

Contents

1	Introduction	2
2	Basic Definitions	2
2.1	λ -calculus λ_2	2
2.2	first-order logic	4
2.3	two-counter automaton	6
3	System P	7
3.1	Definitions	7
3.2	CONS is undecidable	9

1 Introduction

2 Basic Definitions

We will denote the set $\{1, \dots, n\}$ by $[n]$.

2.1 λ -calculus $\lambda 2$

In the following let $\mathcal{V}_T = \{\alpha, a, \beta, b, \dots\}$ be a countable set (of type-variables) and $\mathcal{V}_V = \{x_1, x_2, \dots\}$ be a countable set (of value-variables).

Definition 1. The set of all $\lambda 2$ types over \mathcal{V}_T , denoted by $T_{\lambda 2}$, is the smallest set T satisfying the following conditions:

- $\mathcal{V}_T \subseteq T$,
- if $t_1, t_2 \in T$ then $t_1 \rightarrow t_2 \in T$, and
- if $t \in T$ and $\alpha \in \mathcal{V}_T$ then $\forall \alpha. t \in T$.

The set of all $\lambda 2$ terms over \mathcal{V}_T and \mathcal{V}_V , denoted by $\Lambda_{T_{\lambda 2}}$, is the smallest set Λ_T satisfying the following conditions:

- $\mathcal{V}_V \subseteq \Lambda_T$,
- if $e_1, e_2 \in \Lambda_T$ then $e_1 e_2 \in \Lambda_T$,
- if $x \in \mathcal{V}_V$, $t \in T_{\lambda 2}$, and $e \in \Lambda_T$ then $\lambda x : t. e \in \Lambda_T$,
- if $\alpha \in \mathcal{V}_T$ and $e \in \Lambda_T$ then $\Lambda \alpha. e \in \Lambda_T$, and
- if $e \in \Lambda_T$ and $t \in T_{\lambda 2}$ then $e t \in \Lambda_T$.

Definition 2. Let $e \in \Lambda_{T_{\lambda 2}}$. The free variables of e , denoted by $FV(e)$, are defined inductively as follows:

$$FV(e) = \begin{cases} \{x\} & \text{if } e = x \\ FV(e_1) \cup FV(e_2) & \text{if } e = e_1 e_2 \\ FV(e') \setminus \{x\} & \text{if } e = \lambda x : t. e' \\ FV(e') & \text{if } e = \Lambda \alpha. e' \\ FV(e') & \text{if } e = e' t \end{cases}$$

Or is this definition better?

Definition 3. Let $e \in \Lambda_{T_{\lambda 2}}$. The free variables of e , denoted by $FV(e)$, are defined inductively as follows:

$$\begin{aligned} FV(y) &= \{x\} \\ FV(e_1 e_2) &= FV(e_1) \cup FV(e_2) \\ FV(\lambda x : t. e') &= FV(e') \setminus \{x\} \\ FV(\Lambda \alpha. e') &= FV(e') \\ FV(e' t) &= FV(e') \end{aligned}$$

Definition 4. Let \mathcal{V} be a finite subset of \mathcal{V}_T . A basis $\Gamma = \{(x_1 : t_1), (x_2, t_2), \dots, (x_n, t_n)\}$ is a mapping from \mathcal{V} to $T_{\lambda 2}$.

The free variables of a basis Γ , denoted by $FV(\Gamma)$, are $\bigcup \{FV(t) \mid (x : t) \in \Gamma\}$.

$\lambda 2$ deduction Rules

(Axiom)	$\Gamma, x : t \vdash x : t$	
(λ -Introduction)	$\frac{\Gamma, x : t_1 \vdash e : t_2}{\Gamma \vdash \lambda x. e : t_1 \rightarrow t_2}$	
(λ -Elimination)	$\frac{\Gamma \vdash e_1 : t_1 \rightarrow t_2 \quad \Gamma \vdash e_2 : t_1}{\Gamma \vdash e_1 e_2 : t_2}$	
(\forall -Introduction)	$\frac{\Gamma \vdash e : t}{\Gamma \vdash \Lambda \alpha. e : \forall \alpha. t}$	$\alpha \notin FV(\Gamma)$
(\forall -Elimination)	$\frac{\Gamma \vdash e : \forall \alpha. t}{\Gamma \vdash e t' : t [\alpha := t']}$	$t' \in T_{\lambda 2}$

Definition 5. The inhabitation problem for $\lambda 2$, denoted by **INHAB**, is defined as follows. Given a $\lambda 2$ type t .

Is there a $\lambda 2$ term M such that $\emptyset \vdash M : t$?

But we can rephrase this problem so that it becomes more general: Given a basis Γ and a $\lambda 2$ type t .

Is there a $\lambda 2$ term M such that $\Gamma \vdash M : t$?

Obviously the second version is a special case of the first one. For the other direction consider a basis $\Gamma = \{(x_1 : t_1), \dots, (x_n, t_n)\}$ and a $\lambda 2$ type t . Clearly, for every term M , $\Gamma \vdash M : t$ holds iff $\emptyset \vdash \lambda x_1 : t_1. \dots \lambda x_n : t_n. M : t_1 \rightarrow \dots \rightarrow t_n \rightarrow t$.

2.2 first-order logic

Definition 6. A ranked set is a tuple (Σ, rk) , where Σ is a countable set and $rk: \Sigma \rightarrow \mathbb{N}$ is a function that maps every symbol from Σ to a natural number (its rank).

If the function rk is understood we will just write Σ instead of (Σ, rk) . The set of all elements in Σ with a certain rank k , denoted by $\Sigma^{(k)}$, is defined as $\Sigma^{(k)} := rk^{-1}(k)$.

For the remainder of this section let $\mathcal{V} = \{y_1, y_2, \dots\}$ be a countable set (of variables), \mathcal{F} a ranked set (of function symbols), and \mathcal{P} a ranked set (of predicate symbols).

Definition 7. The set of terms over $(\mathcal{V}, \mathcal{F})$, denoted by $\mathcal{T}_{(\mathcal{V}, \mathcal{F})}$, is the smallest set \mathcal{T} satisfying the following conditions:

- $\mathcal{V} \subseteq \mathcal{T}$, and
- for every $k \in \mathbb{N}$ if $f \in \mathcal{F}^{(k)}$ and $t_1, t_2, \dots, t_k \in \mathcal{T}$ then $f(t_1, t_2, \dots, t_k) \in \mathcal{T}$.

The set of first-order formulas over $(\mathcal{V}, \mathcal{F}, \mathcal{P})$, denoted by $\mathcal{L}_{(\mathcal{V}, \mathcal{F}, \mathcal{P})}$, is the smallest set \mathcal{L} satisfying the following conditions:

- for every $k \in \mathbb{N}$ if $P \in \mathcal{P}^{(k)}$ and $t_1, t_2, \dots, t_k \in \mathcal{T}_{(\mathcal{V}, \mathcal{F})}$ then $P(t_1, t_2, \dots, t_k) \in \mathcal{L}$.
- If $\varphi, \psi \in \mathcal{L}$ then $(\varphi \wedge \psi), (\varphi \vee \psi), \neg\varphi \in \mathcal{L}$, and
- if $y \in \mathcal{V}$ and $\varphi \in \mathcal{L}$ then $\exists y\varphi, \forall y\varphi \in \mathcal{L}$.

We introduce an additional binary operation \rightarrow on formulas, where for some $\varphi, \psi \in \mathcal{L}_{(\mathcal{V}, \mathcal{F}, \mathcal{P})}$ the formula $(\varphi \rightarrow \psi)$ is defined as $(\neg\varphi \vee \psi)$. For nullary relation symbols P we will abbreviate $P()$ to P .

Definition 8. The variables of a term $t \in \mathcal{T}_{(\mathcal{V}, \mathcal{F})}$, denoted by $V(t)$, are defined by:

$$V(t) = \begin{cases} \{y\} & \text{if } t = y \\ V(t_1) \cup V(t_2) \cup \dots \cup V(t_k) & \text{if } t = f(t_1, t_2, \dots, t_k) \end{cases}$$

The free variables of a formula $\varphi \in \mathcal{L}_{(\mathcal{V}, \mathcal{F}, \mathcal{P})}$, denoted by $FV(\varphi)$, are defined as follows:

$$FV(\varphi) = \begin{cases} V(t_1) \cup V(t_2) \cup \dots \cup V(t_k) & \text{if } \varphi = P(t_1, t_2, \dots, t_k) \\ FV(\psi) & \text{if } \varphi = \neg\psi \\ FV(\varphi_1) \cup FV(\varphi_2) & \text{if } \varphi = (\varphi_1 \wedge \varphi_2) \text{ or } \varphi = (\varphi_1 \vee \varphi_2) \\ FV(\psi) \setminus \{y\} & \text{if } \varphi = \forall y\psi \text{ or } \varphi = \exists y\psi \end{cases}$$

Definition 9. Let y be in \mathcal{V} and $t, t' \in \mathcal{T}_{(\mathcal{V}, \mathcal{F})}$. The substitution of y by t' in t , denoted by $t[y := t']$, is defined as follows:

$$t[y := t'] = \begin{cases} t' & \text{if } t = y \\ z & \text{if } t = z \text{ and } z \neq y \\ f(t_1[x := t'], \dots, t_k[x := t']) & \text{if } t = f(t_1, \dots, t_k) \end{cases}$$

Now we can lift this definition to formulas, let φ be in $\mathcal{L}_{(\mathcal{V}, \mathcal{F}, \mathcal{P})}$. The substitution of y by t' in φ , denoted by $\varphi[y := t']$, is defined as follows:

$$\varphi[x := t'] = \begin{cases} P(t_1[y := t'], \dots, t_k[y := t']) & \text{if } \varphi = P(t_1, \dots, t_k) \\ \psi[y := t'] & \text{if } \varphi = \neg\psi \\ \varphi_1[y := t'] \circ \varphi_2[y := t'] & \text{if } \varphi = (\varphi_1 \wedge \varphi_2) \text{ or } \varphi = (\varphi_1 \vee \varphi_2) \\ \varphi & \text{if } \varphi = \forall y\psi \text{ or } \varphi = \exists y\psi \\ Qz(\psi[y := t']) & \text{if } \varphi = Qz\psi, Q \in \{\forall, \exists\} \text{ and } z \neq y \end{cases}$$

Now we come to the semantics of first-order formulas.

Definition 10. An interpretation I over $(\mathcal{V}, \mathcal{F}, \mathcal{P})$ is a triple $(\Delta, \cdot^I, \omega)$ where Δ is a nonempty set (which we call domain), \cdot^I is a function such that $f^I : \Delta^k \rightarrow \Delta$ is a function for every $k \in \mathbb{N}$, $f \in \mathcal{F}^{(k)}$ and $P^I \subseteq \Delta^k$ is a relation for every $k \in \mathbb{N}$, $P \in \mathcal{P}^{(k)}$ and ω is a function from \mathcal{V} to Δ .

Let $I = (\Delta, \cdot^I, \omega)$ be an interpretation, $x \in \mathcal{V}$, and $d \in \Delta$ the interpretation $I[x \rightarrow d]$ is defined as $(\Delta, \cdot^I, \omega[x \rightarrow d])$ where

$$(\omega[x \rightarrow d])(y) = \begin{cases} d & \text{if } y = x \\ \omega(y) & \text{otherwise.} \end{cases}$$

Definition 11. Let $I = (\Delta, \cdot^I, \omega)$ be an interpretation and t a term. The interpretation of t under I , denoted by t^I , is defined as follows:

$$t^I = \begin{cases} \omega(x) & \text{if } t = x \\ f^I(t_1^I, \dots, t_k^I) & \text{if } t = f(t_1, \dots, t_k) \end{cases}$$

Let φ be a formula. The interpretation of φ under I , denoted by φ^I , is defined recursively as follows:

$$\varphi^I = \begin{cases} \top & \text{if } \varphi = P(t_1, \dots, t_k) \text{ and } (t_1^I, \dots, t_k^I) \in P^I \\ \perp & \text{if } \varphi = P(t_1, \dots, t_k) \text{ and } (t_1^I, \dots, t_k^I) \notin P^I \\ \text{not } \psi^I & \text{if } \varphi = \neg\psi \\ \varphi_1^I \text{ and } \varphi_2^I & \text{if } \varphi = (\varphi_1 \wedge \varphi_2) \\ \varphi_1^I \text{ or } \varphi_2^I & \text{if } \varphi = (\varphi_1 \vee \varphi_2) \\ \text{exists } d \in \Delta \psi^I[x \rightarrow d] & \text{if } \varphi = \exists x\psi \\ \text{forall } d \in \Delta \psi^I[x \rightarrow d] & \text{if } \varphi = \forall x\psi \end{cases}$$

The interpretation I is a model of φ , denoted by $I \models \varphi$, if $\varphi^I = \top$.

When we define an interpretation I and we have a nullary predicate symbol P we write $P^I = \top$ instead of $P^I = \{()\}$ and $P^I = \perp$ for $P^I = \emptyset$ (this works because $P()^I = \top$ iff $() \in P^I$).

Definition 12. Let Γ be a finite set of first-order formulas.

We say that an interpretation I is a model of Γ , denoted by $I \models \Gamma$, if $I \models \psi$ for every ψ in Γ .

The formula φ is a semantic consequence of Γ , denoted by $\Gamma \vdash \varphi$, if every model of Γ is also a model of φ .

The free variables of Γ , denoted by $\text{FV}(\Gamma)$, are $\bigcup \{\text{FV}(\varphi) \mid \varphi \in \Gamma\}$.

2.3 two-counter automaton

We will use a version of two-counter automaton which only has two types of transitions. First it can increment a register and second it can decrement a register or jump if the register is already zero. Formally:

Definition 13. A deterministic two-counter automaton is a 4-tuple $M = (\mathcal{Q}, Q_0, Q_f, R)$,

- where \mathcal{Q} is a finite set (of states),
- Q_0 is in \mathcal{Q} (the initial state),
- Q_f is in \mathcal{Q} (the final state), and
- R is a function from $\mathcal{Q} \setminus \{Q_f\}$ to $\mathcal{R}_{\mathcal{Q}}$,
where $\mathcal{R}_{\mathcal{Q}} = \{+(i, Q') \mid i \in \{1, 2\}, Q' \in \mathcal{Q}\} \cup \{-(i, Q_1, Q_2) \mid i \in \{1, 2\}, Q_1, Q_2 \in \mathcal{Q}\}$

A configuration C of our automaton is a triple $\langle Q, m, n \rangle$, where $Q \in \mathcal{Q}$ and $m, n \in \mathbb{N}$. Let r be in $R(\mathcal{Q} \setminus \{Q_f\})$, then \Rightarrow_M^r is a binary relation on the configurations of M such that two configurations $\langle Q, m, n \rangle, \langle \hat{Q}, \hat{m}, \hat{n} \rangle$ of M are in the relation if all of the following conditions hold:

- $Q \neq Q_f, r = R(Q)$,
- if $r = +(1, Q')$ for some $Q' \in \mathcal{Q}$ then $\hat{Q} = Q', \hat{m} = m + 1$, and $\hat{n} = n$,
- if $r = +(2, Q')$ for some $Q' \in \mathcal{Q}$ then $\hat{Q} = Q', \hat{m} = m$, and $\hat{n} = n + 1$,
- if $r = -(1, Q_1, Q_2)$ for some $Q_1, Q_2 \in \mathcal{Q}$ then
 - if $m = 0$ then $\hat{Q} = Q_2, \hat{m} = 0$, and $\hat{n} = n$,
 - if $m \geq 1$ then $\hat{Q} = Q_1, \hat{m} = m - 1$, and $\hat{n} = n$,
- if $r = -(2, Q_1, Q_2)$ for some $Q_1, Q_2 \in \mathcal{Q}$ then
 - if $n = 0$ then $\hat{Q} = Q_2, \hat{m} = m$, and $\hat{n} = 0$,
 - if $n \geq 1$ then $\hat{Q} = Q_1, \hat{m} = m$, and $\hat{n} = n - 1$.

The transition relation of M , denoted by \Rightarrow_M , is defined as $\bigcup_{r \in R(Q \setminus \{Q_f\})} \Rightarrow_M^r$. We denote the transitive reflexive closure of \Rightarrow_M by \Rightarrow_M^* .

Let m, n be in \mathbb{N} , we say that M terminates on input (m, n) if there exist $\hat{m}, \hat{n} \in \mathbb{N}$ such that $\langle Q_0, m, n \rangle \Rightarrow_M^* \langle Q_f, \hat{m}, \hat{n} \rangle$.

Definition 14. The halting problem for two-counter automaton, denoted by **HALT**, is defined as follows. Given a two-counter automaton M .

Does M terminate on input $(0, 0)$?

It is well known that **HALT** is undecidable.

3 System P

3.1 Definitions

In the following let $\mathcal{V}_P = \{\alpha, a, \beta, b, \dots\}$ be a countably infinite subset of \mathcal{V}_T (of variables). Let $\mathcal{P}_P = \{P, Q, \dots\}$ be a set (of predicate symbols) and \mathcal{P} a ranked set such that $\mathcal{P}^{(0)} = \{\mathbf{false}\}$, $\mathcal{P}^{(2)} = \mathcal{P}_P$, and $\mathcal{P}^{(k)} = \emptyset$ for all $k \in \mathbb{N} \setminus \{0, 2\}$. A first-order logic formula φ over $(\mathcal{V}_P, \emptyset, \mathcal{P})$ is an

atomic formula if $\varphi = \mathbf{false}$ or $\varphi = P(a, b)$ for some $P \in \mathcal{P}_P$ and $a, b \in \mathcal{V}_P$.

universal formula if $\varphi = \forall \vec{\alpha} (A_1 \rightarrow A_2 \rightarrow \dots \rightarrow A_n)$ where A_i is an atomic formula for $i \in [n]$, $A_i \neq \mathbf{false}$ for $i \in [n-1]$ and for each $\alpha \in \text{FV}(\varphi) \cap \text{FV}(A_n)$ there exists an $i \in [n-1]$ such that $\alpha \in \text{FV}(A_i)$.

existential formula if there exists $n \geq 0$, atomic formulas $A_i \neq \mathbf{false}$ for $i \in [n]$ such that $\varphi = \forall \vec{\alpha} (A_1 \rightarrow A_2 \rightarrow \dots \rightarrow A_{n-1} \rightarrow \forall \beta (A_n \rightarrow \mathbf{false}) \rightarrow \mathbf{false})$.

The set of formulas of System **P** (= set of **P**-formulas) over $(\mathcal{V}_P, \mathcal{P}_P)$ is the set of all first-order formulas over $(\mathcal{V}_P, \emptyset, \mathcal{P})$ that are either an atomic, universal or existential formula.

Deduction Rules

(Axiom)	$\Gamma, A \vdash A$	
(\rightarrow -Introduction)	$\frac{\Gamma, A \vdash B}{\Gamma \vdash A \rightarrow B}$	
(\rightarrow -Elimination)	$\frac{\Gamma \vdash A \rightarrow B \quad \Gamma \vdash A}{\Gamma \vdash B}$	
(\forall -Introduction)	$\frac{\Gamma \vdash B}{\Gamma \vdash \forall \alpha B}$	$\alpha \notin \text{FV}(\Gamma)$
(\forall -Elimination)	$\frac{\Gamma \vdash \forall \alpha B}{\Gamma \vdash B[\alpha := b]}$	$b \in \mathcal{V}_P$

An Interpretation I of a P formula is a tuple $I = (\Delta, \cdot^I)$ where Δ is a set (called domain), $P^I \subseteq \Delta^k$ and $\alpha^I \in \Delta \dots$

If we interpret **false** with the logical constant false (\perp) (denoted by \vdash_f) we can add a new deduction rule.

(\exists -Introduction)	$\frac{\Gamma, A[\alpha := a] \vdash_f B}{\Gamma, \forall \alpha (A \rightarrow \mathbf{false}) \rightarrow \mathbf{false} \vdash_f B}$	$a \notin \text{FV}(\Gamma, A, B)$
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Proof. Let $I = (\Delta, \cdot^I, \omega)$ be a model of $\Gamma, \forall \alpha (A \rightarrow \mathbf{false}) \rightarrow \mathbf{false}$ with $\mathbf{false}^I = \perp$ and $a \in \mathcal{V}_P$ a variable such that $a \notin \text{FV}(\Gamma, A, B)$.

$$\begin{aligned}
I \models \Gamma, \forall \alpha (A \rightarrow \mathbf{false}) \rightarrow \mathbf{false} &\Rightarrow I \models \forall \alpha (A \rightarrow \mathbf{false}) \rightarrow \mathbf{false} \\
&\Rightarrow (\forall \alpha (A \rightarrow \mathbf{false}))^I \rightarrow \mathbf{false}^I \\
&\Rightarrow (\forall \alpha (A \rightarrow \mathbf{false}))^I \rightarrow \perp \\
&\Rightarrow \neg(\forall \alpha (A \rightarrow \mathbf{false}))^I \\
&\Rightarrow \neg(\forall d \in \Delta : (A \rightarrow \mathbf{false})^{I[\alpha \mapsto d]}) \\
&\Rightarrow \exists d \in \Delta : \neg(A^{I[\alpha \mapsto d]} \rightarrow \mathbf{false}^{I[\alpha \mapsto d]}) \\
&\Rightarrow \exists d \in \Delta : \neg(A^{I[\alpha \mapsto d]} \rightarrow \perp) \\
&\Rightarrow \exists d \in \Delta : \neg(\neg A^{I[\alpha \mapsto d]}) \\
&\Rightarrow \exists d \in \Delta : A^{I[\alpha \mapsto d]}
\end{aligned}$$

Together with $a \notin \text{FV}(\Gamma, A)$, it follows that $I[a \mapsto d]$ is a model of $\Gamma, A[\alpha := a]$. Which implies $I[a \mapsto d] \models B$. Since a is not free in B we conclude that I is also a model of B . \square

Definition 15. The problem to decide whether a given set of **P**-formulas is consistent, denoted by **CONS**, is defined as follows. Given a set of **P**-formulas Γ .

Does $\Gamma \vdash \mathbf{false}$ not hold?

3.2 CONS is undecidable

We will show that $\mathbf{HALT} \leq \mathbf{CONS}$ then the undecidability of \mathbf{CONS} directly follows from the undecidability of \mathbf{HALT} . For a given two-counter automaton M we will effectively construct a set of \mathbf{P} -formulas Γ_M such that

$$M \text{ terminates on input } (0, 0) \quad \text{iff} \quad \Gamma_M \vdash \mathbf{false} \text{ holds in system } \mathbf{P}.$$

Let $M = (\mathcal{Q}, Q_0, Q_f, R)$ be a two-counter automaton, w.l.o.g. $S, P, R_1, R_2, E, D \notin \mathcal{Q}$. In the following we will consider \mathbf{P} -formulas over $(\mathcal{V}_P, \mathcal{P}_P)$, where $\mathcal{P}_P = \mathcal{Q} \uplus \{S, P, R_1, R_2, E, D\}$. We will abbreviate $P(a, a)$ to $P(a)$, note that this way we can use binary predicate symbols as unary ones.

Intuitively $Q(a)$ stands for “ a is in state Q ”, $R_i(a, m)$ stands for “in a the value of register i is m ” for $i \in \{1, 2\}$, $S(a, b)$ states that “ b is a successor of a ”, $P(a, b)$ states that “ b is a predecessor of a ”, $E(a)$ marks “ a as the end of chain”, and $D(a)$ states that “ a is not the end of a chain”.

For a configuration $C = \langle Q, m, n \rangle$ of M we define a set of \mathbf{P} -formulas Γ_C . It contains the following formulas:

- $Q(a)$
- $R_1(a, a_0), P(a_{i-1}, a_i)$ for $i \in \{1, \dots, m\}$
- $R_2(a, b_0), P(b_{i-1}, b_i)$ for $i \in \{1, \dots, n\}$
- $D(a), D(a_i), D(b_j)$ for $i \in \{0, \dots, m-1\}$ and $j \in \{0, \dots, n-1\}$
- $E(a_m), E(b_n)$

Next we need sets of \mathbf{P} -formulas for all possible transitions. For every $Q \in \mathcal{Q} \setminus \{Q_f\}$ and $r \in \mathcal{R}_Q$ we define $\Gamma_{Q,r}$. If $r = +(1, Q')$ for some $Q' \in \mathcal{Q}$ then $\Gamma_{Q,+(1,Q')}$ contains the following formulas:

- $\forall \alpha \beta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow Q'(\beta))$
change of state
- $\forall \alpha \beta \gamma \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow R_1(\beta, \delta) \rightarrow P(\delta, \gamma))$
increment register 1
- $\forall \alpha \beta \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\beta, \delta) \rightarrow D(\delta))$
prevent zero in register 1
- $\forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_2(\alpha, \gamma) \rightarrow R_2(\beta, \gamma))$
do not change the value register 2

If $r = -(1, Q_1, Q_2)$ for some $Q_1, Q_2 \in \mathcal{Q}$ then $\Gamma_{Q,-(1,Q_1,Q_2)}$ contains the following formulas:

- $\forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow E(\gamma) \rightarrow Q_2(\beta))$
jump to Q_2 if register 1 is zero
- $\forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow E(\gamma) \rightarrow R_1(\beta, \gamma))$
if register 1 is zero it stays zero
- $\forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow D(\gamma) \rightarrow Q_1(\beta))$
change state to Q_1 if register 1 is greater zero
- $\forall \alpha \beta \gamma \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow D(\gamma) \rightarrow P(\gamma, \delta) \rightarrow R_1(\beta, \delta))$
decrement register 1
- $\forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_2(\alpha, \gamma) \rightarrow R_2(\beta, \gamma))$
do not change register 2 in both cases

For $r = +(2, Q')$ for some $Q' \in \mathcal{Q}$ or $r = -(2, Q_1, Q_2)$ for some $Q_1, Q_2 \in \mathcal{Q}$ the sets $\Gamma_{Q,r}$ are defined analogously.

We also need a set Γ_1 to ensure that our representation works correctly. The following formula are in Γ_1 :

- $\forall \alpha \beta (S(\alpha, \beta) \rightarrow D(\beta))$
no successor is the end of a chain
- $\forall \alpha (D(\alpha) \rightarrow \forall \beta (R_1(\alpha, \beta) \rightarrow \mathbf{false}) \rightarrow \mathbf{false})$
every element that represents a configuration has a value for register 1
- $\forall \alpha (D(\alpha) \rightarrow \forall \beta (R_2(\alpha, \beta) \rightarrow \mathbf{false}) \rightarrow \mathbf{false})$
every element that represents a configuration has a value for register 2
- $\forall \alpha (\forall \beta (S(\alpha, \beta) \rightarrow \mathbf{false}) \rightarrow \mathbf{false})$
every element has a successor

We define $\Gamma_{\overline{M}}$ as $\bigcup_{Q \in \mathcal{Q} \setminus \{Q_f\}} \Gamma_{Q, R(Q)} \cup \{\forall \alpha (Q_f(\alpha) \rightarrow \mathbf{false})\} \cup \Gamma_1$. Finally we can define Γ_M as $\Gamma_{C_1} \cup \Gamma_{\overline{M}}$, where $C_1 = \langle Q_0, 0, 0 \rangle$ is the initial configuration.

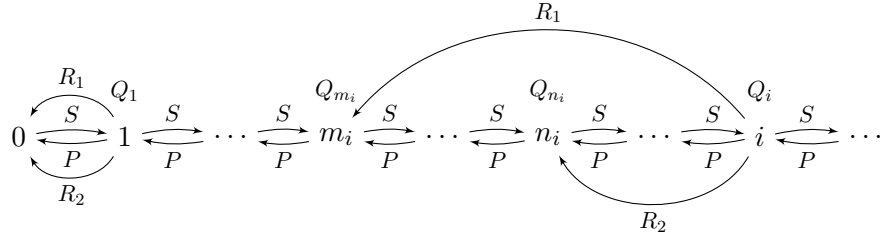
Claim 16.

$$\Gamma_M \vdash \mathbf{false} \text{ holds in system } P \quad \implies \quad M \text{ terminates on input } (0, 0)$$

Proof. Assume M does not terminate then there is an infinite chain $C_1 \Rightarrow_M C_2 \Rightarrow_M C_3 \Rightarrow_M \dots$ ($C_i = \langle Q_i, m_i, n_i \rangle$ for $i \in \mathbb{N}^+$). Now we construct a model of Γ_M which interprets \mathbf{false} with \perp this contradicts $\Gamma_M \vdash \mathbf{false}$.

To illustrate the idea we will use a graphical notation for an interpretation I . By $d_1 \xrightarrow{R} d_2$ we say that $(d_1, d_2) \in R^I$. And we use $\overset{P}{d}$ to say that $(d, d) \in P^I$ for predicate symbols that are used as unary predicate symbols. As domain for our interpretation we will use the natural numbers. Every number will have two tasks: firstly it will represent itself as a possible value for register 1 or 2 and secondly every number i greater than

zero will also represent the i^{th} configuration of our infinite computation. Now the idea for our model of Γ_M looks like this:



We have $0 \in E^I$ and all other numbers are in D^I .

Here is the more formal definition of our model $I = (\mathbb{N}, \cdot^I, \omega)$.

$$\begin{aligned}
P^I &= \{(i+1, i) \mid i \in \mathbb{N}\} & R_1^I &= \{(i, m_i) \mid i \in \mathbb{N}\} & R_2^I &= \{(i, n_i) \mid i \in \mathbb{N}\} \\
Q^I &= \{(i, i) \mid i \in \mathbb{N}^+, Q = Q_i\} & D^I &= \{(i, i) \mid i \in \mathbb{N}^+\} & E^I &= \{(0, 0)\} \\
S^I &= \{(i, i+1) \mid i \in \mathbb{N}\} & \mathbf{false}^I &= \perp
\end{aligned}$$

$$a^I = 1$$

$$a_0^I = 0$$

$$b_0^I = 0$$

Since there are no free variables in Γ_M we can just set $\omega(x) = 0$ for every $x \in \mathcal{V}_P$. It is easy to see that I is indeed a model of Γ_M . \square

Claim 17. *Let $C = \langle Q, m, n \rangle$ be a configuration of M . If a final configuration (i.e. a configuration $\langle Q_f, m', n' \rangle$ for some $n', m' \in \mathbb{N}$) is reachable from C then $\Gamma_C \cup \Gamma_{\overline{M}} \vdash \mathbf{false}$.*

Proof. By induction on the length i of the computation.

Induction Base: $i = 0$

Since a final configuration is reachable in 0 steps C must be this final configuration. So $C = \langle Q_f, m, n \rangle$ for some $n, m \in \mathbb{N}$. Hence, $Q_f(a)$ is in Γ_C for some $a \in \mathcal{V}_P$ and $\forall \alpha(Q_f(\alpha) \rightarrow \mathbf{false})$ is in $\Gamma_{\overline{M}}$, we can easily deduce false.

$$\frac{\frac{\Gamma_C \cup \Gamma_{\overline{M}} \vdash \forall \alpha(Q_f(\alpha) \rightarrow \mathbf{false})}{\Gamma_C \cup \Gamma_{\overline{M}} \vdash Q_f(a) \rightarrow \mathbf{false}} \quad \Gamma_C \cup \Gamma_{\overline{M}} \vdash Q_f(a)}{\Gamma_C \cup \Gamma_{\overline{M}} \vdash \mathbf{false}}$$

Induction Step: $i = i' + 1$

Since $I \models \mathbf{false}$ holds trivially if I interprets \mathbf{false} with \top we only need to consider models of $\Gamma_C \cup \Gamma_{\overline{M}}$ that interpret \mathbf{false} with \perp (note that there are no such models if M terminates which is exactly what we want to prove). As result of this observation we can use the \exists -Introduction rule.

From the fact that a final configuration is reachable from C in i steps we can deduce that there exists a configuration $D = \langle \hat{Q}, \hat{m}, \hat{n} \rangle$ such that $C \Rightarrow_M^r D$ for some $r \in \mathcal{R}_Q$ and a final configuration is reachable from D in i' steps. We also know that $C = \langle Q, m, n \rangle$ for some $Q \in \mathcal{Q} \setminus \{Q_f\}$ and some $m, n \in \mathbb{N}$. The set Γ_C contains the formulas:

$R_1(a, a_0)$, $P(a_{i-1}, a_i)$ and $D(a_{i-1})$ for $i \in \{1, \dots, n\}$,
 $R_2(a, b_0)$, $P(b_{i-1}, b_i)$ and $D(b_{i-1})$ for $i \in \{1, \dots, m\}$,
 $Q(a)$, $D(a)$, $E(a_n)$ and $E(b_m)$.

And Γ_D contains the formulas:

$R_1(\hat{a}, \hat{a}_0)$, $P(\hat{a}_{i-1}, \hat{a}_i)$ and $D(\hat{a}_{i-1})$ for $i \in \{1, \dots, \hat{n}\}$,
 $R_2(\hat{a}, \hat{b}_0)$, $P(\hat{b}_{i-1}, \hat{b}_i)$ and $D(\hat{b}_{i-1})$ for $i \in \{1, \dots, \hat{m}\}$,
 $Q(\hat{a})$, $D(\hat{a})$, $E(\hat{a}_{\hat{n}})$ and $E(\hat{b}_{\hat{m}})$.

The basic idea is to deduce Γ_D from $\Gamma_C \cup \Gamma_{\overline{M}}$ and then apply the induction hypothesis to $\Gamma_D \cup \Gamma_{\overline{M}}$.

$$\frac{\frac{IH}{\Gamma_C \cup \Gamma_{\overline{M}} \cup \Gamma_D \vdash_f \mathbf{false}} \quad \Gamma_C \cup \Gamma_{\overline{M}} \vdash_f \Gamma_D}{\Gamma_C \cup \Gamma_{\overline{M}} \vdash_f \mathbf{false}}$$

We achieve this by looking at the four possible cases for the type of the rule r . We will only consider the cases $r = +(1, Q')$ and $r = -(1, Q_1, Q_2)$, the two remaining cases $r = +(2, Q')$ and $r = -(2, Q_1, Q_2)$ follow by exchanging the roles of register 1 and register 2 in the first two cases.

First we need a new free variable representing the configuration D . Also the value in register 2 does not change, because in both cases we are only concerned with register 1. For the succeeding tableau proofs we will abbreviate **false** by **f** and we will drop $\Gamma_C \cup \Gamma_{\overline{M}}$ and only write new formulas on the left side of \vdash_f .

We first introduce a new variable representing D (let $b \in \mathcal{V}_P \setminus \text{FV}(\Gamma_C \cup \Gamma_{\overline{M}})$).

$$\frac{\begin{array}{c} \vdots \\ \frac{S(a, b), D(b) \vdash_f \mathbf{f}}{S(a, b) \vdash_f D(b) \rightarrow \mathbf{f}} \end{array} \quad \frac{S(a, b) \vdash_f \forall \alpha \beta (S(\alpha, \beta) \rightarrow D(\beta))}{S(a, b) \vdash_f S(a, b) \rightarrow D(b)} \quad \frac{S(a, b) \vdash_f S(a, b)}{S(a, b) \vdash_f D(b)}}{\frac{S(a, b) \vdash_f \mathbf{f}}{\forall \beta (S(a, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f} \vdash_f \mathbf{f}}} \quad \frac{\vdash_f \forall \alpha (\forall \beta (S(\alpha, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f})}{\vdash_f \forall \beta (S(a, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f}}}{\vdash_f \mathbf{f}}$$

Since register 2 should not change we need $R_2(b, b_0)$. Again we will just drop $S(a, b)$ and $D(b)$ on the left side for comprehensibility.

$$\begin{array}{c}
\vdots \\
\frac{R_2(b, b_0) \vdash_f \mathbf{f}}{\vdash_f R_2(b, b_0) \rightarrow \mathbf{f}} \quad \frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_2(\alpha, \gamma) \rightarrow R_2(\beta, \gamma))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_2(a, b_0) \rightarrow R_2(b, b_0)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_2(a, b_0) \rightarrow R_2(b, b_0)} \quad \vdash_f S(a, b)} \\
\frac{\vdash_f R_2(a, b_0) \rightarrow R_2(b, b_0)}{\vdash_f R_2(b, b_0)} \quad \vdash_f R_2(a, b_0)
\end{array}
\vdash_f \mathbf{f}$$

For the case that $\mathbf{r} = +(\mathbf{1}, \mathbf{Q}')$, we have that $\widehat{Q} = Q'$, $\widehat{m} = m + 1$, and $\widehat{n} = n$. So we need to increment register 1 and ensure that the state of b is Q' .

$$\begin{array}{c}
\vdots \\
\frac{Q'(b) \vdash_f \mathbf{f}}{\vdash_f Q'(b) \rightarrow \mathbf{f}} \quad \frac{\frac{\frac{\vdash_f \forall \alpha \beta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow Q'(\beta))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow Q'(b)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow Q'(b)} \quad \vdash_f S(a, b)} \\
\vdash_f Q'(b)
\end{array}
\vdash_f \mathbf{f}$$

To increment register 1 we need a new free variable as anchor for register 1 (let $d \in \mathcal{V}_P \setminus \text{FV}(\Gamma_C \cup \Gamma_{\overline{M}})$ and $d \neq b$).

$$\begin{array}{c}
\vdots \\
\frac{R_1(b, d) \vdash_f \mathbf{f}}{\vdash_f (\forall \beta (R_1(b, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f}) \rightarrow \mathbf{f}} \quad \frac{\frac{\vdash_f \forall \alpha (D(\alpha) \rightarrow \forall \beta (R_1(\alpha, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f})}{\vdash_f D(b) \rightarrow \forall \beta (R_1(b, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f}} \quad \vdash_f D(b)}{\vdash_f \forall \beta (R_1(b, \beta) \rightarrow \mathbf{f}) \rightarrow \mathbf{f}} \\
\vdash_f \mathbf{f}
\end{array}$$

Now we need to connect d with a_0 (the anchor of a for register 1).

$$\begin{array}{c}
\vdots \\
\frac{P(d, a_0) \vdash_f \mathbf{f}}{\vdash_f P(d, a_0) \rightarrow \mathbf{f}} \quad \frac{\frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow R_1(\beta, \delta) \rightarrow P(\delta, \gamma))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(a, a_0) \rightarrow R_1(b, d) \rightarrow Q'(b)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(a, a_0) \rightarrow R_1(b, d) \rightarrow Q'(b)} \quad \vdash_f S(a, b)} \\
\frac{\vdash_f R_1(a, a_0) \rightarrow R_1(b, d) \rightarrow Q'(b)}{\vdash_f R_1(b, d) \rightarrow Q'(b)} \quad \vdash_f R_1(a, a_0)
\end{array}
\vdash_f \mathbf{f}$$

At last we have to make sure that we do not get an artificial zero by deducing $D(d)$.

$$\begin{array}{c}
\vdots \\
\frac{\frac{D(d) \vdash_f \mathbf{f}}{\vdash_f D(d) \rightarrow \mathbf{f}}}{\vdash_f \mathbf{f}}
\end{array}
\quad
\frac{\frac{\frac{\frac{\vdash_f \forall \alpha \beta \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\beta, \delta) \rightarrow D(\delta))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(b, d) \rightarrow D(d)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(b, d) \rightarrow D(d)} \quad \vdash_f S(a, b)}{\vdash_f R_1(b, d) \rightarrow D(d)} \quad \vdash_f R_1(b, d)}{\vdash_f D(d)}$$

Now we already have deduced Γ_D , to see why define $\hat{a} := b$, $\hat{b}_i := b_i$ for $i \in \{0, \dots, m\}$, $\hat{a}_0 := d$, and $\hat{a}_{i+1} := a_i$ for $i \in \{0, \dots, n\}$. Hence we can deduce **false** by induction hypothesis.

The other case, that $\mathbf{r} = -(\mathbf{Q}, \mathbf{1}, \mathbf{Q}_1, \mathbf{Q}_2)$, has to be split into two cases again. If $\mathbf{m} = \mathbf{0}$ then $\hat{Q} = Q_2$, $\hat{m} = 0$, and $\hat{n} = n$. We only need to ensure that the successor state is Q_2 and that register 1 is still zero.

$$\begin{array}{c}
\vdots \\
\frac{\frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow E(\gamma) \rightarrow Q_2(\beta))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(a, a_0) \rightarrow E(a_0) \rightarrow Q_2(b)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(a, a_0) \rightarrow E(a_0) \rightarrow Q_2(b)} \quad \vdash_f S(a, b)}{\vdash_f R_1(a, a_0) \rightarrow E(a_0) \rightarrow Q_2(b)} \quad \vdash_f R_1(a, a_0)}{\vdash_f E(a_0) \rightarrow Q_2(b)} \quad \vdash_f E(a_0)}{\vdash_f Q_2(b)}
\end{array}$$

Register 1 stays zero.

$$\begin{array}{c}
\vdots \\
\frac{\frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow E(\gamma) \rightarrow R_1(\beta, \gamma))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(a, a_0) \rightarrow E(a_0) \rightarrow R_1(b, a_0)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(a, a_0) \rightarrow E(a_0) \rightarrow R_1(b, a_0)} \quad \vdash_f S(a, b)}{\vdash_f R_1(a, a_0) \rightarrow E(a_0) \rightarrow R_1(b, a_0)} \quad \vdash_f R_1(a, a_0)}{\vdash_f E(a_0) \rightarrow R_1(b, a_0)} \quad \vdash_f E(a_0)}{\vdash_f R_1(b, a_0)}
\end{array}$$

If we define $\hat{a} := b$, $\hat{b}_i := b_i$ for $i \in \{0, \dots, m\}$, and $\hat{a}_0 := a_0$ then it is clear that we have deduced all formulas required for Γ_D . So we can use the induction hypothesis to deduce **false**.

In the last case $\mathbf{m} > \mathbf{0}$, so $\hat{Q} = Q_1$, $\hat{m} = m - 1$, and $\hat{n} = n$. First we ensure that b is in state Q_1 .

$$\begin{array}{c}
\frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow D(\gamma) \rightarrow Q_1(\beta))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(a, a_0) \rightarrow D(a_0) \rightarrow Q_1(b)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(a, a_0) \rightarrow D(a_0) \rightarrow Q_1(b)} \quad \vdash_f S(a, b) \\
\vdots \\
\frac{\frac{Q_1(b) \vdash_f \mathbf{f}}{\vdash_f Q_1(b) \rightarrow \mathbf{f}} \quad \frac{\frac{\vdash_f R_1(a, a_0) \rightarrow D(a_0) \rightarrow Q_1(b)}{\vdash_f D(a_0) \rightarrow Q_1(b)} \quad \vdash_f R_1(a, a_0)}{\vdash_f D(a_0) \rightarrow Q_1(b)} \quad \vdash_f D(a_0)}{\vdash_f Q_1(b)} \\
\hline
\vdash_f \mathbf{f}
\end{array}$$

Now we decrement register 1 by taking a_1 (the predecessor of a_0) as anchor of b for register 1.

$$\begin{array}{c}
\frac{\frac{\frac{\vdash_f \forall \alpha \beta \gamma \delta (Q(\alpha) \rightarrow S(\alpha, \beta) \rightarrow R_1(\alpha, \gamma) \rightarrow D(\gamma) \rightarrow P(\gamma, \delta) \rightarrow R_1(\beta, \delta))}{\vdash_f Q(a) \rightarrow S(a, b) \rightarrow R_1(a, a_0) \rightarrow D(a_0) \rightarrow P(a_0, a_1) \rightarrow R_1(b, a_1)} \quad \vdash_f Q(a)}{\vdash_f S(a, b) \rightarrow R_1(a, a_0) \rightarrow D(a_0) \rightarrow P(a_0, a_1) \rightarrow R_1(b, a_1)} \quad \vdash_f S(a, b) \\
\vdots \\
\frac{\frac{R_1(b, a_1) \vdash_f \mathbf{f}}{\vdash_f R_1(b, a_1) \rightarrow \mathbf{f}} \quad \frac{\frac{\vdash_f R_1(a, a_0) \rightarrow D(a_0) \rightarrow P(a_0, a_1) \rightarrow R_1(b, a_1)}{\vdash_f D(a_0) \rightarrow P(a_0, a_1) \rightarrow R_1(b, a_1)} \quad \vdash_f R_1(a, a_0)}{\vdash_f D(a_0) \rightarrow P(a_0, a_1) \rightarrow R_1(b, a_1)} \quad \vdash_f D(a_0)}{\vdash_f P(a_0, a_1) \rightarrow R_1(b, a_1)} \quad \vdash_f P(a_0, a_1)} \\
\hline
\vdash_f \mathbf{f}
\end{array}$$

Again it is obvious that we have deduced Γ_D ($\hat{a} := b, \hat{b}_i := b_i$ for $i \in \{0, \dots, m\}$, and $\hat{a}_{i-1} := a_i$ for $i \in \{1, \dots, n\}$). Hence, by induction hypothesis, we can deduce **false**. \square

Lemma 18.

$$M \text{ terminates on input } (0, 0) \quad \text{iff} \quad \Gamma_M \vdash \mathbf{false} \text{ holds in system } P.$$

Proof. The \Leftarrow direction follows directly from Claim 16. And the \Rightarrow direction is a direct consequence of Claim 17 with $C = \langle Q_0, 0, 0 \rangle$. \square

Theorem 19. *CONS is undecidable.*

Proof. Since by Lemma 18 for a given two-counter automaton M we can effectively construct a set of **P**-formulas Γ_M such that M terminates on input $(0, 0)$ iff Γ_M is not consistent. It follows that **HALT** \leq **CONS**. Hence, since **HALT** is undecidable, we have shown that **CONS** is undecidable too. \square