GARUDA 2.0

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2020
Spring

1   Background

GARUDA was a system that operated on a two stream model of the "user" or program, and that which executed the instructions. GARUDA 2.0, we extend, or refine based on the point of view, this model to operate between the Execution (EXE) and Memory (MEM) stages of the pipeline. We assume a monitor theory shown by the graphic Fig **??**. The monitor appears to operate on a single stream, but the two hanging connections can be considered the two streams of the former model.

The most obvious change we need to make is to enable encryption and decryption of the EffAddr. Our attack vector focuses on a trojan targeting the state register between the EXE and MEM stages. They could cache these addresses and try to access that memory later, or they may try to use them as a side channel. Either way, allowing an adversary to track our memory accesses is clearly problematic. However, when we refer to "encryption", we really mean some reversible obfuscation function. We employ the proof assistant, Coq, to prove the EN and DE blocks are exact inverses. GARUDA is written in Coq for exactly this reason, so requiring a proof that $\forall P, DE(EN P) = P$ should be sufficient.

2   Syntax

$$
\begin{array}{llll}
\text{Instruction Fields} & f_i & ::= & f_{i_1} \mid \cdots \mid f_{i_k} \\
\text{Result Fields} & f_r & ::= & f_{r_1} \mid \cdots \mid f_{r_k} \\
\text{Fields} & f & ::= & f_i \mid f_r \\
\text{Instructions} & i & ::= & \{f_{i_1} = v_{i_1}, \; \ldots \; , \; f_{i_k} = v_{i_k}\} \\
\text{Results} & r & ::= & \{f_{r_1} = v_{r_1}, \; \ldots \; , \; f_{r_k} = v_{r_k}\} \\
\end{array}
$$

$$
\begin{array}{llll}
\text{Predicates} & a, b & ::= & 0 & \textit{False} \\
& & \mid & 1 & \textit{Identity} \\
& & \mid & f = n & \textit{Test} \\
& & \mid & a + b & \textit{Sum} \\
& & \mid & a \cdot b & \textit{Product} \\
& & \mid & \neg\, a & \textit{Negation} \\
\end{array}
$$

$$
\begin{array}{llll}
\text{Policies} & p, q & ::= & \mathbf{test}(a) & \textit{Test} \\
& & \mid & act(p) & \textit{Slice Actions} \\
& & \mid & res(p) & \textit{Slice Results} \\
& & \mid & inj_i & \textit{Injection Action} \\
& & \mid & inj_r & \textit{Injection Result} \\
& & \mid & f \leftarrow n & \textit{Update} \\
& & \mid & p + q & \textit{Choice} \\
& & \mid & p \cdot q & \textit{Sequential Concatenation}
\end{array}
$$

3   Semantics

$$\llbracket \cdot \rrbracket \; : \; \mathbf{Stream}(I) \times \mathbf{Stream}(R) \to$$
$$P(\mathbf{Stream}(I)) \times P(\mathbf{Stream}(R))$$

$$\llbracket 0 \rrbracket (-, -) \triangleq (\varnothing, \varnothing)$$

$$\llbracket 1 \rrbracket (is, rs) \triangleq (\{is\}, \{rs\})$$

$$\llbracket f = n \rrbracket (is, rs) \triangleq (\mathsf{filter}\ (f = n)\ \{is\},\ \mathsf{filter}\ (f = n)\ \{rs\})$$

$$\llbracket a + b \rrbracket (is, rs) \triangleq \llbracket a \rrbracket (is, rs) \cup \llbracket b \rrbracket (is, rs)$$
$$\mathsf{where}\ (S_i^1, S_r^1) \cup (S_i^2, S_r^2) \triangleq (S_i^1 \cup S_i^2, S_r^1 \cup S_r^2)$$

$$\llbracket a \cdot b \rrbracket (is, rs) \triangleq \llbracket a \rrbracket (is, rs) \cap \llbracket b \rrbracket (is, rs)$$
$$\mathsf{where}\ (S_i^1, S_r^1) \cap (S_i^2, S_r^2) \triangleq (S_i^1 \cap S_i^2, S_r^1 \cap S_r^2)$$

$$\llbracket \neg a \rrbracket (is, rs) \triangleq \mathsf{let}\ (S_i, S_r) = \llbracket a \rrbracket (is, rs)$$
$$\mathsf{in}\ (\{is\} - S_i, \{rs\} - S_r)$$

$$\llbracket act(p) \rrbracket (is, rs) \triangleq \mathsf{let}\ (S_i, S_r) = \llbracket p \rrbracket (is, rs)\ \mathsf{in}\ (S_i, \{rs\})$$

$$\llbracket res(p) \rrbracket (is, rs) \triangleq \mathsf{let}\ (S_i, S_r) = \llbracket p \rrbracket (is, rs)\ \mathsf{in}\ (\{is\}, S_r)$$

$$\llbracket inj_i(i) \rrbracket (is, rs) \triangleq (\{i : is\}, \{rs\})$$

$$\llbracket inj_r(r) \rrbracket (is, rs) \triangleq (\{is\}, \{r : rs\})$$

$$\llbracket f \leftarrow n \rrbracket (is, rs) \triangleq (\mathsf{map}\ (f \leftarrow n)\ \{is\},\ \mathsf{map}\ (f \leftarrow n)\ \{rs\})$$

$$\llbracket p + q \rrbracket (is, rs) \triangleq \llbracket p \rrbracket (is, rs) \cup \llbracket q \rrbracket (is, rs)$$
$$\mathsf{where}\ (S_i^1, S_r^1) \cup (S_i^2, S_r^2) \triangleq (S_i^1 \cup S_i^2, S_r^1 \cup S_r^2)$$

$$\llbracket p \cdot q \rrbracket (is, rs) \triangleq \mathsf{let}\ (S_i, S_r) = \llbracket p \rrbracket (is, rs)$$
$$\mathsf{in}\ \bigcup \{\llbracket q \rrbracket (is', rs') \mid is' \in S_i, rs' \in S_r\}$$

$$\llbracket \mathsf{filter}\ f \rrbracket (S) \triangleq \{l \in S \mid f(l) = \mathsf{true}\}$$

$$\llbracket \mathsf{map}\ g \rrbracket (S) \triangleq \{g(l) \mid l \in S\}$$

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4 Intermediate Syntax

Values	v	::=	INSTR | RES
Registers	b	::=	reg

Expressions	e	::=	$read(b)$	*Read Reg*
		|	$write(b, v)$	*Write Value to Reg*
		|	$let\ x = e_1\ in\ e_2$	*Assignment*
		|	$e_1 \mathbin{\|\|} e_2$	*Parallel*
		|	$f(e_1)$	*Apply Function*
		|	$if\ v = n\ then\ e_1\ else\ e_2$	*Conditional*
		|	$e_1\ \&\&\ e_2$	*Product (AND)*
		|	$e_1; e_2$	*Concatination*
		|	$forever\ e$	*Hardwire*

5   Intermediate Semantics

Assume all $\mathbf{C}$ is short for $\mathbf{C}_{(i_{in}, i_{out}, r_{in}, r_{out})}$ if unspecified.

$$
\begin{aligned}
\mathbf{C}[0] \ &= \ let \ i\_bog = \text{new buf} \\
&\qquad\quad r\_bog = \text{new buf} \\
&\quad in \ write(i_{out}, i\_bog) \\
&\qquad\ write(r_{out}, r\_bog) \\
\mathbf{C}[1] \ &= \ write(i_{out}, read(i_{in})) \\
&\qquad\ write(r_{out}, read(r_{in})) \\
\mathbf{C}[f = n] \ &= \ if \ i_{in} = n \ then \\
&\qquad\ write(i_{out}, read(i_{in})) \\
&\qquad\ else \ \mathbf{C}_{(i_{in}, i_{out}, -, -)}[0] \\
&\quad if \ r_{in} = n \ then \\
&\qquad\ write(r_{out}, read(r_{in})) \\
&\qquad\ else \ \mathbf{C}_{(-, -, r_{in}, r_{out})}[0]
\end{aligned}
$$

$$\mathbf{C}[\mathsf{test}(a+b)] = let\ e_{aii}, e_{ari}, e_{bii}, e_{bri} = \text{new buf } in$$
$$DeMux(i_{in}, e_{aii}, e_{bii})\ ||\ DeMux(r_{in}, e_{ari}, e_{bri})$$
$$let\ e_a = \mathbf{C}_{(e_{aii}, e_{aio}, e_{ari}, e_{aro})}[a]$$
$$e_b = \mathbf{C}_{(e_{bii}, e_{bio}, e_{bri}, e_{bro})}[b]$$
$$in\ Mux(e_a\ \ e_b, (i_{out}, r_{out}))$$

$$\mathbf{C}[\mathsf{test}(a \cdot b)] = \mathbf{C}[\mathsf{test}(a) \cdot \mathsf{test}(b)]$$

$$\mathbf{C}[\neg a] = if\ \neg a\ then$$
$$write(i_{out}, read(i_{in}))$$
$$write(r_{out}, read(r_{in}))$$
$$else\ \mathbf{C}[0]$$

$$\mathbf{C}[act(p)] = let\ r\_bog_i = \text{new buf}$$
$$r\_bog_o = \text{new buf}$$
$$in\ e_p = \mathbf{C}_{(i_{in}, i_{out}, r\_bog_i, r\_bog_o)}[p]$$
$$e_p\ ||\ write(r_{out}, read(r_{in}))$$

$$\mathbf{C}[res(p)] = let\ i\_bog_i = \text{new buf}$$
$$i\_bog_o = \text{new buf}$$
$$in\ e_p = \mathbf{C}_{(i\_bog_i, i\_bog_o, r_{in}, r_{out})}[p]$$
$$e_p\ ||\ write(i_{out}, read(i_{in}))$$

$$\mathbf{C}[inj_i V] = write(i_{out}, V)$$

$$\mathbf{C}[inj_r V] = write(r_{out}, V)$$

$$\mathbf{C}[f \leftarrow n] = let\ i' = f(read(i_{in}))$$
$$r' = f(read(r_{in}))$$
$$in\ write(i_{out}, i')$$
$$write(r_{out}, r')$$

$$\mathbf{C}[p + q] = let\ e_p = \mathbf{C}[p]$$
$$e_q = \mathbf{C}[q]$$
$$in\ Mux(e_p, e_q, (i_{out}, r_{out}))$$

$$\mathbf{C}[p \cdot q] = let\ i_{mid} = \text{new buf}$$
$$r_{mid} = \text{new buf}$$
$$e_p = \mathbf{C}_{(i_{in}, i_{mid}, r_{in}, r_{mid})}[p]$$
$$e_q = \mathbf{C}_{(i_{mid}, i_{out}, r_{mid}, r_{out})}[q]$$
$$in\ e_p\ ;\ e_q$$

6 Applications of GARUDA 2.0

6.1 Standard Taint

In the previous version of GARUDA, taint was implemented by tagging the most significant bit of a register. This caused no hardware overhead to maintain in the pipeline, but imposed an obvious bit-resolution hindrance. In GARUDA 2.0, the definition of such a policy is identical, but the compilation is different.

We assume a MIPS-like architecture for this example. The op codes of any given instruction are no more than 3; IN_1, IN_2, and OUT We denote these as RS, RT, and RD.

Let's suppose you want your taint to propogate on the inputs of any arithmetic instructions. Additionally, you prohibit any tainted instructions or addresses from accessing memory. In GARUDA 2.0, we can define this as follows. Please note that ALU can further be expanded to specific types of ALU instructions

$$
\begin{aligned}
\textit{Instruction Fields } f_i \quad &::= \quad \mathsf{Taint_{RS}}, \mathsf{Taint_{RT}}, \mathsf{Taint_{RD}}, \mathsf{OP} \\
\mathsf{OP} \quad &::= \quad \mathsf{MEM_{READ}} \mid \mathsf{MEM_{WRITE}} \mid \mathsf{ALU} \mid \cdots \\
\textit{Result Fields } f_r \quad &::= \quad (*\mathsf{empty}*)
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{Arith} \quad &\triangleq \quad \mathsf{OP} = \mathsf{ALU} \\
\mathsf{Read} \quad &\triangleq \quad \mathsf{OP} = \mathsf{MEM_{READ}} \\
\mathsf{Write} \quad &\triangleq \quad \mathsf{OP} = \mathsf{MEM_{WRITE}} \\
\mathsf{AnyMem} \quad &\triangleq \quad \mathsf{Read} + \mathsf{Write}
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{TaintedInstr} \quad &\triangleq \quad (\mathsf{Taint_{RS}} = \mathsf{TRUE}) + (\mathsf{Taint_{RT}} = \mathsf{TRUE}) \\
\mathsf{TaintRes} \quad &\triangleq \quad \mathsf{Taint_{RD}} \leftarrow \mathsf{TRUE}
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{PropTaintALU} \quad &\triangleq \quad act(\mathsf{Arith} \cdot \mathsf{TaintedInstr} \cdot \mathsf{TaintRes}) \\
&\quad + act(\mathsf{Arith} \cdot \neg\mathsf{TaintedInstr}) \\
\mathsf{NoTaintMem} \quad &\triangleq \quad act(\mathsf{AnyMem} \cdot \neg\mathsf{TaintedInstr}) \\
\mathsf{SecureMem} \quad &\triangleq \quad \mathsf{PropTaintALU} + \mathsf{NoTaintMem} \\
&\quad + act(\neg(\mathsf{Arith} + \mathsf{AnyMem}))
\end{aligned}
$$

6.2   Speculative Taint

[1]

$$
\begin{aligned}
\textit{Instruction Fields } f_i \quad &::= \quad \mathsf{Taint_{RS}, Taint_{RT}, Taint_{RD}, OP} \\
\mathsf{OP} \quad &::= \quad \mathsf{MEM_{READ} \mid MEM_{WRITE} \mid ALU \mid} \cdots \\
\textit{Result Fields } f_r \quad &::= \quad (*\mathsf{empty}*)
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{Arith} \quad &\triangleq \quad \mathsf{OP = ALU} \\
\mathsf{Read} \quad &\triangleq \quad \mathsf{OP = MEM_{READ}} \\
\mathsf{Write} \quad &\triangleq \quad \mathsf{OP = MEM_{WRITE}} \\
\mathsf{AnyMem} \quad &\triangleq \quad \mathsf{Read + Write}
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{TaintedInstr} \quad &\triangleq \quad (\mathsf{Taint_{RS} = TRUE}) + (\mathsf{Taint_{RT} = TRUE}) \\
\mathsf{TaintRes} \quad &\triangleq \quad \mathsf{Taint_{RD} \leftarrow TRUE}
\end{aligned}
$$

$$
\begin{aligned}
\mathsf{PropTaintALU} \quad &\triangleq \quad act(\mathsf{Arith \cdot TaintedInstr \cdot TaintRes}) \\
& \qquad + act(\mathsf{Arith \cdot \neg TaintedInstr}) \\
\mathsf{NoTaintMem} \quad &\triangleq \quad act(\mathsf{AnyMem \cdot \neg TaintedInstr}) \\
\mathsf{SecureMem} \quad &\triangleq \quad \mathsf{PropTaintALU + NoTaintMem} \\
& \qquad + act(\neg(\mathsf{Arith + AnyMem}))
\end{aligned}
$$

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References

[1] Jiyong Yu, Mengjia Yan, Artem Khyzha, Adam Morrison, Josep Torrellas, and Christopher W Fletcher. Speculative taint tracking (stt) a comprehensive protection for speculatively accessed data. In *Proceedings of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture*, pages 954–968, 2019.