal{F}$, he e i a c e de ce be ee a f -π a d MSVL i Tab e 1.

N e ha , i -π, he ecede ce f $\cdot$, i high ha $+$. H e , i MSVL, he ecede ce f ;, i ha $\vee$. The ef e, e a a e he e i be e ed d i g he a a i a id c i e c a big i .

(2) The c e de ce be ee he a geb aic a f -π a d MSVL.

Tab e 2 h he c e de ce be ee e a geb aic a f -π a d MSVL.

5 Soundness of transformation

T e he d e f he a a i e gi e he de i i f bi a-i he LTS f a -π ce a d he e f ed c i c g a i f a MSVL g . Ba ed he de i i , he d e f he a a i i e .

Definition 5 A bi a e a i B' he ce e f LTS$_P$ a d he e f he e f MSVL ed c i c g a i CS$_{\mathcal{F}(P)}$ i a bi a i iff $(P, \mathbb{C}_0) \in B'$, he e $\mathbb{C}_0$ i he i i ia c g a i f $\mathcal{F}(P)$, a d if $(P', \mathbb{C}') \in B'$ he he f i g h d:

- if $P' \xrightarrow{\pi_c} P''$ he he e e i $\mathbb{C}''$ ch ha $\mathbb{C}' \overset{*}{\rightarrowtail} \mathbb{C}''$, he e $\mathbb{C}' = (p', \sigma', s', i')$ a d $\mathbb{C}''=(p'', \sigma'', s'', i'')$, i h $p' \equiv \mathcal{F}(\pi_c)$; p'', $\sigma''=\sigma'$, $s''=s'[w_{\mathcal{F}(\pi_c)}]$ ($w_{\mathcal{F}(\pi_c)}$ i he c e di g a e f $\mathcal{F}(\pi_c)$) a d $i'' = i'$, a d $(P'', \mathbb{C}'') \in B'$;
- if $P' \xrightarrow{\pi_t} P''$ he he e e i $\mathbb{C}''$ ch ha $\mathbb{C}' \rightarrow \mathbb{C}''$, he e $\mathbb{C}' = (p', \sigma', s_{i'}, i')$ a d $\mathbb{C}'' = (p'', \sigma'', s_{i'+1}, i' + 1)$, i h $p' \equiv \mathcal{F}(\pi_t)$; p'' a d $\sigma'' = \sigma'.\langle s_{i'}[w_{\mathcal{F}(\pi_t)}]\rangle$ ($w_{\mathcal{F}(\pi_t)}$ i he c e di g a e f $\mathcal{F}(\pi_t)$), a d $(P'', \mathbb{C}'') \in B'$;

if $\mathbb{C}' \overset{*}{\rightarrowtail} \mathbb{C}''$, ha e $\mathbb{C}' = (p', \sigma', s', i')$ a d $\mathbb{C}'' = (p'', \sigma'', s'', i'')$, i h $p' \equiv p_c; p''$, $\sigma'' = \sigma', s'' = s'[w_{p_c}]$ (p_c e e e a , ica i i i e e $d(C_x, C_y)$ ecei $e(C_x, C_y)$) a d $i'' = i'$, he ha e e i P'' ch ha $P' \overset{\pi_{p_c}}{\Longrightarrow} P''$, ha e π_{p_c} i he c e di g -π i a a e ac i e f p_c a d $(\mathbb{C}'', P'') \in B'$;
if $\mathbb{C}' \rightarrow \mathbb{C}''$, ha e $\mathbb{C}' = (p', \sigma', s_{i'}, i')$ a d $\mathbb{C}'' = (p'', \sigma'', s_{i'+1}, i' + 1)$, i h $p' \equiv x_{p_1}$=true $\wedge \cdots \wedge x_{p_n}$=true $\wedge \bigcirc p''$ a d $\sigma''=\sigma'.\langle s_{i'}[(\text{true}, \neg p_{x_{p_1}})/x_{p_1}] \cdots [(\text{true}, \neg p_{x_{pn}})\ /x_{p_n}]\rangle$) $p' \equiv \bigcirc p''$ a d $\sigma''=\sigma'.\langle s_{i'}\rangle$, he ha e e i P'' ch ha $P' \overset{I_p}{\Longrightarrow} P''$, ha e $I_p=\{\tilde{p}_1, \ldots, \tilde{p}_n\}$ $P' \overset{skip}{\Longrightarrow} P''$ a d $(\mathbb{C}'', P'') \in B'$.

ha e he e a i $\overset{\pi'}{\Rightarrow}$ f a $\pi' \in \{\overline{x}\langle y\rangle, x(y), \overline{x}(y), I_p, skip\}$ i de ed a f :

1. $P \Rightarrow Q$ ea ha ha e i a e e ce f a e i a a ac i $P \overset{\tau}{\rightarrow} P_1 \cdots P_n \overset{\tau}{\rightarrow} Q$. F a , $\Rightarrow \overset{\text{def}}{=} \overset{\tau}{\rightarrow}^*$, he a i i e e e i e c e f $\overset{\tau}{\rightarrow}$.
2. $P \overset{\pi'}{\Rightarrow} Q$ ea $P \Rightarrow P_1 \overset{\pi'}{\rightarrow} P_n \Rightarrow Q$. F a , $\overset{\pi'}{\Rightarrow} \overset{\text{def}}{=} \Rightarrow \overset{\pi'}{\rightarrow} \Rightarrow$.

If $(P', \mathbb{C}') \in B'$, e a ha $\mathbb{C}'$ i a e P'. Si i a , if $(\mathbb{C}', P') \in B'$, e a ha P' i a e $\mathbb{C}'$.

Theorem 2 *The transformation is soundness. More precisely, for each p-π process P, there is a bisimulation between the processes of* LTS_P *generated by the execution of P and configurations of* $CS_{\mathcal{F}(P)}$ *produced by MSVL program* $\mathcal{F}(P)$ *reductions.*

Proof The f ceed b i d c i he c e f -π ce e . A ca ee, he a ai ce e e i MSVL g e e ha f e a a i i i he a , e ca d c e di g a i i i he a a a d ice a a. I i he a a f ca e b ca e a a i c c de he c e di g eci ca i i a e each ha c e . Si ce he f f P i a e $\mathbb{C}_0$ a d $\mathbb{C}_0$ i a e P a e i a e e $\mathbb{C}_0$ i a e P ha e.

Base (1) F ce 0: i ce i d e hi g, i ca be i a ed b he c g a i $\mathbb{C} = (\varepsilon, \epsilon, s_0, 0)$.

(2) F i a a e ac i e g a ded c e $\bar{x}\langle y\rangle \cdot P$: he i e a i i i ca a i $\bar{x}\langle y\rangle \cdot P \xrightarrow{\bar{x}\langle y\rangle} P$ a d $\mathcal{F}(\bar{x}\langle y\rangle \cdot P) \overset{\text{def}}{=} e\ d(C_x, C_y); \mathcal{F}(P)$. F hi a i i f -$\pi$, e ca d he c e di g a i i f MSVL, i hi a a e $\mathbb{C} \overset{*}{\rightarrowtail} \mathbb{C}'$ (i hich $\mathbb{C}=(p, \sigma, s, i)$, $\mathbb{C}'=(p', \sigma', s', i')$ a d $p \equiv \mathcal{F}(\bar{x}\langle y\rangle); p'$, $\sigma'=\sigma$, $s'=s[w_{\mathcal{F}(\bar{x}\langle y\rangle)}]$, $i'=i$). The f f $x(y) \cdot P$, $\tau \cdot P$ a d $\varepsilon \cdot P$ a e i a .

(3) F i a ac i e g a ded c e $I_p \cdot P$: he a i i ca e e c e i $I_p \cdot P \xrightarrow{I_p} P$ a d $\mathcal{F}(I_p \cdot P) \overset{\text{def}}{=} x_{p_1}$=true $\wedge \cdots \wedge x_{p_n}$=true $\wedge\ skip; \mathcal{F}(P) \equiv x_{p_1}$=true $\wedge \cdots \wedge x_{p_n}$=true $\wedge \bigcirc \mathcal{F}(P)$. Si i a , f hi -$\pi$ a i i , he b ai ed c e di g MSVL a i i a e $\mathbb{C}' \rightarrow \mathbb{C}''$, ha e $\mathbb{C}'=(p', \sigma', s_{i'}, i')$ a d $\mathbb{C}''=(p'', \sigma'', s_{i'+1}, i' + 1)$, i h $p' \equiv \mathcal{F}(I_p); p''$ a d $\sigma'' = \sigma'.\langle s_{i'}[(\text{true}, \neg p_{x_{p_1}})\ /x_{p_1}] \cdots [(\text{true}, \neg p_{x_{p_n}})/x_{p_n}]\rangle$. F $skip \cdot P$, he a i i ca a i $skip \cdot P \xrightarrow{skip} P$ a d $\mathcal{F}(skip \cdot P) \overset{\text{def}}{=} skip; \mathcal{F}(P) \equiv \bigcirc P$. F hi -$\pi$ a i i , he f d c e di g MSVL a i i i $\mathbb{C}' \rightarrow \mathbb{C}''$, ha e $\mathbb{C}' = (p', \sigma', s_{i'}, i')$ a d $\mathbb{C}'' = (p'', \sigma'', s_{i'+1}, i' + 1)$, i h $p' \equiv \mathcal{F}(skip); p''$ a d $\sigma'' = \sigma'.\langle s_{i'}\rangle$.

Induction (1) F de i i ic ch ice c e $P_1 + P_2$: a i i i ca e ec e de e d P_1 a d P_2. We a e ha $P_1 \xrightarrow{\pi_{o_1}} P_1'$ a d $P_2 \xrightarrow{\pi_{o_2}} P_2'$, a d f ha he a e i , a ed b a i i $\mathbb{C}_1 \xrightarrow{*} \mathbb{C}_1'$ a d $\mathbb{C}_2 \xrightarrow{*} \mathbb{C}_2'$ e ec i e . Si ce $\mathcal{F}(P_1+P_2) \stackrel{\text{def}}{=} \mathcal{F}(P_1) \vee \mathcal{F}(P_2)$ ha a i i P_1+P_2 ca f i be i , a ed b a i i $\mathbb{C} \xrightarrow{*} \mathbb{C}_1'$ a d $\mathbb{C} \xrightarrow{*} \mathbb{C}_2'$ h e $\Pi_1(\mathbb{C}) = \mathcal{F}(P_1 + P_2)$, $\Pi_1(\mathbb{C}_1) = \mathcal{F}(P_1)$ a d $\Pi_1(\mathbb{C}_2) = \mathcal{F}(P_2)$. H e he jec i f c i Π_1 i ed a bef e.

(2) F a a e c e $P_1|P_2$: a i i i ca e ec e i i a de e d P_1 a d P_2. We a e ha $P_1 \xrightarrow{\pi_{o_1}} P_1'$ a d $P_2 \xrightarrow{\pi_{o_2}} P_2'$, a d he a e i i e i , a ed b a i i $\mathbb{C}_1 \xrightarrow{*} \mathbb{C}_1'$ a d $\mathbb{C}_2 \xrightarrow{*} \mathbb{C}_2'$ e ec i e . $\mathcal{F}(P_1|P_2) \stackrel{\text{def}}{=} \mathcal{F}(P_1) \,||\, \mathcal{F}(P_2)$, ha e ha e ha ha a i i $P_1|P_2$ ca e ec e i be i , a ed b a i i $\mathbb{C} \xrightarrow{*} \mathbb{C}_1' \Uparrow \mathbb{C}_2$, $\mathbb{C} \xrightarrow{*} \mathbb{C}_1 \Uparrow \mathbb{C}_2'$ $\mathbb{C} \xrightarrow{*} \mathbb{C}_1' \Uparrow \mathbb{C}_2'$ h e $\Pi_1(\mathbb{C}) = \mathcal{F}(P_1|P_2)$, $\Pi_1(\mathbb{C}_1) = \mathcal{F}(P_1)$ a d $\Pi_1(\mathbb{C}_2) = \mathcal{F}(P_2)$. We e he a $\Uparrow$ c j i c g a i . F i a ce, c j i c g a i $\mathbb{C} = (p, \sigma, s, i)$ a d $\mathbb{C}' = (p', \sigma', s', i')$ (H e $\sigma'{=}\sigma$, $s'{=}s$ a d $i'{=}i$ a d he a e he c di i be a i ed b c j i c g a i) e ha e $\mathbb{C} \Uparrow \mathbb{C}' \stackrel{\text{def}}{=} (p||p', \sigma, s, i)$.

(3) F a ch c e $[a_1 = a_2]P$: a i i i ca e ec e a e de e de P. If he e a_1 a d a_2 a e e i a e , he beha i f $[a_1 = a_2]P$ h d be a P, e e a 0. We a e ha $P \xrightarrow{\pi_o} P'$ a d hi a i i i be i , a ed b a i i $\mathbb{C}' \xrightarrow{*} \mathbb{C}''$. Acc di g $\mathcal{F}([a_1 = a_2]P) \stackrel{\text{def}}{=}$ if $C_{a_1} = C_{a_2}$ then $\mathcal{F}(P)$ else ε e ha e ha if he c di i i a i ed ha a i i $[a_1 = a_2]P$ ca f i be i , a ed b $\mathbb{C} \xrightarrow{*} \mathbb{C}''$ h e $\Pi_1(\mathbb{C}) = \mathcal{F}([a_1 = a_2]P)$ a d $\Pi_1(\mathbb{C}') = \mathcal{F}(P)$.

(4) F e ic i c e $\nu a\ P$: a i i i ca e ec e a e ba ed P. We a e ha $P \xrightarrow{\pi_o} P'$ a d hi a i i i be i , a ed b a i i $\mathbb{C}' \xrightarrow{*} \mathbb{C}''$. B $\mathcal{F}(\nu a\ P) \stackrel{\text{def}}{=} \exists C_a$:(frame$(C_a) \wedge \mathcal{F}(P))$ e ge ha ha a i i $\nu a\ P$ ca f i be i , a ed b $\mathbb{C} \xrightarrow{*} \mathbb{C}'''$ h e $\Pi_1(\mathbb{C}) = \mathcal{F}(\nu a\ P)$ a d $\Pi_1(\mathbb{C}''') = \exists C_a$:(frame$(C_a) \wedge \Pi_1(\mathbb{C}''))$.

(5) F ce i a ce $A\langle a_1, \ldots, a_n\rangle$: a i i i ca e ec e a e decided b he de i i f $A(x_1, \ldots, x_n)$. Acc di g $A(x_1, \ldots, x_n)$, he a a i f $A\langle a_1, \ldots, a_n\rangle$ eed c ide ca e , he f i be gi e a f .

1. Wi h ec i e ca i he de i i f A: Si ce $A(x_1, \ldots, x_n)$ i de ed b P_A, e a e $P_A \xrightarrow{\pi_{o_i}} P_i$ $(1 \le i \le m$ a d $m \in \mathbb{N})$ a d he e a i i a e i , a ed b a i i $\mathbb{C}_i \xrightarrow{*} \mathbb{C}_i'$ $(1 \le i \le m$ a d $m \in \mathbb{N})$. Si ce $\mathcal{F}(A\langle a_1, \ldots, a_n\rangle) \stackrel{\text{def}}{=} \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(P_A)$ e ha e ha ha a i i $A\langle a_1, \ldots, a_n\rangle$ ca f i be i , a ed b $\mathbb{C} \xrightarrow{*} \mathbb{C}_1''$, $\mathbb{C} \xrightarrow{*} \mathbb{C}_2''$, a d $\mathbb{C} \xrightarrow{*} \mathbb{C}_m''$ h e $\Pi_1(\mathbb{C}) = \mathcal{F}(A\langle a_1, \ldots, a_n\rangle)$ a d $\Pi_1(\mathbb{C}_i'') = \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\Pi_1(\mathbb{C}_i')$.
2. Wi h ec i e ca i he de i i f A a d $A(x_1, \ldots, x_n) \equiv \pi_1^s + \pi_1^{'s} \cdot A\langle x_1, \ldots, x_n\rangle$: Si ce he a a i a ec i i ced e ge a gi e e i a i e f $A\langle a_1, \ldots, a_n\rangle$. The f i be gi e b i d c i he i a i e j.

Base case F j=0, $A_0\langle a_1, \ldots, a_n\rangle \equiv \{\overrightarrow{a}/\overrightarrow{x}\}\pi_1^s$, h e π_1^s de e $\pi_{1_1} \cdot \cdots \cdot \pi_{1_{n_1}}$, e a e ha $\{\overrightarrow{a}/\overrightarrow{x}\}\pi_1^s \xrightarrow{\{\overrightarrow{a}/\overrightarrow{x}\}\pi_{o_{1_1}}} P_1 \ldots P_{n_1-1} \xrightarrow{\{\overrightarrow{a}/\overrightarrow{x}\}\pi_{o_{1_{n_1}}}} 0$, h e $\pi_{o_{1_1}}$ a d $\pi_{o_{1_{n_1}}}$ e he c e di g b abe ac i f π_{1_1} a d $\pi_{1_{n_1}}$ e ec i e . Si ce $\mathcal{F}(A_0\langle a_1, \ldots, a_n\rangle) := \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s)$, e c e ha e ha he e a i i i be , a ed b $\mathbb{C} \xrightarrow{*} \mathbb{C}_1 \cdots \mathbb{C}_{n_1-1} \xrightarrow{*} \mathbb{C}'$, h e $\Pi_1(\mathbb{C}) = \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s)$ a d $\Pi_1(\mathbb{C}') = \varepsilon$.

Induction S e ha f $\mathcal{F}(A_{j-1}\langle a_1, \ldots, a_n\rangle)$, a i i i ca f i be , a ed b $\mathbb{C}_{j-1} \xrightarrow{*} \mathbb{C}'_{j-1}$. The , f j, e ha e ha $\mathcal{F}(A_j\langle a_1, \ldots, a_n\rangle) := \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s) \vee (\{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1'^s); \mathcal{F}(A_{j-1}\langle a_1, \ldots, a_n\rangle))$. Wha a i i i ca f i be , a ed b $\mathbb{C}_j \xrightarrow{*} \mathbb{C}_1 \cdots \mathbb{C}_{n_1-1} \xrightarrow{*} \mathbb{C}'_j$, h e $\Pi_1(\mathbb{C}_j) = \{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1^s)$ a d $\Pi_1(\mathbb{C}'_j) = \varepsilon$ (a i he ba e ca e) $\mathbb{C}_j \xrightarrow{*} \mathbb{C}_{j-1}$, h e $\Pi_1(\mathbb{C}_j) = (\{\overrightarrow{C_a}/\overrightarrow{C_x}\}\mathcal{F}(\pi_1'^s); \mathcal{F}(A_{j-1}\langle a_1, \ldots, a_n\rangle))$. The ef e, The 2 h d . □

6 Case study

I hi ec i he a ic ched i g a g i (RMSA) (Li a d La a d 1973) de ed b -π. B he a f a i $\mathcal{F}$, i i a ed a MSVL a d he ce i ed b ech i e f MSVL.

RMSA dea i h he ched abi i f a e f i dic a . Se a c c i ha e bee gi e i he e ea , b he e h d a e decidab e i ica e. I hi a e i if hi de chec i g ba ed a f a i a d MSVL. The a e be c id ed eed a i f he c di i : (1)The e e f each a a e i dic i h c a i a be ee e e . (2)The dead i e c ai ecif ha each e e be e ed bef e he e e e f he e a cc . The a g i e he a i h h e e ec i g e ha e he highe i i .

I hi a e c ide he e f a i $\{(A : 2, 8), (B : 3, 10), (C : 4, 12)\}$ h e f a e e , a $(A : 2, 8)$, he be 2 i A' e ec i g e a d he ec d 8 i i c c e. The a g i c i f a ched i g ce S, a A *TA*, a B *TB* a d a C *TC*. F he e a e a e ha each a i e he c e di g ac i $\overline{start}\langle t\rangle$ begi i e ec i a d $\overline{stop}\langle t\rangle$ e e i e ec i . The i a be ee he ac i i he e ec i g e. I addi i e e ha he ai i g dead i e f a e a he diff e ce be ee he e ec i g e a d he c c e. Si ce A ha he h e e ec i g e, i i i i highe a d a i B a d C. Si i a , B a i C. Th , a A ca ica e i h he ched i g ce e e i e ec i a d he ai f i dead i e, . U i e a A, a B a d C ca ib be i ed b A ha he ha e f e ia ch ice : d i g he e ec i ai i g f he dead i e, i ed b h a i g.

The a g i de ed i -π be . Acc di g he i i , a B i be e ec ed i A ha bee e ec ed e e . Th , A e $\overline{d_a}$ igge he e ec i f B. Si i a , B e ec e $\overline{d_b}$ igge he e ec i f C. Whe he ai i g dead i e f A ai i e , A e $\overline{i_b}$ a d $\overline{i_c}$ i ai B a d C e ec i e . A , B i i e $\overline{i_c}$ i ai C.

$$
\begin{aligned}
& \nu\ \overrightarrow{n}\ (S\langle\overrightarrow{n_s}\rangle \mid TA\langle\overrightarrow{n_{ta}}\rangle \mid TB\langle\overrightarrow{n_{tb}}\rangle \mid TC\langle\overrightarrow{n_{tc}}\rangle) \\
S(\overrightarrow{n_s}) & \stackrel{\text{def}}{=} await(s_{start}(m_1).S\langle\overrightarrow{n_s}\rangle) + await(s_{stop}(m_2).S\langle\overrightarrow{n_s}\rangle) + \tau \\
TA(\overrightarrow{n_{ta}}) & \stackrel{\text{def}}{=} await(\overline{s_{start}}\langle t_a\rangle.skip^2.await(\overline{s_{stop}}\langle t_a\rangle.await(\overline{d_a}.skip^6.(TA\langle\overrightarrow{n_{ta}}\rangle| \\
& \quad await(\overline{i_c})|await(\overline{i_b}))))) + \tau \\
TB(\overrightarrow{n_{tb}}) & \stackrel{\text{def}}{=} await(d_a.await(\overline{s_{start}}\langle t_b\rangle.(skip^3.await(\overline{s_{stop}}\langle t_b\rangle.await(\overline{d_b}.TB\langle\overrightarrow{n_{tb}}\rangle)) \\
& \quad +await(i_b.TB\langle\overrightarrow{n_{tb}}\rangle)))) + skip^7.\tau.(TB\langle\overrightarrow{n_{tb}}\rangle|await(\overline{i_c})) + await(i_b. \\
& \quad TB\langle\overrightarrow{n_{tb}}\rangle) + \tau \\
TC(\overrightarrow{n_{tc}}) & \stackrel{\text{def}}{=} await(d_b.await(\overline{s_{start}}\langle t_c\rangle.(skip^4.await(\overline{s_{stop}}\langle t_c\rangle.TC\langle\overrightarrow{n_{tc}}\rangle) + await \\
& \quad (i_c.TC\langle\overrightarrow{n_{tc}}\rangle)))) + skip^8.\tau.TC\langle\overrightarrow{n_{tc}}\rangle + await(i_c.TC\langle\overrightarrow{n_{tc}}\rangle) + \tau
\end{aligned}
$$

where $\overrightarrow{n} = s_{start}, s_{stop}, t_a, t_b, t_c, d_a, d_b, i_b, i_c$, $\overrightarrow{n_s} = s_{start}, s_{stop}$, $\overrightarrow{n_{ta}} = s_{start}, s_{stop}, t_a, d_a, i_b, i_c$, $\overrightarrow{n_{tb}} = s_{start}, s_{stop}, t_b, d_a, d_b, i_b, i_c$, $\overrightarrow{n_{tc}} = s_{start}, s_{stop}, t_c, d_b, i_c$.

B he a f ai $\mathcal{F}$ gi e i Sec . 4, he w i be a a ed a f w .

$$
\begin{aligned}
& \mathcal{F}(\nu\ \overrightarrow{n}\ (S\langle\overrightarrow{n_s}\rangle \mid TA\langle\overrightarrow{n_{ta}}\rangle \mid TB\langle\overrightarrow{n_{tb}}\rangle \mid TC\langle\overrightarrow{n_{tc}}\rangle)) \\
\equiv\ & \mathsf{prog}_1 \wedge \mathcal{F}(S\langle\overrightarrow{n_s}\rangle \mid TA\langle\overrightarrow{n_{ta}}\rangle \mid TB\langle\overrightarrow{n_{tb}}\rangle \mid TC\langle\overrightarrow{n_{tc}}\rangle) \\
\equiv\ & \mathsf{prog}_1 \wedge (\mathcal{F}(S\langle\overrightarrow{n_s}\rangle) \mid\mid \mathcal{F}(TA\langle\overrightarrow{n_{ta}}\rangle) \mid\mid \mathcal{F}(TB\langle\overrightarrow{n_{tb}}\rangle) \mid\mid \mathcal{F}(TC\langle\overrightarrow{n_{tc}}\rangle)) \\
\equiv^*\ & \mathsf{prog}_1 \wedge (\\
& \quad j_1 := 0; \\
& \quad \mathcal{F}(S_{-1}\langle\overrightarrow{n_s}\rangle) := \varepsilon; \\
& \quad \mathcal{F}(S_0\langle\overrightarrow{n_s}\rangle) := (p_I \wedge \varepsilon); \\
& \quad \texttt{while}\ (j_1 < N_1) \\
& \quad \texttt{do}\ (j_1 := j_1 + 1; \\
& \quad \mathcal{F}(S_{j_1}\langle\overrightarrow{n_s}\rangle) := (p_I \wedge \varepsilon) \vee \\
& \quad (\exists C_{m_1} : \mathsf{frame}(C_{m_1}) \wedge (w\ ai\_ecei\ e(C_{s_{start}}, C_{m_1}); \mathcal{F}(S_{j_1-1}\langle\overrightarrow{n_s}\rangle))) \vee \\
& \quad (\exists C_{m_2} : \mathsf{frame}(C_{m_2}) \wedge (w\ ai\_ecei\ e(C_{s_{stop}}, C_{m_2}); \mathcal{F}(S_{j_1-1}\langle\overrightarrow{n_s}\rangle))))) \\
& \mid\mid j_2 := 0; \\
& \quad \mathcal{F}(TA_{-1}\langle\overrightarrow{n_{ta}}\rangle) := \varepsilon; \\
& \quad \mathcal{F}(TA_0\langle\overrightarrow{n_{ta}}\rangle) := (p_I \wedge \varepsilon); \\
& \quad \texttt{while}\ (j_2 < N_2) \\
& \quad \texttt{do}\ (j_2 := j_2 + 1; \\
& \quad \mathcal{F}(TA_{j_2}\langle\overrightarrow{n_{ta}}\rangle) := (p_I \wedge \varepsilon) \vee \\
& \quad (w\ ai\_e\ d(C_{s_{start}}, C_{t_a}); skip^2; w\ ai\_e\ d(C_{s_{stop}}, C_{t_a}); w\ ai\_e\ d(C_{d_a}, nil); \\
& \quad skip^6; (\mathcal{F}(TA_{j_2-1}\langle\overrightarrow{n_{ta}}\rangle) \mid\mid w\ ai\_e\ d(C_{i_b}, nil) \mid\mid w\ ai\_e\ d(C_{i_c}, nil)))) \\
& \mid\mid j_3 := 0; \\
& \quad \mathcal{F}(TB_{-1}\langle\overrightarrow{n_{tb}}\rangle) := \varepsilon; \\
& \quad \mathcal{F}(TB_0\langle\overrightarrow{n_{tb}}\rangle) := (p_I \wedge \varepsilon); \\
& \quad \texttt{while}\ (j_3 < N_3) \\
& \quad \texttt{do}\ (j_3 := j_3 + 1;
\end{aligned}
$$

$\mathcal{F}(TB_{j_3}\langle\overrightarrow{n_{tb}}\rangle) :=(p_I \wedge \varepsilon)\vee$
(ai ecei e(C_{d_a}, nil); ai e d(C_{start}, C_{t_b}); $((skip^3$; ai e d(C_{stop}, C_{t_b});
ai e d(C_{d_b}, nil); $\mathcal{F}(TB_{j_3-1}\langle\overrightarrow{n_{tb}}\rangle)) \vee$(ai ecei e$(C_{i_b}, nil)$; $\mathcal{F}(TB_{j_3-1}$
$\langle\overrightarrow{n_{tb}}\rangle)))) \vee (skip^7; (p_I \wedge \varepsilon); (\mathcal{F}(TB_{j_3-1}\langle\overrightarrow{n_{tb}}\rangle) \|$ ai e d$(C_{i_c})))\vee$
(ai ecei e(C_{i_b}, nil); $\mathcal{F}(TB_{j_3-1}\langle\overrightarrow{n_{tb}}\rangle)))$
$\| j_4 :=0$;
$\mathcal{F}(TC_{-1}\langle\overrightarrow{n_{tc}}\rangle) :=\varepsilon$;
$\mathcal{F}(\mathrm{TC}_0\langle\overrightarrow{n_{tc}}\rangle) :=(p_I \wedge \varepsilon)$;
while $(j_4 < N_4)$
do $(j_4 := j_4 + 1$;
$\mathcal{F}(\mathrm{TC}_{j_4}\langle\overrightarrow{n_{tc}}\rangle) :=(p_I \wedge \varepsilon)\vee$
(ai ecei e(C_{d_b}, nil); ai e d(C_{start}, C_{t_c}); $((skip^4$; ai e d(C_{stop}, C_{t_c});
$\mathcal{F}(\mathrm{TC}_{j_4-1}\langle\overrightarrow{n_{tc}}\rangle)) \vee$(ai ecei e$(C_{i_c}, nil)$; $\mathcal{F}(\mathrm{TC}_{j_4-1}\langle\overrightarrow{n_{tc}}\rangle)))) \vee (skip^8; (p_I \wedge \varepsilon)$;
$\mathcal{F}(\mathrm{TC}_{j_4-1}\langle\overrightarrow{n_{tc}}\rangle)) \vee$(ai ecei e$(C_{i_c}, nil)$; $\mathcal{F}(\mathrm{TC}_{j_4-1}\langle\overrightarrow{n_{tc}}\rangle))))$
(he e prog$_1$ de e $\exists C_{start}, C_{stop}, C_{t_a}, C_{t_b}, C_{t_c}, C_{d_a}, C_{d_b}, C_{i_b}, C_{i_c}$: frame
$(C_{start}, C_{stop}, C_{t_a}, C_{t_b}, C_{t_c}, C_{d_a}, C_{d_b}, C_{i_b}, C_{i_c})$.)

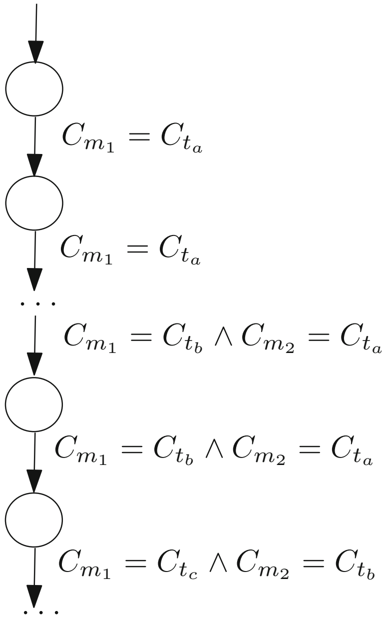
he e $N_i (1 \le i \le 4)$ i a c a i ege .

F ce i a ce $S\langle\overrightarrow{n_s}\rangle, TA\langle\overrightarrow{n_{ta}}\rangle, TB\langle\overrightarrow{n_{tb}}\rangle$ a d $TC\langle\overrightarrow{n_{tc}}\rangle$, he e e ec i e ca i hei de i i . Th , hei a ai , i i e he ec d a ai e f he ce i a ce.

Acc di g he b ai ed MSVL e i if ie e- de e de de ed i -π ea f MSVL. T hi e d a de i g ai a d i ca i f MSVL. Ac a , he ca i he f i g h de : (1) i de i de, gi e he MSVL p f a , he a e ace f he ca ici be gi e a a NFG (N a F G a h) f p (D a e a . 2008a); (2) i h he i ai de, a e ec i a h f he NFG f he i e e ed a he i h e ec ai a a ic f MSVL (Ya g a d D a 2008); (3) de he i ca i de, gi e a de de ibed b a MSVL p, a d a eci ed b a PPTL (R i i a PTL) , a ϕ, i ca a a ica be chec ed he he he ai e he (he he $p \to \phi$ i a id) (D a a d Tia 2008). The ai idea f he i ca i i ha he he he p a i e he ϕ ca e i a e be chec ed b e a ai g he he $\neg(p \to \phi) \equiv p \wedge \neg\phi$ i ai ab e. Thee f e, he ai abi i f a ai he f $p \wedge \neg\phi$ i chec ed b c c i g he NFG f $p \wedge \neg\phi$, a d he de ec i g he he he e e i a h i he NFG. If he e e a h , he i ai ed. O he ha d, he c e e ca be gi e hich ea he d e a i f he . I hi ic e e f c he i ca i de.

I de i de f MSVL, he a e ace f he a g i h di c ed bef e ca be ea ed a d e e ed a a NFG i Fig. 2. I he NFG, a edge de e he c e a e a ig e f he iab e , e.g., $C_{m_1} = C$ ea ha he c e e ec i g a i TA a d $C_{m_2} = C_{tb}$ h ha he a e e ed a i TB. N ice ha , i hi NFG e f c he ai iab e , ig i g h e i h i e ce di c i .

Fig. 2 NFG f a g i h



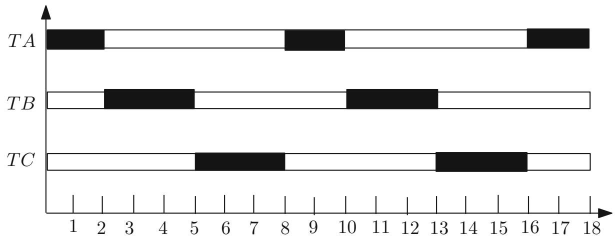


Fig. 3 E ec i f a g i h

The e ec i a f he a g i h i de a ed i Fig. 3.

F hi a g i h e a a e i he he a gi e g f a a e ched a-be . T hi e d e e if he ha a f he a i ee be e ec ed i h i gi he c c e . F c e ie ce f di c i , i-i p_a a d q and

Fig. 4 Vai cai e 1

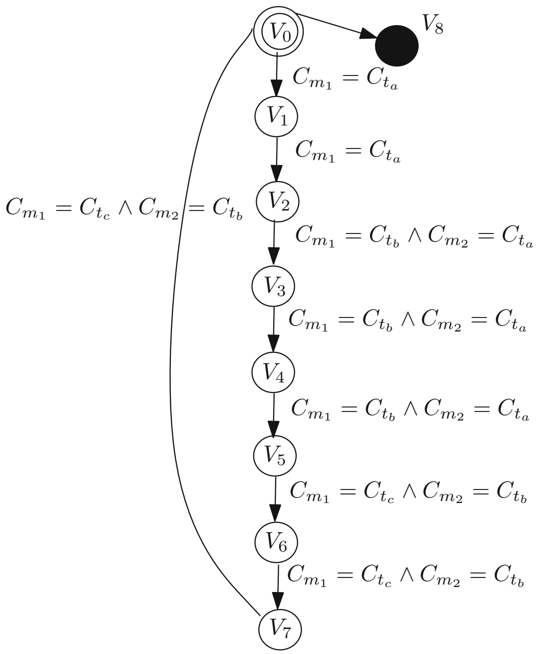
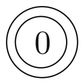


Fig. 5 Vai cai e 2



he begi i g f he MSVL c de f he ai cai i e-de e de ie, he he c de ih de chec . The e i g NFG i d ced a h i Fig. 4. Ob i , he e e i i ie a h he e de $V_i\,(0 \le i \le 7)$ a ea ie f e a d q_c e a ea ha e ca b ai ha TC ha e bee e e e ec ed. He ce, he ca be a i ed.

I de a e e ha hi f a ca be ched ab e e ha e adj he c e f he a . C ide he adj ed e $\{(A:2,9), (B:3,10), (C:4,12)\}$. F hi e e d he de i g, a ai a d i cai agai . A NFG ih edge i d ced a h i Fig. 5. The e ea ha he a i ai ab e ha he a g ih f he adj ed a a i e he .

I addi i e ca a if he i a i e-de e de ie f he a g ih , ch a , a e c i i , i i , e c. D e he i f ace i he c e e i cai f he e ie he e.

7 Conclusion

I hi a , We e a c a a ai $\mathcal{F}$ -π ce e MSVL . Thi e ab e a e e f he he ie a d ech i e f MSVL a a e -π ce e . M e eci e , -π i ab e de , a e a d if i i ce e b ea f MSVL. I he f e e i f he i e iga e he ibi - i f a f i g MSVL g i -π ce e ha a igh e a i hi be ee MSVL a d -π c d be e ab i hed. I addi i , i g f a - f a i be ee -π ce e a d MSVL g a e eeded.

Acknowledgments Thi e ea ch i ed b he Na i a R g Ke Ba ic Re ea ch R jec f Chi a (973 R g) G a . 2010CB328102, Na i a Na a Scie ce F da i f Chi a da G a . 61133001, 61202038, 61272117, 61272118, 61322202 a d 91218301.

References

Be g a J, K J (1985) A geb a f c ica i g ce e i h ab ac i . J The C Sci 37:77 121

D a Z (1996) A e e dedi e a e a gica da f i g ech i ef e a gic g i g. Ph.D The i , U i e i f Ne ca e U T e

D a Z (2006) Te a gic a d e a gic g i g. Scie ce R e , Beiji g

D a Z, Tia C (2008) A i ed de chec i g a ach i h jec i e a gic. I : R ceedi g f ICFEM 2008. LNCS 5256, 167 186

D a Z, K M, H C (1994) R jec i i e a gic g i g. I : R ceedi g f gic g i g a d a ic ea i g. LNAI 822, S i ge , 333 344

D a Z, Tia C, Zha g L (2008a) A deci i ced e f i i a jec i e a gic i h i i de . Ac a I f 45(1):43 78

D a Z, Ya g X, K M (2008b) F ed e a gic g i g. Sci C R g 70(1):31 61

H a e C (1985) C ica i g e e ia ce e . R e ice-Ha , L d

Li C, La a d J (1973) Sched i g a g i h f i g i a ha d- ea i e e i e . J A c C Mach 20(1):46 61

L L, D a Z (2012) A e e ded π-ca c . R c CNSI 2012:632 637

L L, D a Z (2013) A a f a i f -π . I : R ceedi g f ICTAC 2013. LNCS 8049, 267 281

Mi e R (1980) A ca c f c ica i g e . Lec e N e i C e Scie ce 92. S i ge , Heide be g

Mi e R (1999) C ica i g a d bi e e : he π-ca c . C b idge U i e i R e , C b idge

Mi e R, Pa J, Wa e D (1992) A ca c f bi e ce e . I f C 100:1 77

Sa gi gi D, Wa e D (2002) The π-ca c : a he f bi e ce e . C b idge U i e i R e , C b idge

Ta i A (1955) A a ice- he e ica i he e a d i a ica i . Pac J Ma h 5:285 309

Wi e G (1993) The f a e a ic f g i g a g age : a i d c i . C b idge U i e i R e , C b idge

Ya g X, D a Z (2008) O e a i a e a ic f f ed e a. d i:10.1016/j.j a .2008.08.001

Ya g X, D a Z, Ma Q (2010) A a ic e i ca i f ie a e c c e e i g e a gic eci ca i . Ma h S c C Sci 20(5):865 914