CARET analysis of multithreaded programs

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Motivation

Malware detection is a big challenge.

Existing Techniques (not robust)

- Signature-matching based technique: can easily be overcome by obfuscation techniques
- Code emulation based techniques: limitation in execution time

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Solution to have a robust technique

Model-checking for malware detection

- allow us to analyse the behaviors (not the syntax) of the program without executing it

Model-checking for Malware Detection

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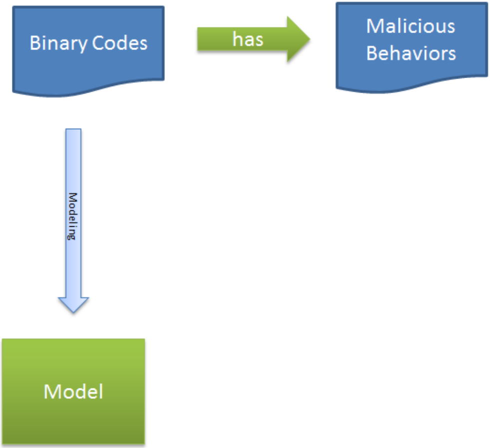
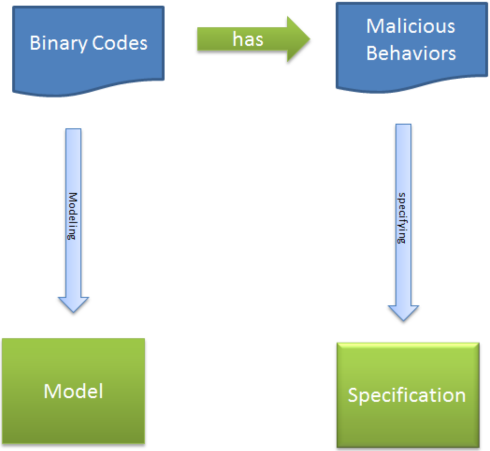
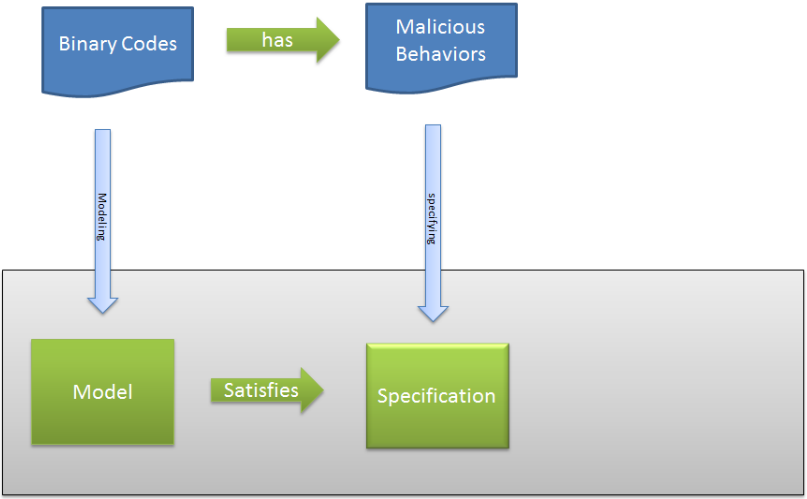



Binary Codes
has
Malicious Behaviors
Modeling
specifying
Model
Specification

Model-checking for Malware Detection



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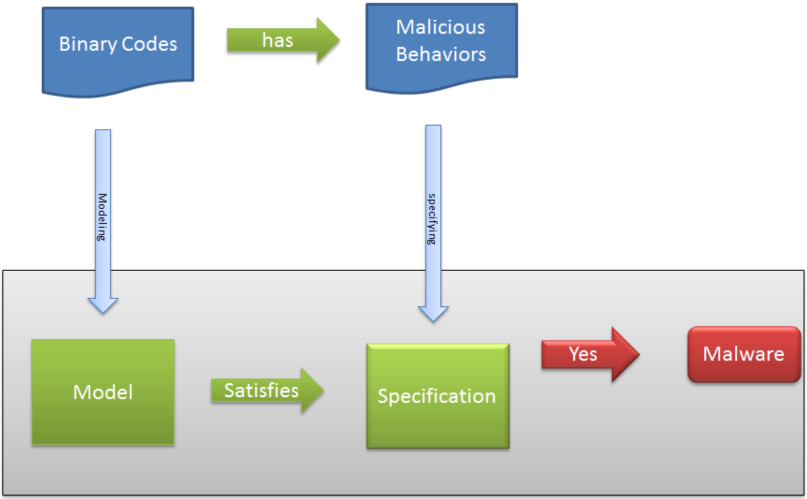

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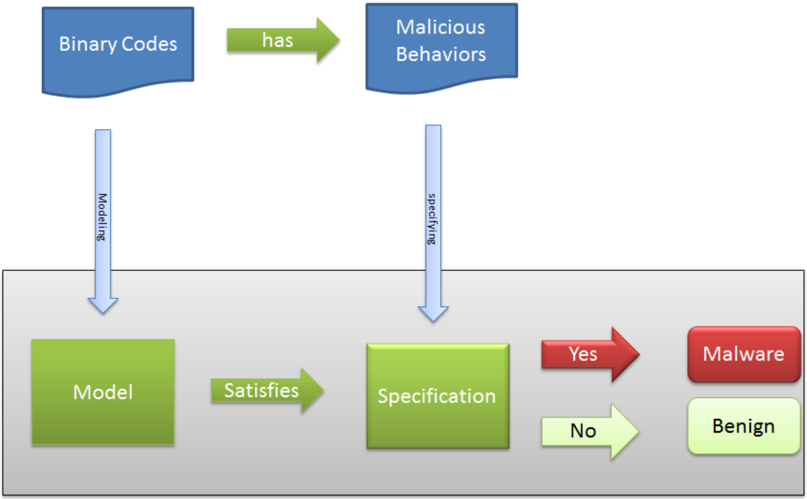

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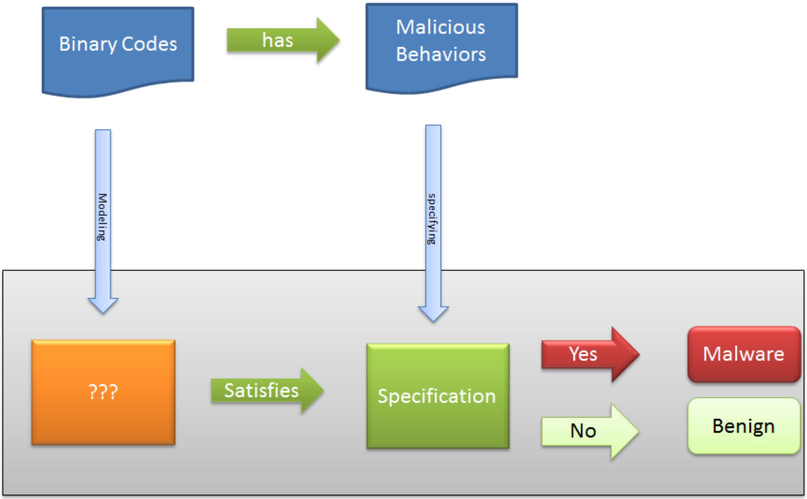

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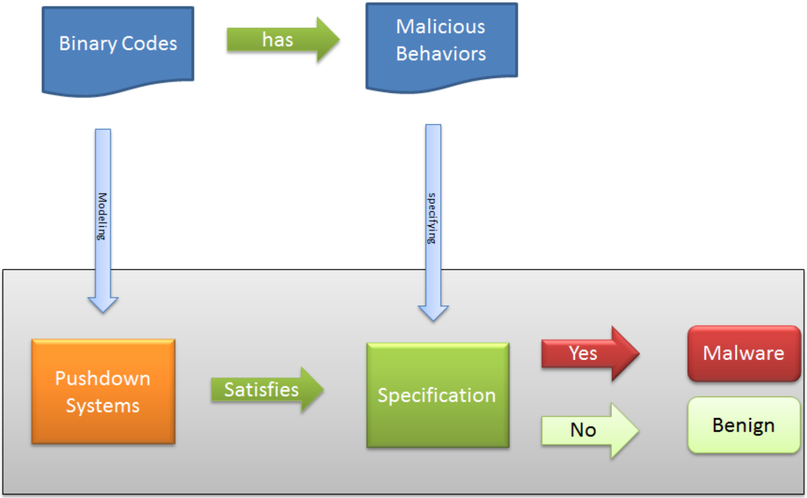

Why Pushdown Systems?

Stack of binary codes

important for malware detection [Song and Touili 2012, 2013]

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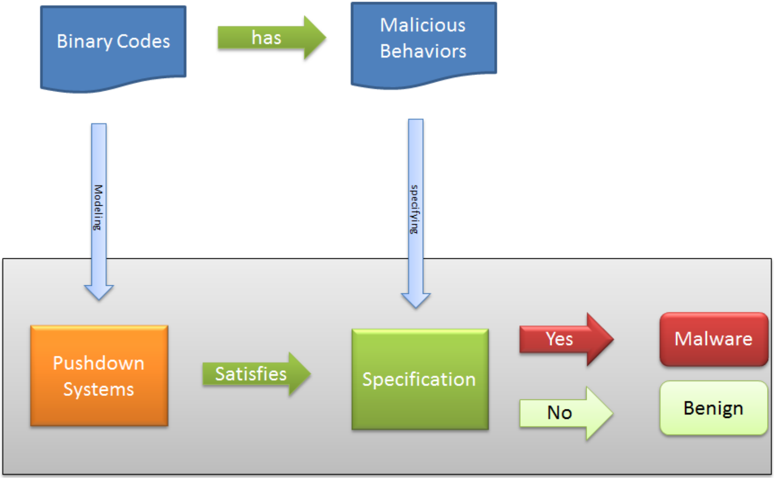
PDSs for Binary Codes

- Control locations of PDSs correspond to program points
- Stack of PDSs correspond to stack of binary programs

Model-checking for Malware Detection



$\Longrightarrow$ **Problem: This can be applied only for sequential programs. However, several malware is concurrent.**

Concurrent Malware Example

The email worm Bagle

is a multithreaded malware:

- Main thread: register itself into the registry listing: to be started at the boot time
- Thread 2: listen on port 6777 to receive different commands; allow the attackers to upload new file, ...
- Thread 3: contacts a list of websites every 10 minutes: to announce the infection of the current machine
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How instances of threads are spawn?

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- The number of instances is not fixed, depending on specific executions
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$\Longrightarrow$ **Bagle is a multithreaded malware, with dynamic thread creation during its execution. How to model such a concurrent malware?**

How to model such concurrent malware?

Ideas

1. PDS is a natural model for sequential malware.
2. $\Longrightarrow$ networks of PDSs can model concurrent malware.
3. $\Longrightarrow$ networks of PDSs with dynamic creation can model concurrent malware with dynamic creations.
4. $\Longrightarrow$ Dynamic Pushdown Networks [Bouajjani, Müller-Olm and Touili 2005] match our needs.

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Dynamic Pushdown Networks (DPNs)

- A DPN: a networks of Dynamic PDSs
- a Dynamic PDS: is a PDS with the ability to spawn new instances of PDSs during its runs

Definition of PDSs

A Pushdown System (PDS) $\mathcal{P}$ is a tuple (P, Γ, Δ), where

- P is a finite set of control locations
- Γ is a finite set of stack alphabet
- Δ is the set of transition rules of the following form:
  - (r_1): $p\gamma \xrightarrow{call} p_1\gamma_1\gamma_2$
  - (r_2): $p\gamma \xrightarrow{ret} p_1\epsilon$
  - (r_3): $p\gamma \xrightarrow{int} p_1\omega$

  where $p, p_1 \in P$, $\gamma, \gamma_1, \gamma_2 \in \Gamma$, $\omega \in \Gamma^*$

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- usually models a statement of the form $\gamma \xrightarrow{call \quad proc} \gamma_2$
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A configuration: $p\omega$ where $p \in P$ is the current control location, $\omega \in \Gamma^*$ is the current stack content.

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- $(NonSpawn)(r_1)$ $p\gamma \xrightarrow{call}_i p_1\gamma_1\gamma_2$
- $(NonSpawn)(r_2)$ $p\gamma \xrightarrow{ret}_i p_1\epsilon$
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- $(Spawn)\ (r_4)\ p\gamma \xrightarrow{call}_i p_1\gamma_1\gamma_2 \rhd p_s\omega_s$
- $(Spawn)\ (r_5)\ p\gamma \xrightarrow{ret}_i p_1\epsilon \rhd p_s\omega_s$
- $(Spawn)\ (r_6)\ p\gamma \xrightarrow{int}_i p_1\omega_1 \rhd p_s\omega_s$

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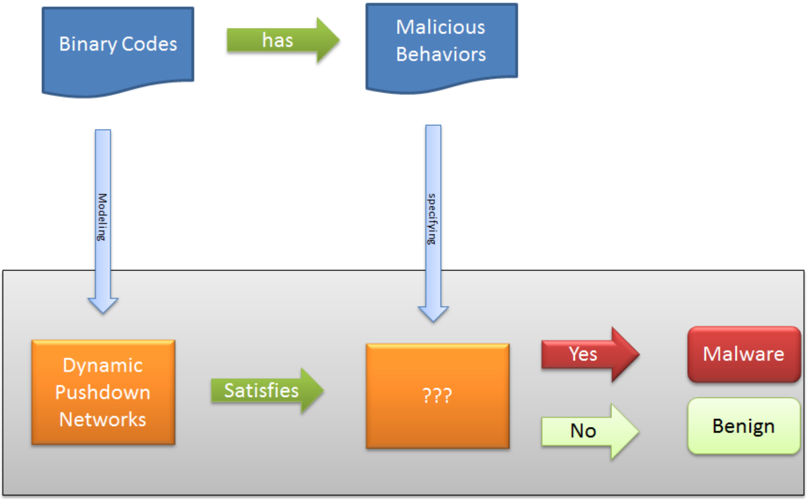

Specification Formalisms for Malware Behaviors

Recent works: extensions of LTL, CTL were used as specifications

- CTPL [Kinder, Katzenbeisser,Schallhart and Veith 2005]
- SLTPL, SCTPL [Song and Touili 2012, 2013]

However, these are not expressive enough for malicious behaviors

Malicious Behavior Example

Spyware Behavior

search directories for personal information (emails, bank account info, ...)

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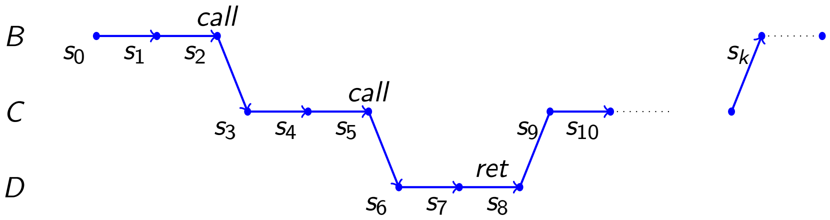
Then,..

- Cannot be expressed by LTL or CTL since it requires that the return value of the function FindFirstFileA should be used as the input to the function FindNextFileA
- $\Longrightarrow$ we need a formalism that can talk about matching calls and returns $\Longrightarrow$ CARET.

- linear temporal logic of Calls and Returns [Alur, Etessami and Madhusudan 2004]
- Interpreted over transition systems where each state is associated with a tag in the set {call, ret, int}
  - call : a call statement
  - ret : a return statement
  - int : an internal statement (neither call nor return)

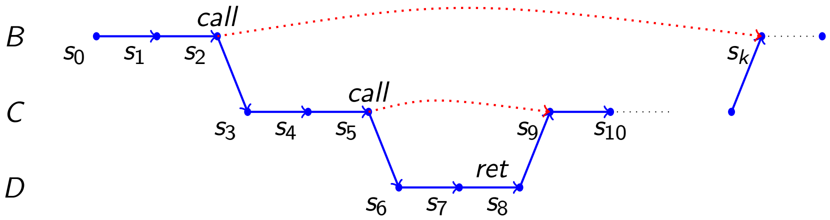
Global Successor

- Global Successor(X^g): standard successor ($X^g(s_i) = s_{i+1}$)
- Global Path: standard path like for LTL



Abstract Successor

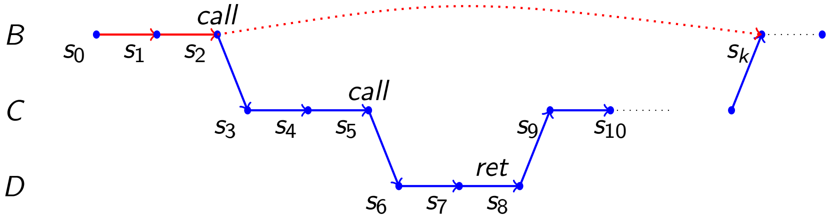
- Abstract Successor (X^a)
  - The abstract successor of a *call* is its corresponding return-point
- Abstract Path: apply repeatedly the abstract successor



Abstract Path

Abstract path:

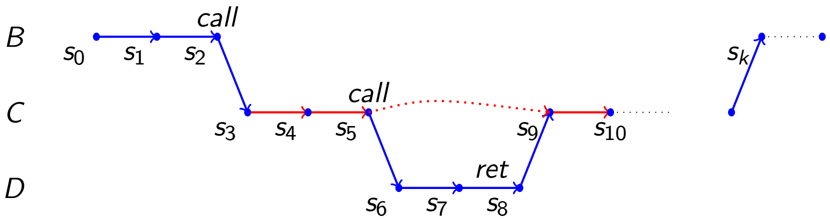
- From s_0: $s_0 s_1 s_2 s_k \ldots$.



Abstract Path

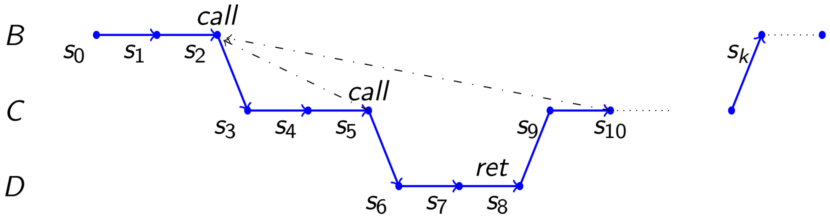
Abstract path:

- From s_3: $s_3 s_4 s_5 s_9 s_{10} \ldots$.

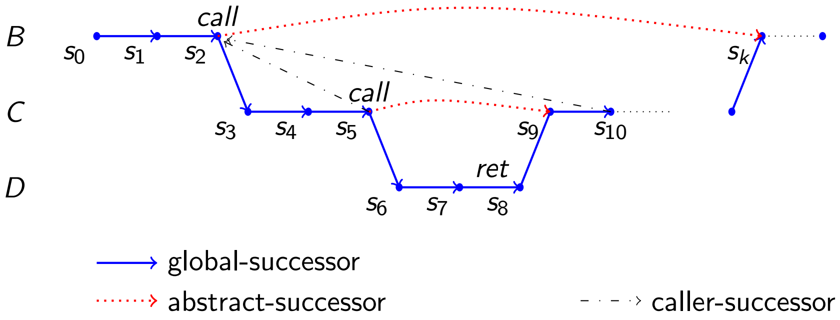


Caller Successor

- Caller Successors (X^c)
  - the caller successor of a point is the caller point of the current procedure
- Caller Path: apply repeatedly the caller successor



CARET successors



CARET Definition

Given a finite set of atomic propositions AP. A CARET formula over AP is defined as follows:

$$\psi := e \mid \{call, ret, int\} \mid \psi \vee \psi \mid \neg\psi \mid X^g\psi \mid X^a\psi \mid X^c\psi \mid \psi U^a\psi \mid \psi U^g\psi \mid \psi U^c\psi$$

where

- $e \in AP$: atomic proposition
- X^g: global successor
- X^a: abstract successor
- X^c: caller successor
- U^g: until operator on global path
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Using CARET to describe ...

$$\psi_{sf} = \bigvee_{d \in D} F^g(\text{call}(\text{FindFirstFileA}) \wedge X^a(eax = d) \wedge F^a(\text{call}(\text{FindNextFileA}) \wedge d\Gamma^*))$$

Spyware Behavior Formula

Malicious behavior by CARET

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$\Longrightarrow$ ψ_{sf}: there exists a path s.t there is a call to *FindFirstFileA* where the return value is d, and after this call finishes, there is a call to *FindNextFileA* s.t d is used as parameter.

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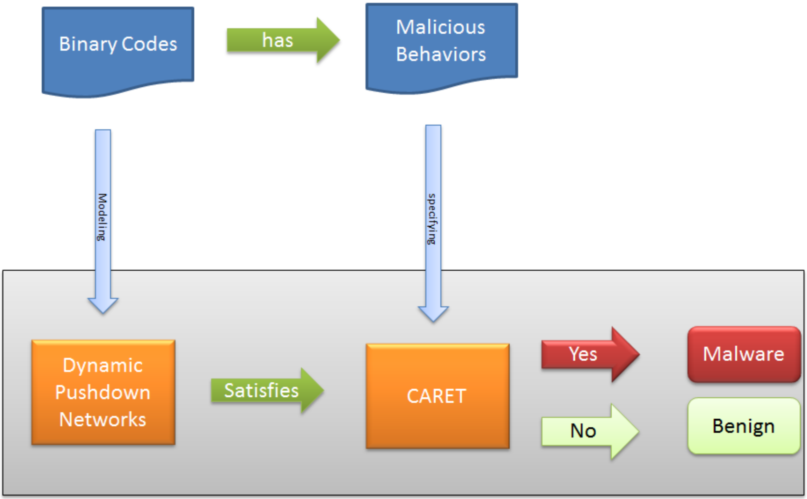

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4. $\Longrightarrow$ We consider: model-checking single-indexed CARET properties for DPNs, where:
   - single-indexed properties: properties in the form $f = f_1 \wedge f_2 \ldots \wedge f_n$, where f_i is the CARET formula corresponding to $\mathcal{P}_i$

Problem to solve

Given:

- a DPN $\mathcal{M} = \{\mathcal{P}_1, \mathcal{P}_2, ..., \mathcal{P}_n\}$
- a single-indexed CARET formula $f = f_1 \wedge f_2 ... \wedge f_n$

Model-checking problem:

- Does there exist an execution of $\mathcal{M}$ s.t. every instance of the DPDS $\mathcal{P}_i$ satisfies the corresponding CARET formula f_i?

Theorem

Single-indexed CARET Model Checking for DPNs is decidable.

Intuition:

- We reduce this problem to the emptiness problem of Büchi Dynamic Pushdown Networks (BDPNs) [Song and Touili 2013, 2016].

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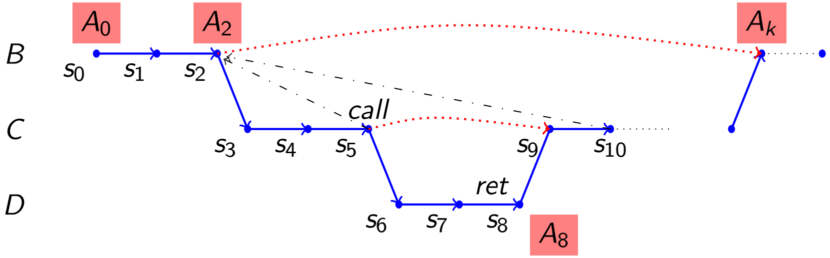
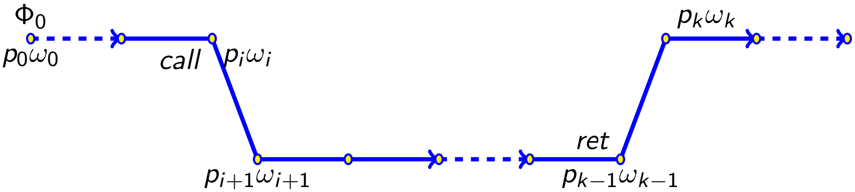
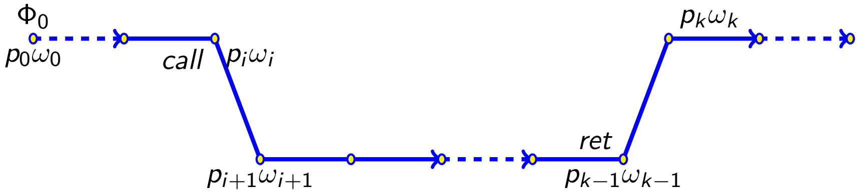
  - The problem of checking whether an instance of $\mathcal{P}_i$ starting from $p\omega$ satisfies f_i can be reduced to the membership problem of $\mathcal{BP}_i$

At state s_i, we encode a set of formulas A_i such that for every $\phi \in A_i$, ϕ holds at s_i



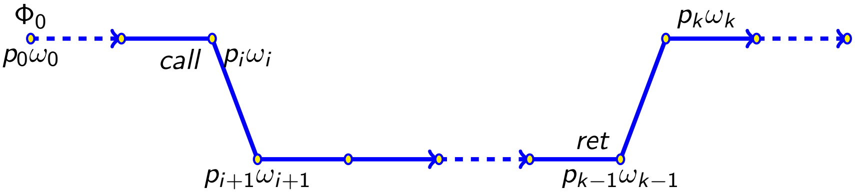
BDPDS Computation-X Operators-Call statements





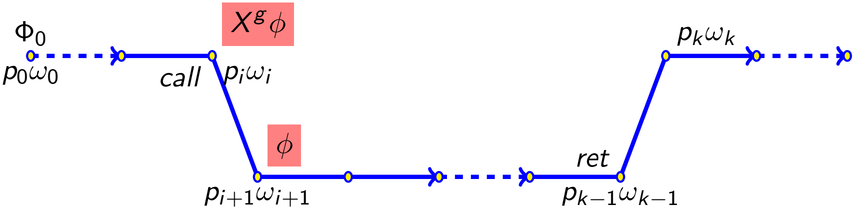
for $p_i\gamma \xrightarrow{call} p_{i+1}\gamma'\gamma''$ in $\mathcal{P}_i$:

BDPDS Computation-X Operators-Call statements



for $p_i\gamma \xrightarrow{call} p_{i+1}\gamma'\gamma''$ in $\mathcal{P}_i$:

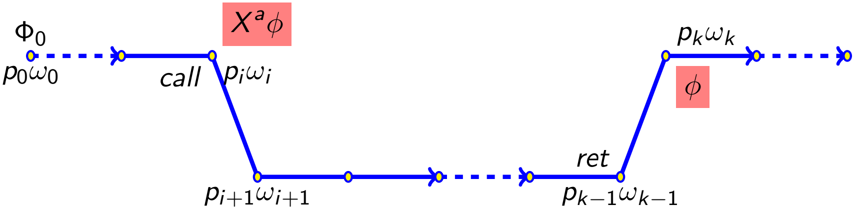
- $(\!| p_i, \{X^g\phi\} |\!)\gamma \rightarrow (\!| p_{i+1}, \{\phi\} |\!)\gamma\gamma''$ in $\mathcal{BP}_i$



$p_i\omega_i \models X^g\phi$ iff $p_{i+1}\omega_{i+1} \models \phi$

for $p_i\gamma \xrightarrow{call} p_{i+1}\gamma'\gamma''$ in $\mathcal{P}_i$:

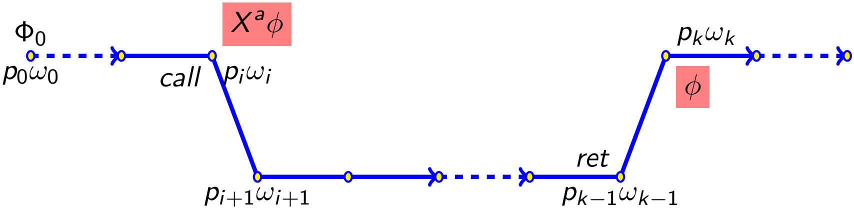
- $(\!|p_i, \{X^g\phi\}|\!)\gamma \rightarrow (\!|p_{i+1}, \{\phi\}|\!)\gamma\gamma''$ in $\mathcal{BP}_i$



$p_i\omega_i \models X^a\phi$ iff $p_k\omega_k \models \phi$

for $p_i\gamma \xrightarrow{call} p_{i+1}\gamma'\gamma''$ in $\mathcal{P}_i$:

- $(\!|p_i, \{X^g\phi\}|\!)\gamma \to (\!|p_{i+1}, \{\phi\}|\!)\gamma\gamma''$ in $\mathcal{BP}_i$



$p_i\omega_i \models X^a\phi$ iff $p_k\omega_k \models \phi$

for $p_i\gamma \xrightarrow{call} p_{i+1}\gamma'\gamma''$ in $\mathcal{P}_i$:

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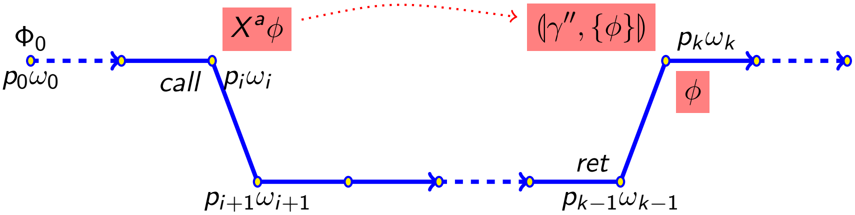
- $(\!|p_i, \{X^a\phi\}|\!)\gamma \rightarrow p_{i+1}\gamma' \boxed{(\!|\gamma'', \{\phi\}|\!)}$ in $\mathcal{BP}_i$

BDPDS Computation-X Operators-Call statements



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- $\llparenthesis p_i, \{X^a\phi\} \rrparenthesis \gamma \rightarrow p_{i+1}\gamma' \boxed{\llparenthesis \gamma'', \{\phi\} \rrparenthesis}$ in $\mathcal{BP}_i$

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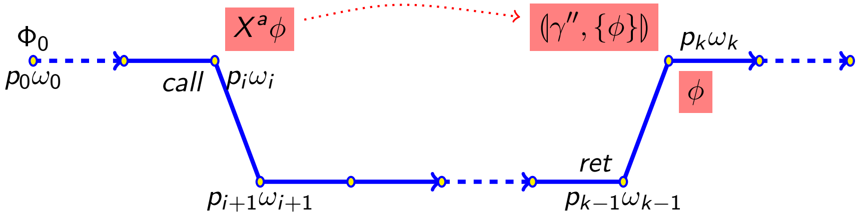

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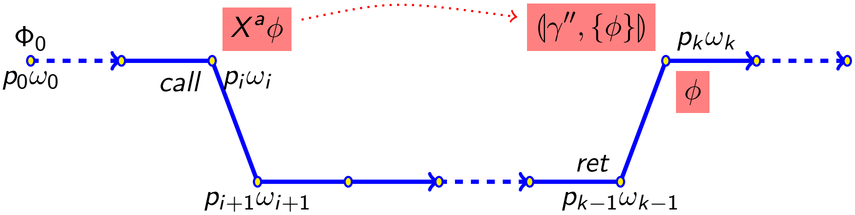
for $p_{k-1}\beta \xrightarrow{ret} p_k\epsilon$ in $\mathcal{P}_i$



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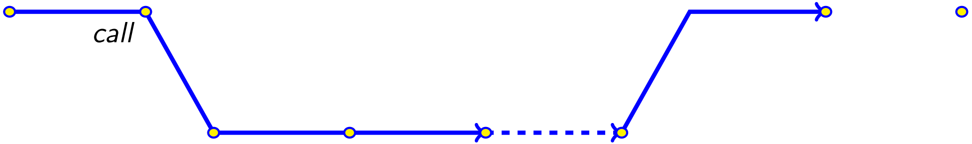
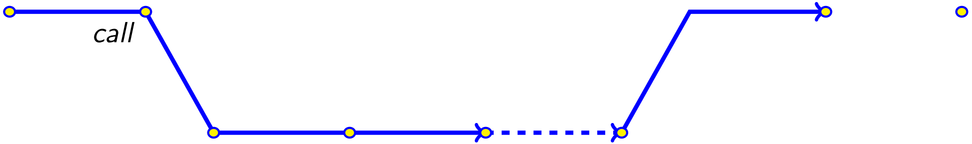
for $p_{k-1}\beta \xrightarrow{ret} p_k\epsilon$ in $\mathcal{P}_i$:

- $p_k \boxed{(\!|\gamma'', \{\phi\}|\!)} \rightarrow (\!|p_k, \boxed{\{\phi\}}|\!)\gamma''$



for $p_i\gamma \xrightarrow{int} p_{i+1}\omega$ in $\mathcal{P}_i$:



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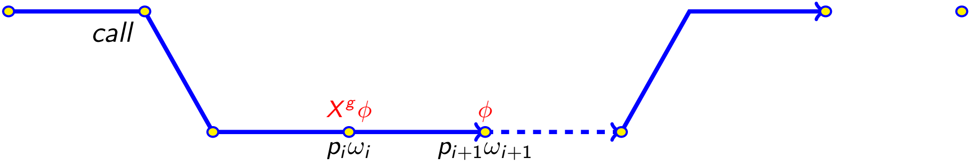
- $(\!| p_i, \{X^g\phi\} |\!)\gamma \rightarrow (\!| p_{i+1}, \{\phi\} |\!)\omega$ in $\mathcal{BP}_i$

BDPDS Computation-X Operators- Int statements



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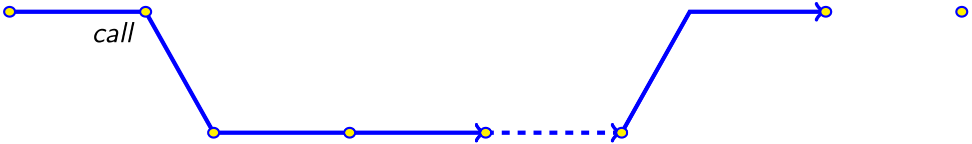

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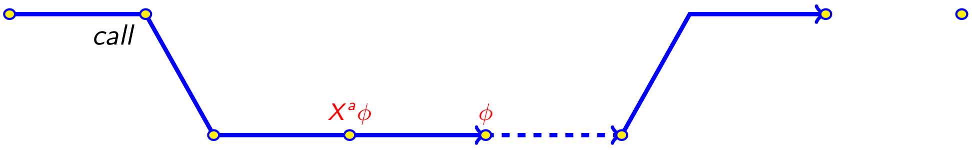

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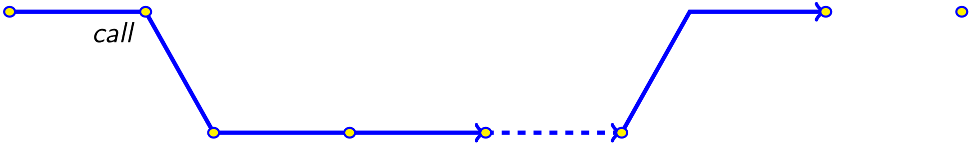

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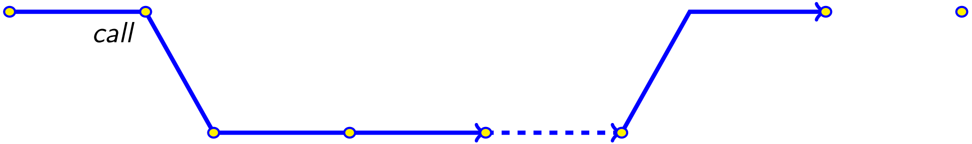
for $p_i\gamma \xrightarrow{int} p_{i+1}\omega \triangleright p_s\omega_s$ in $\mathcal{P}_i$ ($p_s\omega_s \in \mathcal{P}_j$):



for $p_i\gamma \xrightarrow{int} p_{i+1}\omega$ in $\mathcal{P}_i$:

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- $(\!|p_i, \{X^g\phi\}|\!)\gamma \rightarrow (\!|p_{i+1}, \{\phi\}|\!)\omega \rhd (\!|p_s, f_j|\!)\omega_s$ in $\mathcal{BP}_i$
- $(\!|p_i, \{X^a\phi\}|\!)\gamma \rightarrow (\!|p_{i+1}, \{\phi\}|\!)\omega \rhd (\!|p_s, f_j|\!)\omega_s$ in $\mathcal{BP}_i$

Theorem

Theorem

Given a DPN $\mathcal{M} = \{\mathcal{P}_1, ..., \mathcal{P}_n\}$, a single-indexed CARET formula $f = f_1 \wedge f_2 ... \wedge f_n$, we can compute a BDPN $\mathcal{BM} = \{\mathcal{BP}_1, ..., \mathcal{BP}_n\}$ such that $\mathcal{M} \models f$ iff $\mathcal{BM}$ has an accepting run.

DPNs communicating via Locks (L-DPNs)

L-DPNs

a L-DPN is a DPN where pushdown processes communicate via locks.

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Theorem

Single-indexed CARET model-checking for L-DPNs with nested Lock access can be reduced to single-indexed CARET model-checking for DPNs

Q & A

Thank you for your listening!