ProveNFix: Temporal Property guided Program Repair

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Can temporal property analysis be modular?

“Each function is analysed only once and

can be replaced by their verified properties.”

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Three main difficulties：

1. Temporal logic property entailment checker.
2. Writing temporal specifications for each function is tedious and challenging.
3. The classic pre/post-conditions is not enough, e.g.,

   "some meaningful operations can only happen if the return value of loading the certificate is positive"

Future-condition

Defined in header `<stdlib.h>`		
`void free( void* ptr );`		

```
void free (void *ptr);
// post: (ptr=null ∧ ϵ) ∨ (ptr≠null ∧ free(ptr))
// future: true ∧ 𝒢 (!_(ptr))
```

The behavior is undefined if after `free()` returns, an access is made through the pointer `ptr` (unless another allocation function happened to result in a pointer value equal to `ptr`).

Future-condition

Defined in header `<stdlib.h>`		
`void* malloc( size_t size );`		

On success, returns the pointer to the beginning of newly allocated memory. To avoid a memory leak, the returned pointer must be deallocated with `free()` or `realloc()`.

Future-condition

On failure, returns a null pointer.

```
void *malloc (size_t size);
// pre: size>0 ∧ _*
// post: (ret=null ∧ ϵ) ∨ (ret≠null ∧ malloc(ret))
// future: ret≠null → ℱ (free(ret))
```

Future-condition based modular analysis

$$\dfrac{nm(x^*) \mapsto (\Phi_{pre}, \Phi_{post}) \in \mathcal{E} \quad \boxed{\Phi \sqsubseteq [y^*/x^*]\Phi_{pre}} \quad \Phi'_{post} = [r/ret, y^*/x^*]\Phi_{post} \quad \mathcal{E} \vdash \{\Phi \cdot \Phi'_{post}\}\ e\ \{\Phi_e\}}{\mathcal{E} \vdash \{\Phi\}\ r = nm(y^*);\ e\ \{\Phi'_{post} \cdot \Phi_e\}}\ [\mathit{FR\text{-}Call}]$$

Entailment Checking

A collection of specifications

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$$\frac{nm(x^*) \mapsto (\Phi_{pre}, \Phi_{post}, \Phi_{future}) \in \mathcal{E} \quad \Phi \sqsubseteq [y^*/x^*]\Phi_{pre} \quad \Phi'_{post} = [r/ret, y^*/x^*]\Phi_{post} \quad \mathcal{E} \vdash \{\Phi \cdot \Phi'_{post}\}\ e\ \{\Phi_e\} \quad \Phi_e \sqsubseteq [r/ret, y^*/x^*]\Phi_{future}}{\mathcal{E} \vdash \{\Phi\}\ r = nm(y^*);\ e\ \{\Phi'_{post} \cdot \Phi_e\}} \ [FR\text{-}Call]$$

Entailment Checking → $\Phi \sqsubseteq [y^*/x^*]\Phi_{pre}$

A collection of specifications → $\mathcal{E}$

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Specification inference via bi-abduction

```
void *malloc (size_t size);
// future: (ret=null ∧ 𝒢 (!_(ret))) ∨ (ret≠null ∧ ℱ (free(ret))
```

```
void wrap_malloc_I (int* ptr)
// future: ptr=null ∧ 𝒢 (!_(ptr))
          ∨ ptr≠null ∧ ℱ (free(ptr))
{ ptr = malloc (4); return;}
```

```
int* wrap_malloc_II ()
// future: ret=null ∧ 𝒢 (!_(ret))
          ∨ ret≠null ∧ ℱ (free(ret))
{ int* ptr = malloc (4); return ptr;}
```

Specification inference via bi-abduction

```
void *malloc (size_t size);
// future: (ret=null ∧ 𝒢 (!_(ret))) ∨ (ret≠null ∧ ℱ (free(ret))
```

```
int* wrap_malloc_III ()
// future: true ∧ ℱ (free(ret))
{ int* ptr = malloc (4);
  if (ptr == NULL) exit(-1);
  return ptr;}
```

Specification inference via bi-abduction

```
void *malloc (size_t size);
// future: (ret=null ∧ 𝒢 (!_(ret))) ∨ (ret≠null ∧ ℱ (free(ret))
```

```
int* wrap_malloc_III ()
// future: true ∧ ℱ (free(ret))
{ int* ptr = malloc (4);
  if (ptr == NULL) exit(-1);
  return ptr;}
```

```
int* wrap_malloc_IV ()
// future: true ∧ _*
{ int* ptr = malloc (4);
 + if (ptr != NULL) free(ptr); // a repair
  return NULL;}
```

Failed entailment: $\mathtt{true} \wedge \mathcal{E} \not\sqsubseteq \mathtt{ptr{\neq}null} \wedge \mathcal{F}\,(\mathtt{free(ptr)})$

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Term rewriting system for regular expressions

- Flexible specifications, which can be combined with other logic;
- Efficient entailment checker with inductive proofs.

$$
\begin{array}{llll}
(\mathit{IntRE}) & \Phi & ::= & \bigvee(\pi \wedge \theta) \\
(\mathit{Traces}) & \theta & ::= & \bot \mid \epsilon \mid \mathrm{I} \mid \theta_1 \cdot \theta_2 \mid \theta_1 \vee \theta_2 \mid \theta^{\star} \\
(\mathit{Events}) & \mathrm{I} & ::= & \mathrm{A}(v) \mid \mathrm{A}(\_) \mid !\mathrm{A}(v) \mid !\_(v) \mid \_ \mid \mathrm{I}_1 \wedge \mathrm{I}_2 \\
(\mathit{Pure}) & \pi & ::= & T \mid F \mid bop(t_1, t_2) \mid \pi_1 \wedge \pi_2 \mid \pi_1 \vee \pi_2 \mid \neg\pi \mid \exists x.\pi \\
(\mathit{Terms}) & t & ::= & v \mid t_1 + t_2 \mid t_1 - t_2 \\
(\mathit{Values}) & v & ::= & c \mid x \mid null
\end{array}
$$

Fig. 10. Syntax of the spec language, *IntRE*.

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- Efficient entailment checker with inductive proofs.

Examples:

$x>2 \land E \sqsubseteq x>1 \land (E \lor F)$

$x>0 \land E \not\sqsubseteq x>1 \land (E \lor F)$

$true \land E \not\sqsubseteq true \land (E . F)$

$$
\dfrac{\dfrac{\dfrac{(a \lor b)^{\star} \sqsubseteq (a \lor b \lor bb)^{\star} \ \text{[Reoccur]}}{\varepsilon \cdot (a \lor b)^{\star} \sqsubseteq \varepsilon \cdot (a \lor b \lor bb)^{\star}}}{a \cdot (a \lor b)^{\star} \sqsubseteq (a \lor b \lor bb)^{\star}} \qquad \dfrac{\text{[Reoccur]}}{b \cdot (a \lor b)^{\star} \sqsubseteq \ \ldots}}{(a \lor b)^{\star} \sqsubseteq (a \lor b \lor bb)^{\star}}
$$

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A term rewriting system for regular expressions

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Primitive spec + spec inference!

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Experiment 1: detecting bugs

Primitive APIs	Pre	Post	Future	Targeted Bug Type
open/socket/fopen/fdopen/opendir	✗	✗	✓	Resource Leak
close/fclose/endmntent/fflush/closedir	✗	✓	✗	
malloc/realloc/calloc/localtime	✗	✗	✓	Null Pointer Dereference
→ *(pointer dereference)*	✗	✓	✗	
malloc	✓	✓	✓	Memory Usage (Leak, Use-After-Free, Double Free)
free	✓	✓	✓	

- 17 predefined primitive specs.
- ProveNFix is finding 72.2% more true bugs, with a 17% loss of missing true bugs.

Project	kLoC	#NPD		#ML		#RL		Time	
		Infer	ProveNFix	Infer	ProveNFix	Infer	ProveNFix	Infer	ProveNFix
Swoole(a4256e4)	44.5	30+7	30+23	16+4	12+16	13+1	13+6	2m 50s	39.54s
lxc(72cc48f)	63.3	7+9	5+19	11+6	10+12	5+1	5+5	55.62s	1m 28s
WavPack(22977b2)	36	23+7	20+21	3	3+9	0+2	0	27.99s	23.77s
flex(d3de49f)	23.9	14+4	14+4	3	3+1	0	0+1	32.25s	47.75s
p11-kit	76.2	3+5	2+2	13+3	12+15	5	5+1	1m 57s	1m 4s
x264(d4099dd)	67.7	0	0	12	11+5	2	2+3	2m 33s	23.168s
recutils-1.8	81.9	25	22+8	13+10	11+29	1	1+7	9m 10s	38.29s
inetutils-1.9.4	117.2	7+4	5+8	9+3	7+10	1	1+5	30.26s	1m 5s
snort-2.9.13	378.2	44+12	33+34	26+4	15+16	1+2	1+1	8m 49s	3m 13s
grub(c6b9a0a)	331.1	13+12	6+5	1	1	0+3	0	3m 27s	1m 1s
Total	1,220.00	166+60	137+124	107+30	85+113	26+9	27+29	31m 12s	10m 44s

Automated repair via deductive synthesis

Algorithm 1 Algorithm for the Deductive Synthesis

Require: $\mathcal{E}, (\pi \wedge \theta_{target})$

Ensure: An expression e_R such that $\mathcal{E} \vdash \{T \wedge \epsilon\}\ e_R\ \{\pi \wedge \theta_{target}\}$

$e_{acc} = ()$
for each $nm\ (x^*) \mapsto [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E}$ **do**
  if $\theta_{target} = \epsilon$ **then return** `if` π `then` e_{acc} `else` $()$
  else
    `// there exist a set of program variables` y^*
    $\theta'_{target} = (\pi \wedge [y^*/x^*]\Phi_{post})^{-1}\theta_{target}$
    $e_{acc} = e_{acc};\ nm(y^*)$
  end if
end for
return without any suitable patches

Example: `true` ∧ $\mathcal{E}$ $\not\sqsubseteq$ `ptr≠null` ∧ `_^*.(free(ptr))`

⇒ synthesis(`ptr≠null` ∧ `_^*.(free(ptr))`) ⇒ `if (ptr != NULL) free(ptr);`

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    $\boxed{\textbf{if } \theta_{target} = \epsilon \textbf{ then return } \texttt{if } \pi \texttt{ then } e_{acc} \texttt{ else } ()}$

    else

        `// there exist a set of program variables` y^*

        $\theta'_{target} = (\pi \wedge [y^*/x^*]\Phi_{post})^{-1}\theta_{target}$

        $e_{acc} = e_{acc};\ nm(y^*)$

    end if

end for

return without any suitable patches

Example: `true` $\wedge$ $\mathcal{E}$ $\not\models$ `ptr≠null` $\wedge$ `_^*.(free(ptr))`

$\Rightarrow$ synthesis(`ptr≠null` $\wedge$ `_^*.(free(ptr))`) $\Rightarrow$ `if (ptr != NULL) free(ptr);`

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Ensure: An expression e_R such that $\mathcal{E} \vdash \{T \wedge \epsilon\}\ e_R\ \{\pi \wedge \theta_{target}\}$

```
e_acc = ()
for each nm (x*) ↦ [Φ_pre, Φ_post, Φ_future] ∈ ℰ do
    if θ_target = ϵ then return if π then e_acc else ()
    else
        // there exist a set of program variables y*
        θ'_target = (π ∧ [y*/x*]Φ_post)^-1 θ_target
        e_acc = e_acc; nm(y*)
    end if
end for
return without any suitable patches
```

Example: `true ∧ ℰ` $\not\vDash$ `ptr≠null ∧ _^*.(free(ptr))`

$\Rightarrow$ synthesis(`ptr≠null ∧ _^*.(free(ptr))`) $\Rightarrow$ `if (ptr != NULL) free(ptr);`

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Algorithm 1 Algorithm for the Deductive Synthesis

Require: $\mathcal{E}$, $(\pi \wedge \theta_{target})$

Ensure: An expression e_R such that $\mathcal{E} \vdash \{T \wedge \epsilon\}\ e_R\ \{\pi \wedge \theta_{target}\}$

$e_{acc} = ()$
for each $nm\ (x^*) \mapsto [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E}$ **do**
  if $\theta_{target} = \epsilon$ **then return** `if` π `then` e_{acc} `else` $()$
  else
    `// there exist a set of program variables` y^*
    $\theta'_{target} = (\pi \wedge [y^*/x^*]\Phi_{post})^{-1}\theta_{target}$
    $e_{acc} = e_{acc};\ nm(y^*)$
  end if
end for
return without any suitable patches

- Only supporting inserting/deleting calls.
- Do need re-analysis.

Example: `true` ∧ $\mathcal{E}$ $\not\models$ `ptr≠null ∧ _^*.(free(ptr))`

⇒ synthesis(`ptr≠null ∧ _^*.(free(ptr))`) ⇒ `if (ptr != NULL) free(ptr);`

Experiment 2: Repairing bugs

Project	NPD		ML		RL		Time	Infer-v0.9.3			
	#	ProveNFix	#	ProveNFix	#	ProveNFix		#ML	SAVER	#RL	FootPatch
Swoole	53	53	32	28	19	19	4.33s	15+3	11	6+1	6
lxc	26	24	23	22	10	10	3.882s	3+5	3	2+1	0
WavPack	44	41	12	12	0	0	11.435s	1+2	0	2	1
flex	18	18	4	4	1	1	39.38s	3+4	0	0	0
p11-kit	5	4	28	27	6	6	2.452s	33+9	24	2	1
x264	0	0	17	14	5	5	6.375s	10	10	0	0
recutils-1.8	33	30	42	36	8	8	1.261s	10+11	8	1	0
inetutils-1.9.4	15	13	19	17	6	6	1.517s	4+5	4	2+1	1
snort-2.9.13	78	67	42	13	2	2	10.57s	16+27	10	0	0
grub	18	11	1	1	0	0	40.626s	0	0	0	0
Total(Fix Rate)	290	261(90%)	220	174 (79%)	57	57 (100%)	2m 2s	95+66	70(73.7%)	15+3	9(60%)

- ❖ 90% fix - null pointer dereferences,
- ❖ 79% fix - memory leaks
- ❖ 100% fix - resource leaks.

SAVER's pre-analysis time:

26.3 seconds for the flex project

39.5 minutes for the snort-2.9.13 project

Experiment 4: usefulness of spec inference

- 2 predefined primitive specs, OpenSSL-3.1.2, 556.3 kLoC,
- 143.11 seconds to generate future-conditions for 128 OpenSSL APIs
- Example: SSL_CTX_new (meth) ; // future : ((ret=0) /\ return (ret))

OpenSSL Applications	kLoC	Issue ID	Target API	Github Status	ProveNFix	Time
keepalive(843ffc80)	59.1	1003	SSL_CTX_new	✓	✓	5.62s
		1004	SSL_new	✓	✓	
thc-ipv6(011376c)	30.9	28	BN_new	✓	✓	3.32s
		29	BN_set_word	✓	✗	
FreeRADIUS(94149dc)	258.9	2309	BIO_new	✓	✓	38.89s
		2310	i2a_ASN1_OBJECT	✓	✓	
trafficserver(5ee6a5f)	34.1	4292	SSL_CTX_new	✓	✓	21.55s
		4293	SSL_new	✓	✓	
		4294	SSL_write	✓	✓	
sslsplit(19a16bd)	18.7	224	SSL_CTX_use_certificate	✓	✓	2.69s
		225	SSL_use_PrivateKey	✓	✓	
proxytunnel(f7831a2)	3.1	36	SSL_connect	✓	✓	0.62s
		37	SSL_new	✓	✓	

Zuxing Gu, Jiecheng Wu, Chi Li, Min Zhou, and Ming Gu. 2019. SSLDoc: Automatically Diagnosing Incorrect SSL API Usages in C Programs.

Conclusion

Thanks!

- Compositional static analyzer via temporal properties.
- Specified 17 APIs; found 515 vulnerabilities from 1 million LOC; with a 90% fix rate.
- Specification: a novel *future-condition.*
- Specification inference via bi-abduction.
- The inferred spec can be used to analysis protocol applications, e.g., OpenSSL.