Forensic Memory Analysis: From Stack and Code to Execution History.

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Summary

- State of the art.
- Our approach.
- Program execution modeling.
  - Control Flow Graphs.
  - Local automata model.
  - Push Down System model.
- ADM logic.
- Stack modeling using ADM.
- Implementation.
- Future research directions.

State of the Art

- The Memory Analysis Challenge (DFRWS 2005 Challenge) resulted in 2 new tools:

- Memparser by Chris Betz
  - Enumerates processes (PsActiveProcessList)
  - Dumps process memory to disk
  - Dumps process strings to disk
  - Displays Process Environment Information
  - Displays all DLLs loaded by process

- Kntlist by George M. Garner Jr. and Robert Jan Mora
  - Copies, compresses, creates checksums & sends a physical memory to a remote location.
  - Enumerates processes (PsActiveProcessList).
  - Enumerates handle table.
  - Enumerates driver objects (PsLoadedModuleList).
  - Enumerates network information such as interface list, arp list, address object and TCB table.
  - References are examined to find hidden data.
  - Object table, its members and objects inside object directory point to processes and threads.
  - Enumerates contents of IDT, GDT and SST to identify loaded modules.

Related work

- M. Burdach presents an approach to retrieve process and file information from the memory of Unix operating system by following the unbroken links between data structures in the memory.

- FATKit (an extensible frame work) which provides the analyst with the ability of automatically deriving digital object definition from c source codes and extracting the objects from the memory.

- A. Schuster proposed an approach to define signatures for executive object structures in the memory and recover the hidden and lost structures by scanning the memory looking for the predefined signatures.
  - Defining a signature that uniquely identify most of the data structures are not achievable except for a small set of kernel structures.
  - There are chances that this small set of kernel structures are overwritten by the kernel after a process has finished its execution while there is still some useful information about the process in other structures for which defining a signature which uniquely identifies the structure is impractical.

Our Approach

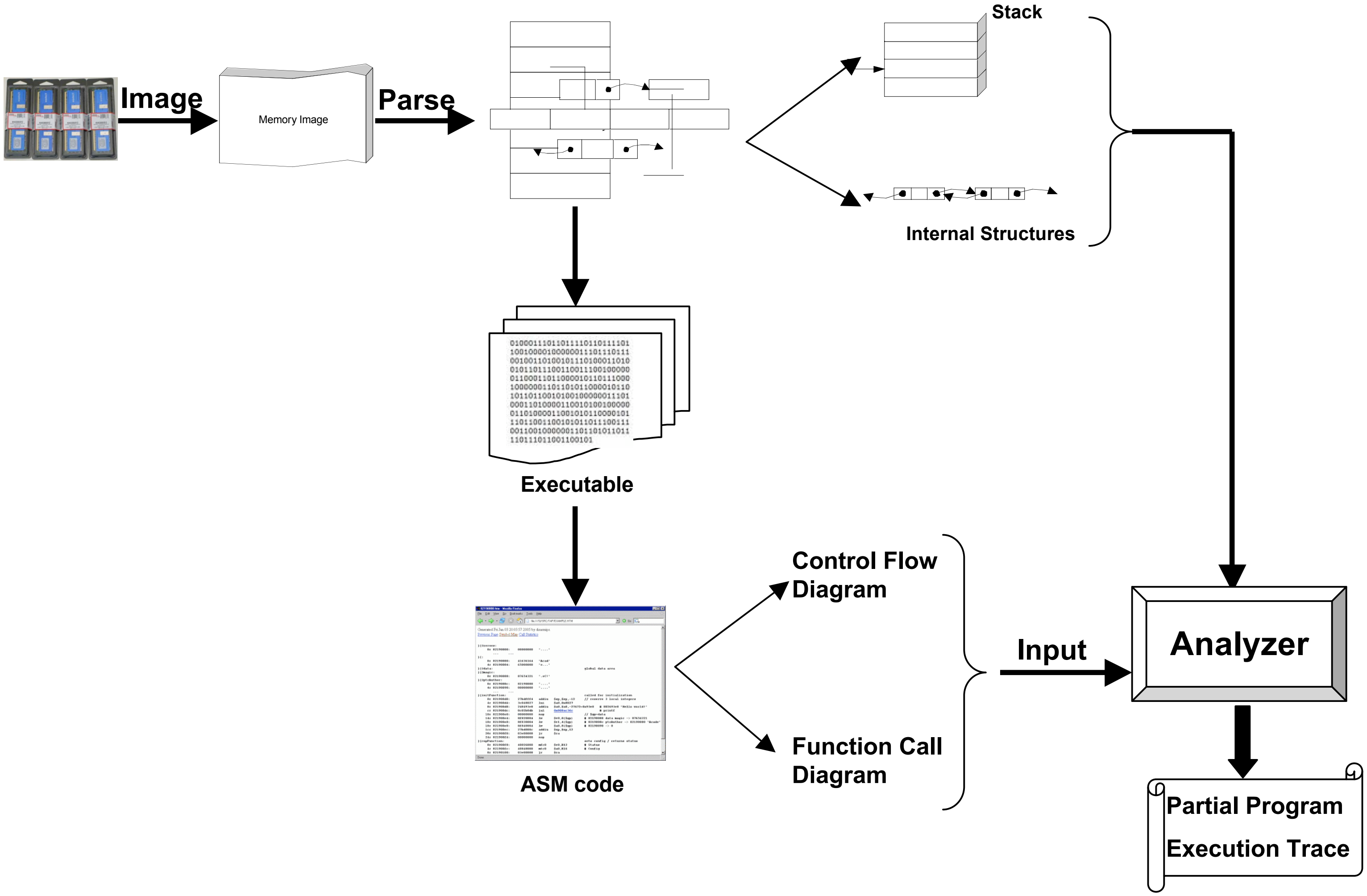
- Most of the previous work on forensics memory analysis has been on extraction and presentation of forensically relevant structures.

- Our objective is to create a timeline of what has exactly been done during the incident in the form of an execution trace.

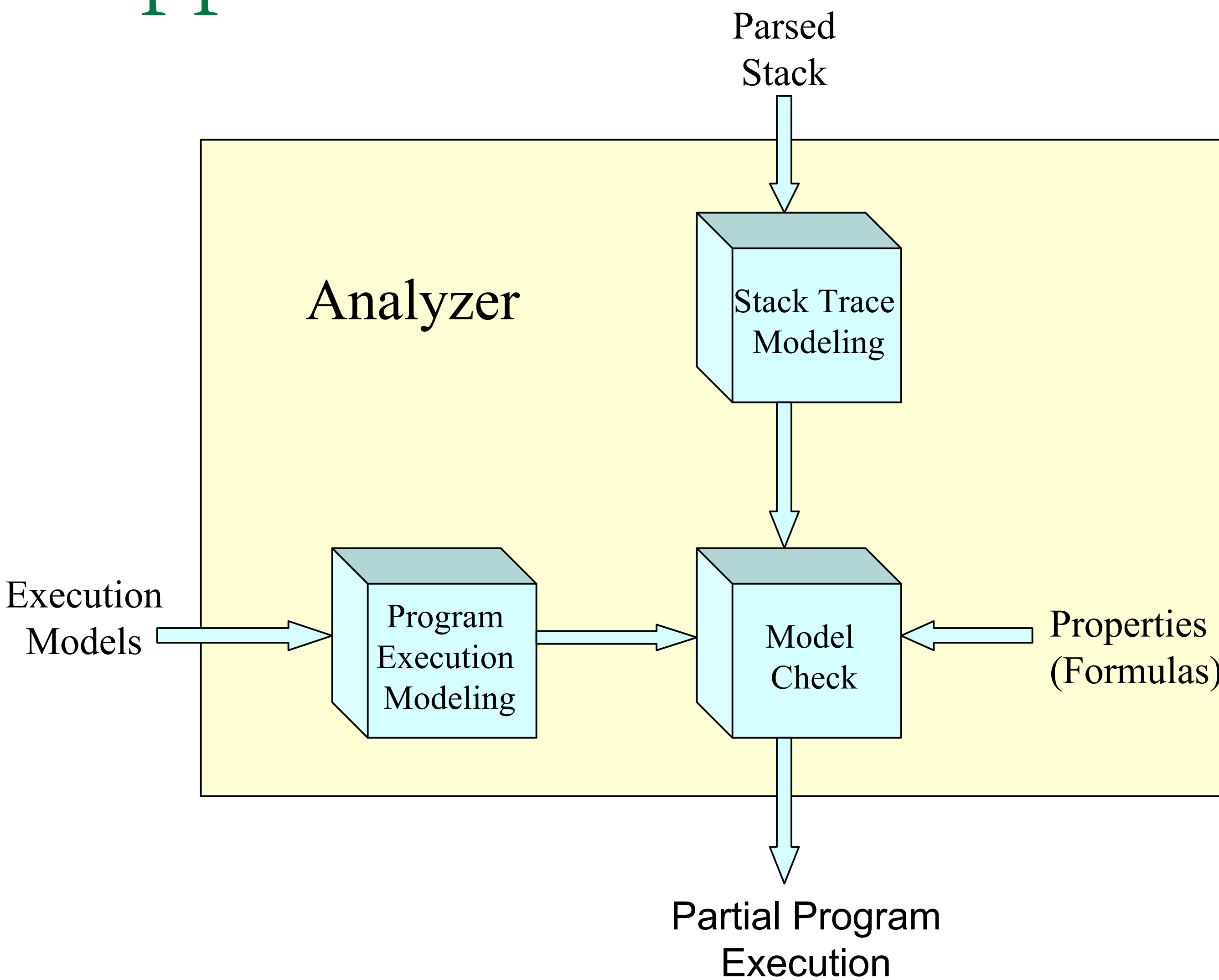
Our Approach

- For each function call made by a process, a stack frame is created and stored on the stack.
- The stack frame contains the parameters passed to that function, the address of the caller and the local variables.
- These function call traces entail the history of what a process has done.
- After a function returns, the stack pointer will be moved down to the previous frame.
- However, the stack frame still resides in the memory at the location where the stack pointer is pointing after the function returns. (overwritten)
- We also have access to the binary code. We can extract a partial execution path of the process at the time of the incident that includes the data which has been processed.
- Data flow analysis and control flow analysis techniques are utilized to recover the partial execution history of a program.

Our Approach



Our Approach



Advantage

- The analysis is performed on the extracted assembly code of the process from the memory and there is no need for the external provision of the source code or executable.
- The technique integrates the formal analytical power of process logic and program models to retrieve the execution history of the process.
- The result of the analysis could reveal important fact about what a process has done rather than what is currently existing in the memory.

Modeling program execution

- The program execution is modeled in three step.
  - First, we create the Control Flow Graph(CFG) of each function in the process.
  - Second, we transform these CFGs into local automata models.
  - Third, the local automata models of each function are combined to form a Push Down System (PDS).

Modeling program execution

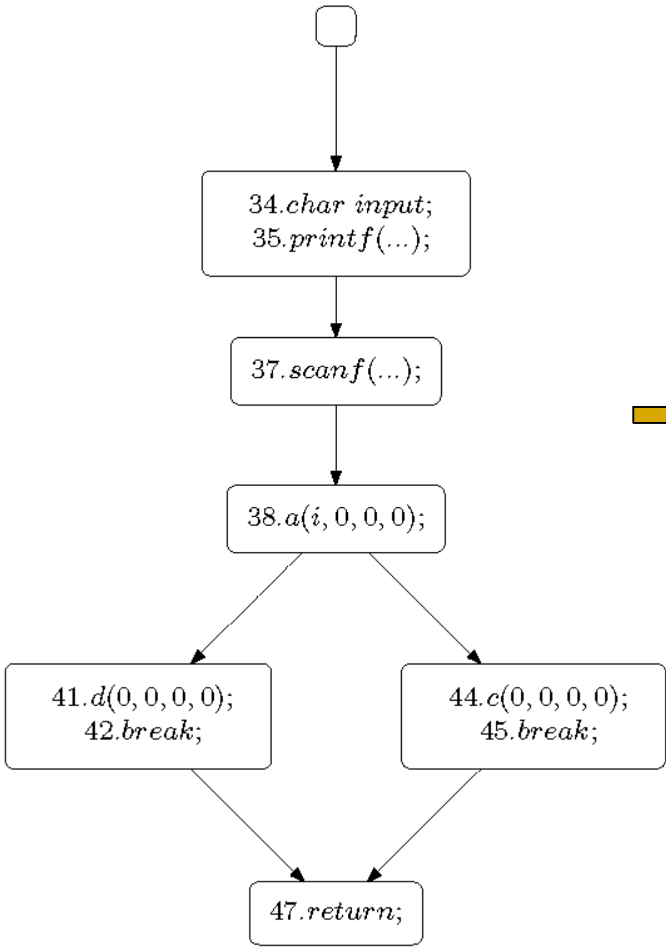
- A control flow graph (CFG) is a structure that characterizes possible execution paths in a program.
- Vertices of the graph contain one or more instructions of the program that execute sequentially.
- Edges in the graph show how control flow transfers between blocks.
- The first step of our approach is the generation of a control flow graph of each function called in the program.

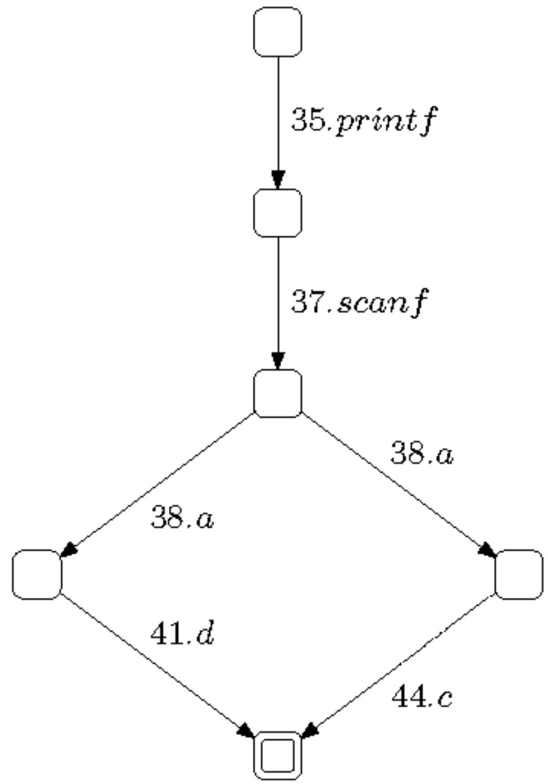
Example

```
#include <iostream>
void op(int i);
void h(int i, int j) {
    return;
}
void g(int i, int j) {
    return;
}
void b(int i, int j, int k, int l) {
    return;
}
void e(int i, int j, int k, int l) {
    op(2);
}
void a(int i, int j, int k, int l) {
    if (i == 49) {
        g(i,j);
        e(i,j,k,l);
        return;
    }else{
        h(i,j);
        return;
    }
}
void c(int i, int j, int k, int l) {
    b(i,j,k,l);
    return;
}
void d(int i, int j, int k, int l) {
    h(i,j,k,l);
    return;
}
void op(int i) {
    char input;
    printf("Input a value
            betwean 1, 2:\n");

    scanf("%c", &input);
       a(i,0,0,0);
    switch (input) {
        case '1':
            d(0,0,0,0);
            break;
        case '2':
            c(0,0,0,0);
            break;
    }
    return;
}
void inc(int i) {
    if (i < 10) {
        inc(i+1);
    } else {
        op(1);
        return;
    }
}
void main() {
    inc(0);
}
```

```
void op(int i) {
    char input;
    printf("Input a value
            between 1, 2:\n");

    scanf("%c", &input);
       a(i,0,0,0);
    switch (input) {
        case '1':
            d(0,0,0,0);
            break;
        case '2':
            c(0,0,0,0);
            break;
    }
    return;
}
```

CFG of function *op*   Local Automaton



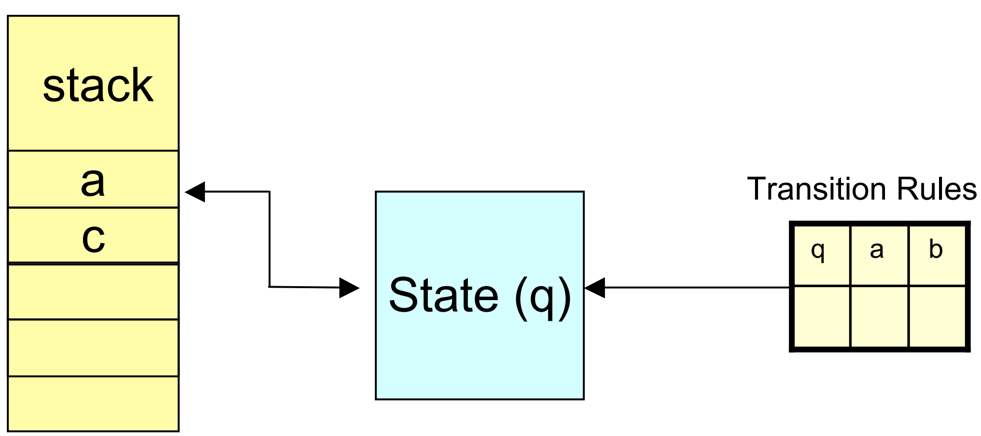


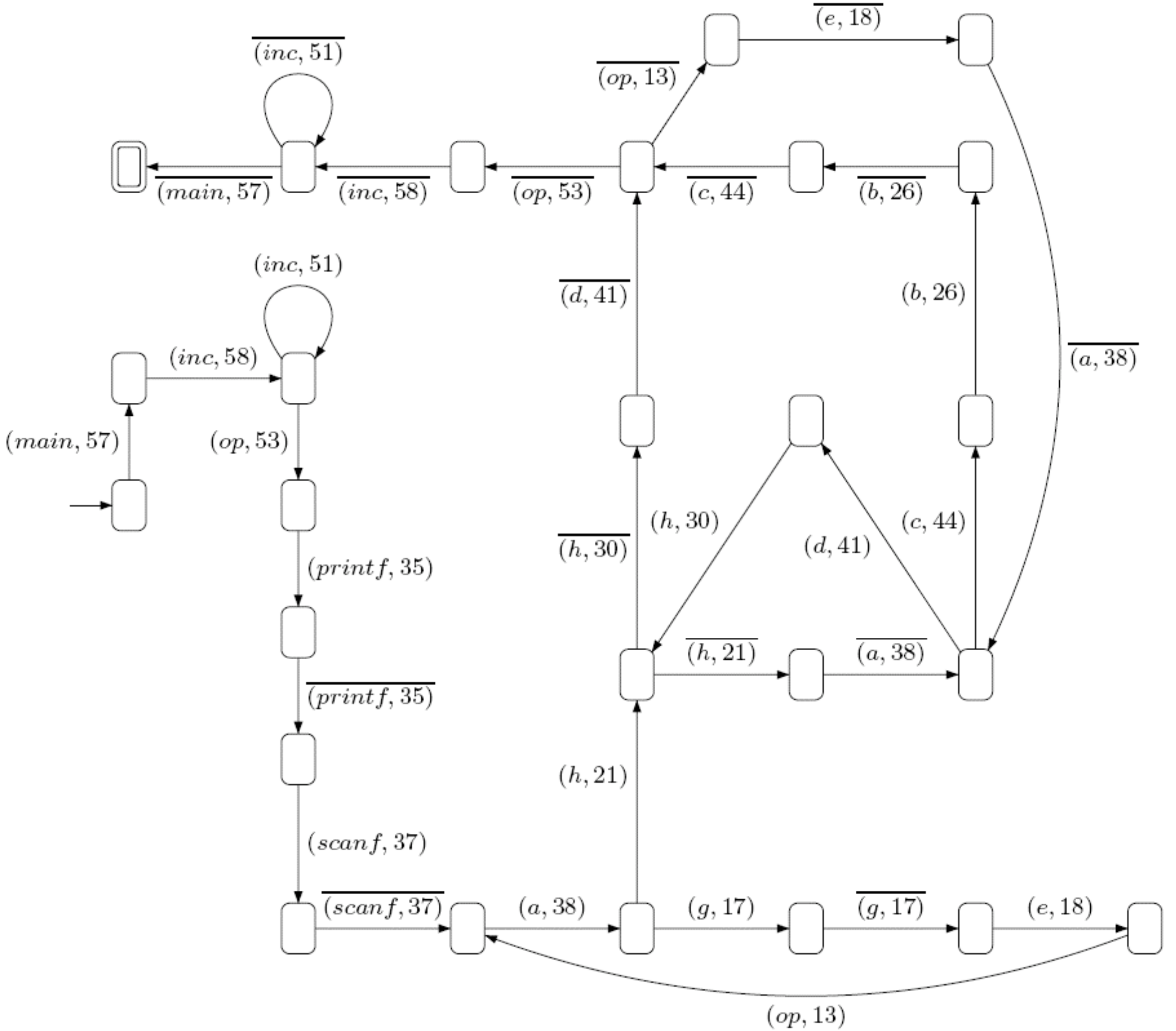
Combining the models

- Until now, we have modeled the execution of the program as a set of local state machines.
- Next step is to combine these local models into a model that represents the whole program.
- The local models can be combined to form a Push Down System (PDS).
- As the result of this combination, we can accurately model the execution of the program in terms of function call and returns.

Push Down Systems

- A PDS is a triple $P=(Q,\Gamma,\sigma)$ where Q is the final set of control locations, Γ is the finite set of stack alphabets and $\sigma \subseteq (Q\times\Gamma)\times(Q\times\Gamma^*)$ is a finite set of transition rules.




$\overline{(e, 18)}$
$\overline{(inc, 51)}$
$\overline{(op, 13)}$
$\overline{(main, 57)}$
$\overline{(inc, 58)}$
$\overline{(op, 53)}$
$\overline{(c, 44)}$
$\overline{(b, 26)}$
$(inc, 51)$
$\overline{(d, 41)}$
$(b, 26)$
$\overline{(a, 38)}$
$(inc, 58)$
$(main, 57)$
$(op, 53)$
$(h, 30)$
$(c, 44)$
$\overline{(h, 30)}$
$(d, 41)$
$(printf, 35)$
$\overline{(h, 21)}$
$\overline{(a, 38)}$
$\overline{(printf, 35)}$
$(h, 21)$
$(scanf, 37)$
$\overline{(scanf, 37)}$
$(a, 38)$
$(g, 17)$
$\overline{(g, 17)}$
$(e, 18)$
$(op, 13)$

Modeling the stack

- The process execution is modeled.

- A set of rules could be derived from the function call implementation using stacking mechanism.
  - If stack frame *b* is on top of stack frame *c*, then either *c* has called *b* or *b* has been called before *c*.

  - The function call history should generate exactly the same stack trace and should not overwrite any of the currently existing stack frames.

ADM Logic

- ADM is a temporal, dynamic, linear and modal logic.
- It has been designed initially to capture the specification of security properties in the context of cryptographic protocols.
- Such a logic is also proved to be very relevant and useful in the context of cyber forensics analysis.

ADM Syntax

- The syntax of the logic is based on patterns that are sequences of actions and pattern variables.

- A pattern is defined by the following grammar:

$$p := \; a.p \mid x.p \mid \epsilon$$

Where:

ϵ - stands for the empty pattern

a - is an action

p - is a pattern variable

The set of action variables is denoted by $\mathcal{V}_a$

The set of pattern variables is defined by $\mathcal{V}_p$

ADM Logic Syntax

- Let X be a formula variable, then the set of logic formulas is obtained by the grammar given below:

$$\Phi ::= X \mid \neg\Phi \mid [p_1 \looparrowright p_2]\Phi \mid \Phi_1 \wedge \Phi_2 \mid \nu X.\Phi$$

Where:

$\neg$ and $\wedge$ represent negation and conjunction respectively.

$p_1 \looparrowright p_2$ is a model operator indexed by the two patterns p_1 and p_2.

$\nu X.\Phi$ is a recursive formula, the greatest fixed point operator ν binds all free occurrences of X in Φ.

ADM Logic Syntax (cont.)

- For further convenience we use the following standard abbreviations:

$$
\begin{array}{lcl}
tt & \equiv & \nu X.X \\
ff & \equiv & \mu X.X \\
\langle p_1 \nleftrightarrow p_2 \rangle \Phi & \equiv & \neg [p_1 \nleftrightarrow p_2] \neg \Phi \\
\mu X.\Phi & \equiv & \neg \nu X.\neg \Phi[\neg X/X] \\
\Phi_1 \vee \Phi_2 & \equiv & \neg(\neg \Phi_1 \wedge \neg \Phi_2) \\
\Phi_1 \rightarrow \Phi_2 & \equiv & \neg \Phi_1 \vee \Phi_2 \\
\Phi_1 \leftrightarrow \Phi_2 & \equiv & \Phi_1 \rightarrow \Phi_2 \wedge \Phi_2 \rightarrow \Phi_1
\end{array}
$$

Where $\Phi[\Gamma/X]$ represents the simultaneous replacement of all free occurrences of X in Φ by Γ.

ADM Denotational Senamtics

- Suppose that *Sub* denotes the set of all possible substitutions σ such that:

$$\sigma \in [\mathcal{V}_p \rightarrow \mathcal{T}] \circ [\mathcal{V}_a \rightarrow \mathcal{A}]$$

Where:

$\mathcal{V}_p$ is the set of pattern variables.

$\mathcal{V}_a$ is the set of action variables.

$\mathcal{T}$ is the set of all valid traces.

Env is the set of all possible environments in $[\mathcal{V} \rightarrow 2^{\mathcal{T}}]$

Furthermore, we use $e[X \mapsto U]$ to denote the environment e' defined as follows:

$$\begin{array}{ll} e'(Y) = e(Y) & \text{if } Y \neq X \\ e'(X) = U & \end{array}$$

Semantics

- The semantics of formulas is given by the function:

$$[\![\_]\!]_{\_}^{\_,\_} : \mathcal{L} \times \mathcal{T} \times Sub \times Env \rightarrow 2^{\mathcal{T}}$$

  Defined inductively on the structures of formulas as shown in the next slide, where $t_\downarrow$ is the set of traces inductively defined as follows:

$$\begin{array}{ll} (i) & t \in t_\downarrow \\ (ii) & t_1.a.t_2 \in t_\downarrow \Rightarrow t_1.t_2 \in t_\downarrow \end{array}$$

- Informally $t_\downarrow$ contains all subtraces that could be extracted from t by eliminating some actions from the beginning, from the middle and/or from the end of t.
- Given a trace t, the semantics of a formula will be all the traces in $t_\downarrow$ respecting the conditions specified by this formula.

Semantics (cont.)

$$\begin{array}{rcl}
[\![X]\!]_e^{t,\sigma} & = & e(X) \\
[\![\neg\Phi]\!]_e^{t,\sigma} & = & t_{\downarrow} - [\![\Phi]\!]_e^{t,\sigma} \\
[\![\Phi_1 \wedge \Phi_2]\!]_e^{t,\sigma} & = & [\![\Phi_1]\!]_e^{t,\sigma} \cap [\![\Phi_2]\!]_e^{t,\sigma} \\
[\![[p_1 \looparrowright p_2]\Phi]\!]_e^{t,\sigma} & = & \{u \in t_{\downarrow} \mid \forall\sigma' :\ p_1\sigma\sigma' = u \Rightarrow p_2\sigma\sigma' \in [\![\Phi]\!]_e^{p_2\sigma\sigma', \sigma'\circ\sigma}\} \\
[\![\nu X.\Phi]\!]_e^{t,\sigma} & = & \nu f \text{ where } \left\{ \begin{array}{lccc} f : & 2^{\mathcal{T}} & \longrightarrow & 2^{\mathcal{T}} \\ & U & \longmapsto & [\![\ \Phi\ ]\!]_{e[X \mapsto U]}^{t,\sigma} \end{array} \right.
\end{array}$$

Environment

- Environments are used to give a semantics to the formula X and to deal with recursive formulae.

- Substitutions are internal parameters used to give a semantics to the formula $[p_1 \looparrowright p_2]\Phi$.

- Given an environment e and a substitution σ, we say that a trace ***t*** satisfies if:

$$t \in [\![\Phi]\!]_e^{t,\sigma}$$

- Intuitively, the trace t satisfies the formula $[p_1 \looparrowright p_2]\Phi$ if for all substitutions σ such that $p_1\sigma = t$, the new trace $p_2\sigma$ (the modified version of the trace t) satisfies the remaining part of the formula Φ.

Example

- Suppose that we want to verify whether trace *t* satisfies the formula *Φ* such that:

$$\begin{cases} t = b.a.c.b.d.a \\ \Phi = \langle x_1.a.x_2.b.x_3 \hookleftarrow x_1.x_2.x_3 \rangle \langle x_4.b.x_5.d.x_6 \hookleftarrow x_4.x_5.x_6 \rangle tt \end{cases}$$

More precisely we want to verify if $t \in [\![\Phi]\!]_{\emptyset}^{t,\emptyset}$.

Verification

- Step1: Verify if there exists at least one substitution such that the trace t is equal to $(x_1.a.x_2.b.x_3)\sigma_1$
  - This part is satisfied, since the following substitution fills the required condition.
  $$\sigma_1 = \{x_1 \mapsto b,\ x_2 \mapsto c,\ x_3 \mapsto d.a\}$$
  - The second version of the trace will be:
  $$t_1 \ = \ (x_1.x_2.x_3)\sigma \ = b.c.d.a$$
- Step2: Verify if there exist at least one substitution such that the resulting trace is equal to $(x_4.b.x_5.d.x_6)\sigma_2$
  - Again This part is satisfied with the following substitution:
  $$\{x_4 \mapsto \epsilon,\ x_5 \mapsto c,\ x_6 \mapsto a\}$$

Modeling the stack

- A stack frame contains the address from which the program execution should continue after the function is returned.
- Based on this address, both the **callee** and the **caller** and the exact address of the **call site** in the code are identifiable.
- Each stack frame in our trace represents a unique call site.
- The PDS model also captures program flows based on the call site instead of the function name.
- Therefore, each stack frame can be associated with a PDS transition.
- Each **stack frame** in our trace is modeled as **a triple (a,b,c)** which represents function a being called by function b at call site c.
- The **transitions of the PDS model** are annotated by the call site as **(a,c)** showing the call to function a at call site c.

Modeling the stack

- The left over on the stack can be thought of as a trace of function calls.
- Therefore, the properties of the stack can be modeled using ADM logic.
  - b was called and returned before c:

$$< x_1.b.x_2.b'.x_3.c.x_4 \looparrowright \epsilon > tt.$$

  - b has called c:

$$\nu X < x_1.b.c.x_2 \looparrowright \epsilon > tt \vee$$
$$< x_3.b.x_4.y_1.x_5.y_1'.x_6.c.x_7 \looparrowright x_3.b.x_4.x_5.x_6.c.x_7 > X.$$

Modeling the stack

- Remember the two rules:
  - If stack frame *b* is on top of stack frame *c*, then either *c* has called *b* or *b* has been called and returned before *c*.
  - The function call history should generate exactly the same stack trace and should not overwrite any of the currently existing stack frames.
- The first property is modeled before.
- With ADM logic we can only express properties on one single trace.
- To model the second property we need to combine the program execution trace with the stack properties.

Combined Execution Trace

- **Definition.** If S is the stack trace and E represent an execution path that is accepted by the PDS model of the program, the *combined execution trace* is defined as follows: *comb(S,E) = S.|.E*

- Essentially, the combined execution trace is the concatenation of both traces while separating the traces using the | symbol.

Modeling the stack properties

- **The function call history should generate exactly the same stack trace and should not overwrite any of the currently existing stack frames.**

- This property can be modeled as below:

$$\nu X \langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle (\nu Y \ \langle z_2.x_4.allow \looparrowright x_4 \rangle Y$$
$$\vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow \rangle Y.) \wedge [(z_1, -, c).x_1 \looparrowright x_6] X.$$

- The trace variables starting with x are subtraces and the variables starting with z are single events.

- For each function call made after the return of the function representing the stack frame (z'_1), the formula removes one *allow* from the end and for each function return it adds an *allow* at the end.

- This way, the formula does not allow the paths that overwrite the stack frame being analyzed.

$$\nu X\langle (z_1,-,c).x_1.|.x_2.(\bar{z_1},c).x_3 \looparrowright x_3\rangle(\nu Y\ \langle z_2.x_4.allow \looparrowright x_4\rangle Y$$
$$\vee\ \langle \bar{z_3}.x_5 \looparrowright x_5.allow\rangle Y.) \wedge [(z_1,-,c).x_1 \looparrowright x_6]X.$$

(c,l_3)
(b,l_2)
(a,l_1)

(a,-,l_1).(b,a,l_2).(c,b,l_3).|.(a,l_1).(b,l_2).(d,l_3).(d`,$l_3$).(c,$l_4$).(c`,l_4).(b`,$l_2$).(a`,l_1)

$$\nu X\langle (z_1,-,c).x_1.|.x_2.(\bar{z_1},c).x_3 \looparrowright x_3\rangle$$

z_1 → a

c → l_1

x_3 is empty → the first recursion is satisfied.

$$[(z_1,-,c).x_1 \looparrowright x_6]$$

(b,a,l_2).(c,b,l_3).|.(a,l_1).(b,l_2).(d,l_3).(d`,$l_3$).(c,$l_4$).(c`,l_4).(b`,$l_2$).(a`,l_1)

$$\nu X \langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle (\nu Y\ \langle z_2.x_4.allow \looparrowright x_4 \rangle Y$$
$$\vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow \rangle Y.) \wedge [(z_1, -, c).x_1 \looparrowright x_6] X.$$

(c,l_3)
(b,l_2)
(a,l_1)

(b,a,l_2).(c,b,l_3).|.(a,l_1).(b,l_2).(d,l_3).(d`,$l_3$).(c,$l_4$).(c`,l_4).(b`,$l_2$).(a`,l_1)

$$\nu X \langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle$$

$z_1 \rightarrow b$

$c \rightarrow l_2$

x_3 is (a`,l_1)

$$(\nu Y\ \langle z_2.x_4.allow \looparrowright x_4 \rangle Y \vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow \rangle Y.)$$

$z_3 \rightarrow a$

$c \rightarrow l_1$

Satisfied

$$\nu X\langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3\rangle(\nu Y\ \langle z_2.x_4.allow \looparrowright x_4\rangle Y \vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow\rangle Y.) \wedge [(z_1, -, c).x_1 \looparrowright x_6]X.$$

(c,b,l_3).|.(a,l_1).(b,l_2).(d,l_3).(d\`,$l_3$).(c,$l_4$).(c\`,l_4).(b\`,$l_2$).(a\`,l_1)

(c,l_3)
(b,l_2)
(a,l_1)

$$\nu X\langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3\rangle$$

$z_1 \rightarrow c$

$c \rightarrow l_3$

x_3 is *(b\`,$l_2$).(a\`,l_1)*

$$(\nu Y\ \langle z_2.x_4.allow \looparrowright x_4\rangle Y \vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow\rangle Y.)$$

$z_3 \rightarrow b$

$c \rightarrow l_2$

First iteration

$z_3 \rightarrow a$

$c \rightarrow l_1$

Second iteration

Satisfied

$$\nu X \langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle (\nu Y\ \langle z_2.x_4.allow \looparrowright x_4 \rangle Y \vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow \rangle Y.) \wedge [(z_1, -, c).x_1 \looparrowright x_6] X.$$

(c,l_3)
(b,l_2)
(a,l_1)

$(c,b,l_3).|.(a,l_1).(b,l_2).(d,l_3).(d`,l_3).(c,l_4).(c`,l_4).(e,l_5).(e`,l_5)(b`,l_2).(a`,l_1)$

$$\nu X \langle (z_1, -, c).x_1.|.x_2.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle \quad \left[\begin{array}{l} z_1 \to c \\ c \to l_3 \end{array}\right.$$

x_3 is $(e,l_5).(e`,l_5)(b`,l_2).(a`,l_1)$

$$(\nu Y\ \underline{\langle z_2.x_4.allow \looparrowright x_4 \rangle} Y \vee \langle \bar{z_3}.x_5 \looparrowright x_5.allow \rangle Y.) \quad \left[\begin{array}{l} z_2 \to e \\ c \to l_5 \end{array}\right.$$

First iteration

X

Modeling the whole stack

- In order to model the whole stack we add all the properties specified above in one formula in five steps:
  - Find the call and return states corresponding to the first frame:

$$\langle (z_1, -, c). - .x_1.|.\underline{x}_2.(z_1, c).x_3.(\bar{z_1}, c).x_4 \looparrowright x_3 \rangle$$
$$(\nu Z \langle (z_3, l).x_5.(\bar{z_3}, l).x_6 \looparrowright x_5.x_6 \rangle Z \vee empty.tt)$$

  - Make sure that the stack frame is not overwritten by the following function calls:

$$\nu X \langle (z_1, -, c). - .x_1.|.x_7.(\bar{z_1}, c).x_3 \looparrowright x_3 \rangle (\nu Y \ \langle z_2.x_8.allow \looparrowright x_8 \rangle Y$$
$$\vee \langle \bar{z_3}.x_9 \looparrowright x_9.allow \rangle Y.)$$

Modeling the whole stack

- Specify interrelationships between two consecutive stack frames:

$$
\begin{aligned}
& z_2 \rightarrow z_1 \equiv \\
& \nu U \langle (z_1, -, c).(z_2, z_1, d).x_1.|.x_2.(z_1, c).(z_2, d).x_{10} \\
& \qquad\qquad \hookleftarrow \epsilon \rangle tt \vee \\
& \quad \langle (z_1, -, c).(z_2, z_1, d).x_1.|.x_2.(z_1, c).x_{11}.(z_3, e). \\
& \qquad\qquad x_{12}.(\bar{z_3}, e).x_{13}.(z_2, d).x_{10} \hookleftarrow \\
& \qquad (z_1, -, c).(z_2, z_1, d).x_1.|.x_2.(z_1, c).x_{11}.x_{12}.x_{13}. \\
& \qquad\qquad (z_2, d).x_{10} \rangle U.
\end{aligned}
$$

$$
\begin{aligned}
& z_2 \langle z_1 \equiv \\
& \langle (z_1, -, c).(z_2, -, d).x_1.|.x_{13}.(z_2, d).x_{14}.(\bar{z_2}, d).x_{15} \\
& \qquad\qquad .(z_1, c).x_3.(\bar{z_1}, c).x_4 \hookleftarrow \epsilon \rangle tt.
\end{aligned}
$$

Modeling the whole stack

- To preserve the place of the function call that corespond to the next frame and was found in the previous formula, we mark the trace at the specified location.

$$if\ z_1 \rightarrow z_2 :$$
$$\langle (z_1, -, -).(z_2, z_1, -).x_1.|.x_{16}.(z_2, -).x_{10} \looparrowright$$
$$(z_2, -, -).x_1.|.x_{16}. \uparrow .(z_2, -). \downarrow .x_9 \rangle$$

$$if\ z_2 \langle z_1 :$$
$$\langle (z_1, -, c).(z_2, -, d).x_1.|.x_{13}.(z_2, d).x_{17} \looparrowright$$
$$(z_2, -, -).x_1.|.x_{13}. \uparrow .(z_2, -). \downarrow .x_{17} \rangle$$

- These markers should be removed in the next interation by the following formula.

$$\langle (z_1, -, -).(z_2, -, -).x_1.|.x_2. \downarrow .(z_1, -). \uparrow .x_{18} \looparrowright$$
$$(z_1, -, -).(z_2, -, -).x_1.|.x_2.(z_1, -).x_{18} \rangle$$

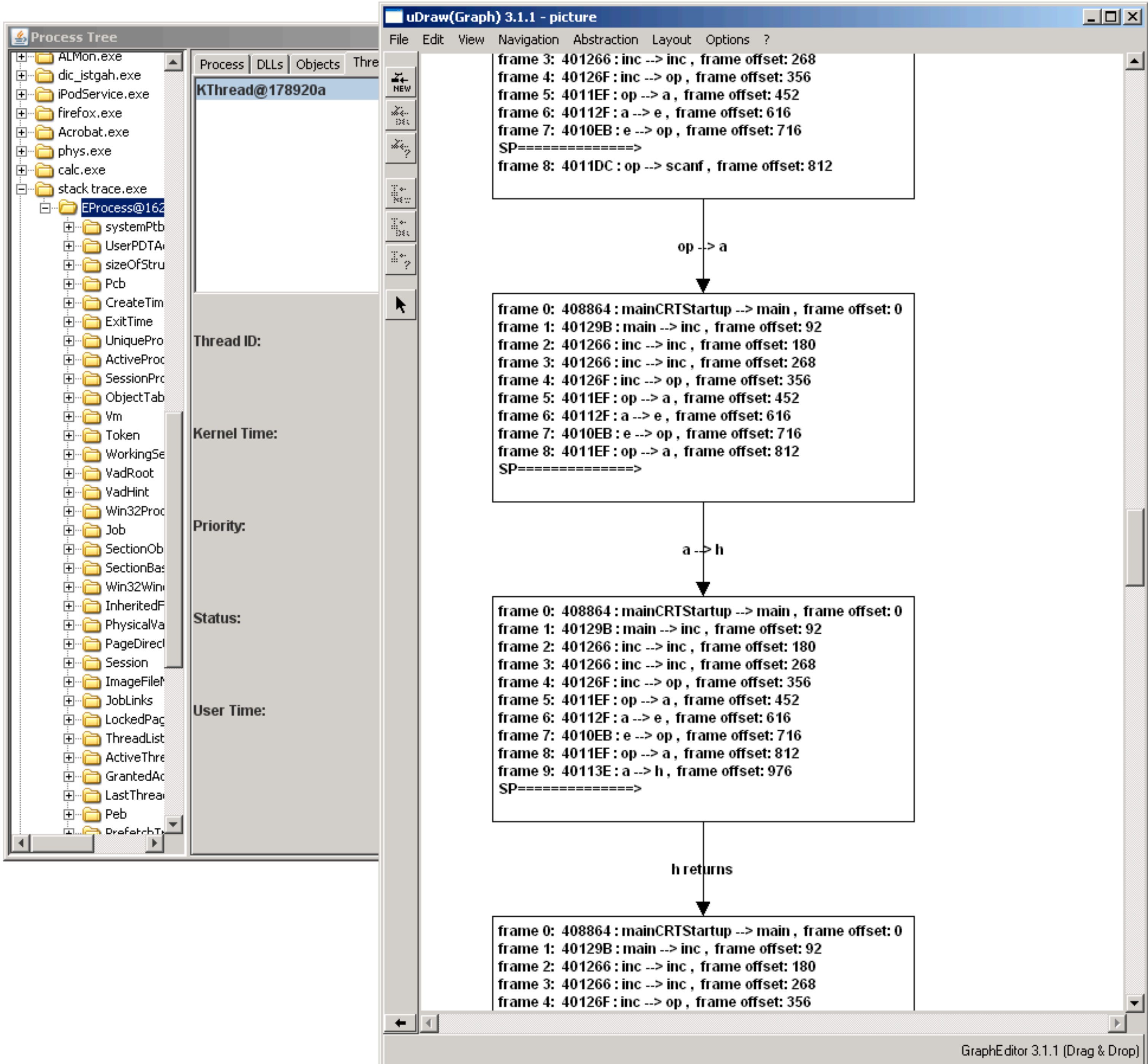
Modeling the whole stack

- To model the whole stack, we combine all the formulae using proper operators (∨,∧).
- The complete query could be simplified by defining some macros as below:

$$
\begin{aligned}
&FindCallCite(a,d,e)\wedge\\
&\nu X.Unmark(a,d)(NotOverWrite(a,d,e)\wedge\\
&\quad((Call(a,b,d,f)\wedge MarkIfCall(a,b,f)X.)\vee\\
&\quad(Before(a,b,g)\wedge MarkIfBefore(a,b,g)X.)))
\end{aligned}
$$

Some implementation details

- The verification of the logic is implemented based on the tablue based proof system of the logic.
- Windows memory forensic analyzer is developed as part of our integrated forensic analysis framework.
- The stack of the process is extracted from memory by parsing the structures of the process manager (EPROCESS, …).
- In order to parse the stack we use two techniques:
    - The OLD_EBP field on the stack holds the address of the previous frame OLD_EBP and therefore stack frames are chained together and the stack parser can follow this chain to correctly identify each stack frame.
        - Some compilers tend to use the EBP pointer within the function as a general purpose register and therefore in this case we can not trace back stack frames using this technique.
    - Look for return addresses that point to right after a call instruction. The stack will be traversed word by word testing which address is pointing to an instruction after a call instruction.


Process Tree
ALMon.exe
dic_istgah.exe
iPodService.exe
firefox.exe
Acrobat.exe
phys.exe
calc.exe
stack trace.exe
EProcess@162
systemPtb
UserPDTA
sizeOfStru
Pcb
CreateTim
ExitTime
UniquePro
ActiveProc
SessionPro
ObjectTab
Vm
Token
WorkingSe
VadRoot
VadHint
Win32Proc
Job
SectionOb
SectionBas
Win32Win
InheritedF
PhysicalVa
PageDirect
Session
ImageFileN
JobLinks
LockedPag
ThreadList
ActiveThre
GrantedAc
LastThrea
Peb
Process
DLLs
Objects
Thre
KThread@178920a
Thread ID:
Kernel Time:
Priority:
Status:
User Time:
uDraw(Graph) 3.1.1 - picture
File
Edit
View
Navigation
Abstraction
Layout
Options
?
NEW
frame 3: 401266 : inc --> inc , frame offset: 268
frame 4: 40126F : inc --> op , frame offset: 356
frame 5: 4011EF : op --> a , frame offset: 452
frame 6: 40112F : a --> e , frame offset: 616
frame 7: 4010EB : e --> op , frame offset: 716
SP==============>
frame 8: 4011DC : op --> scanf , frame offset: 812
op --> a
frame 0: 408864 : mainCRTStartup --> main , frame offset: 0
frame 1: 40129B : main --> inc , frame offset: 92
frame 2: 401266 : inc --> inc , frame offset: 180
frame 3: 401266 : inc --> inc , frame offset: 268
frame 4: 40126F : inc --> op , frame offset: 356
frame 5: 4011EF : op --> a , frame offset: 452
frame 6: 40112F : a --> e , frame offset: 616
frame 7: 4010EB : e --> op , frame offset: 716
frame 8: 4011EF : op --> a , frame offset: 812
SP==============>
a --> h
frame 0: 408864 : mainCRTStartup --> main , frame offset: 0
frame 1: 40129B : main --> inc , frame offset: 92
frame 2: 401266 : inc --> inc , frame offset: 180
frame 3: 401266 : inc --> inc , frame offset: 268
frame 4: 40126F : inc --> op , frame offset: 356
frame 5: 4011EF : op --> a , frame offset: 452
frame 6: 40112F : a --> e , frame offset: 616
frame 7: 4010EB : e --> op , frame offset: 716
frame 8: 4011EF : op --> a , frame offset: 812
frame 9: 40113E : a --> h , frame offset: 976
SP==============>
h returns
frame 0: 408864 : mainCRTStartup --> main , frame offset: 0
frame 1: 40129B : main --> inc , frame offset: 92
frame 2: 401266 : inc --> inc , frame offset: 180
frame 3: 401266 : inc --> inc , frame offset: 268
frame 4: 40126F : inc --> op , frame offset: 356
GraphEditor 3.1.1 (Drag & Drop)

Future research direction

- Improve the model checking algorithm.
- The same technique could be very useful in debugging of the crash dumps.
- There is a wealth of information in memory dumps that can be used to more specifically detect the process execution history such as thread heap and kernel structures.
- The stack trace and stack residue retrieved by our approach could be considered as a log from system activities and could be correlated with other sources such as network logs, operating system logs, etc.