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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Modular Analysis:

1. Assume-guarantee paradigm (divide and conquer)
2. A set of forward/backwards reasoning rules

Some Forward Reasoning Rules

Entailment Checking

$$\frac{\vdash \{\Phi_{pre}\}\, \mathtt{e}\ \{\Phi_C\} \qquad \Phi_C \sqsubseteq \Phi_{post}}{\vdash \tau\ \mathbf{mn}\ (\tau\ \mathbf{x})^*\ \{\mathbf{requires}\ \Phi_{pre}\ \mathbf{ensures}\ \Phi_{post}\}\ \{\mathtt{e}\}}\ [\mathtt{FV\text{-}Meth}]$$

$$\frac{\Phi'_C {=} \Phi_C \cdot \underline{\mathbf{a}}}{\vdash \{\Phi_C\}\ \mathbf{event}[\underline{\mathbf{a}}]\ \{\Phi'_C\}}\ [\mathtt{FV\text{-}Event}] \qquad \frac{\vdash \{\Phi_C\}\ \mathtt{e}_1\ \{\Phi'_C\} \qquad \vdash \{\Phi'_C\}\ \mathtt{e}_2\ \{\Phi''_C\}}{\vdash \{\Phi_C\}\ \mathtt{e}_1; \mathtt{e}_2\ \{\Phi''_C\}}\ [\mathtt{FV\text{-}Seq}]$$

$$\frac{\vdash \{\mathbf{v} \wedge \Phi_C\}\ \mathtt{e}_1\ \{\Phi'_C\} \qquad \vdash \{\neg \mathbf{v} \wedge \Phi_C\}\ \mathtt{e}_2\ \{\Phi''_C\}}{\vdash \{\Phi_C\}\ \mathbf{if}\ \mathbf{v}\ \mathbf{then}\ \mathtt{e}_1\ \mathbf{else}\ \mathtt{e}_2\ \{\Phi'_C \vee \Phi''_C\}}\ [\mathtt{FV\text{-}If\text{-}Else}]$$

? $[\mathtt{FV\text{-}Call}]$

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Modular Analysis:

1. Assume-guarantee paradigm (divide and conquer)
2. A set of forward/backwards reasoning rules
3. Entailment/Inclusion Checking : $x > 1 \sqsubseteq x > 0$

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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 );`

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`).

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

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()`.

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 vs. Post-condtion ?

main.c

```c
int x = 0;
void test()
// pre:    x=0
// post:   x=1

{ x = x + 1;
  return;
}

int main() {
    test();
    x = x + 2;
}
```

Future-condition vs. Post-condtion ?

main.c

```c
int x = 0;
void test()
// pre:    x=0
// post:   x=1
// future: Finally (x=3)
{ x = x + 1;
  return;
}

int main() {
    test();
    x = x + 2;
}
```

Future-condition based modular analysis

$$nm(x^*) \mapsto (\Phi_{pre}, \Phi_{post}) \in \mathcal{E}$$

Entailment Checking → $\Phi \sqsubseteq [y^*/x^*]\Phi_{pre}$ $\quad \Phi'_{post} = [r/ret, y^*/x^*]\Phi_{post}$

$$\mathcal{E} \vdash \{\Phi \cdot \Phi'_{post}\}\ e\ \{\Phi_e\}$$

A collection of specifications → $\mathcal{E} \vdash \{\Phi\}\ r = nm(y^*);\ e\ \{\Phi'_{post} \cdot \Phi_e\}$ [FR-Call]

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

Future-condition based modular analysis

Entailment Checking →

A collection of specifications →

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

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

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;}
```

Specification inference via bi-abduction

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

  return NULL;}
```

Failed entailment: true ∧ ℰ ⋢ ptr≠null ∧ ℱ (free(ptr))

Can temporal property analysis be modular?

"Each function is analysed only once and

can be replaced by their verified properties."

Three main difficulties：

1. Temporal logic property entailment checker. **Primitive spec + spec inference!**

2. ~~Writing temporal specifications for each function is tedious and challenging.~~

3. ~~The classic pre/post-conditions is not enough, e.g.,~~ **Future-condition!**

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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.

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

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

Term rewriting system for regular expressions

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Examples:

$x>2 \wedge E \sqsubseteq x>1 \wedge (E \vee F)$

$x>0 \wedge E \not\sqsubseteq x>1 \wedge (E \vee F)$

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

$$(a \vee b)^{\star} \sqsubseteq (a \vee b \vee bb)^{\star} \quad \text{[Reoccur]}$$

$$\epsilon \cdot (a \vee b)^{\star} \sqsubseteq \epsilon \cdot (a \vee b \vee bb)^{\star} \qquad \text{[Reoccur]}$$

$$a \cdot (a \vee b)^{\star} \sqsubseteq (a \vee b \vee bb)^{\star} \qquad b \cdot (a \vee b)^{\star} \sqsubseteq \ldots$$

$$(a \vee b)^{\star} \sqsubseteq (a \vee b \vee bb)^{\star}$$

Can temporal property analysis be modular?

Can!

"Each function is analysed only once and can be replaced by their verified properties." ✓

Three main difficulties:

A term rewriting system for regular expressions

1. ~~Temporal logic property entailment checker.~~ **Primitive spec + spec inference!**
2. ~~Writing temporal specifications for each function is tedious and challenging.~~
3. ~~The classic pre/post-conditions is not enough, e.g.,~~ **Future-condition!**

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

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

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```
int* wrap_malloc_IV ()
// future: true ∧ _*
{ int* ptr = malloc (4);

  return NULL;}
```

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

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```
int* wrap_malloc_IV ()
// future: true ∧ _*
{ int* ptr = malloc (4);
  int* ptr1 = ptr;
  return NULL;}
```

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

Automated repair via deductive synthesis

Algorithm 1 Algorithm for the Deductive Synthesis

Require: $\mathcal{E}, (\pi \land \theta_{target})$
Ensure: An expression e_R such that $\mathcal{E} \vdash \{T \land \epsilon\}\ e_R\ \{\pi \land \theta_{target}\}$

$e_{acc} = ()$
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^*
    $\theta'_{target} = (\pi \land [y^*/x^*]\Phi_{post})^{-1}\theta_{target}$
    $e_{acc} = e_{acc};\ nm(y^*)$
  end if
end for
return without any suitable patches

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

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

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

$e_{acc} = ()$
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    $\theta'_{target} = (\pi \wedge [y^*/x^*]\Phi_{post})^{-1}\theta_{target}$
    $e_{acc} = e_{acc};\ nm(y^*)$
  end if
end for
return without any suitable patches

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

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

$\Rightarrow$ synthesis(`ptr≠null` $\wedge$ `_^*.(free(ptr))`) $\Rightarrow$ `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	✓	✓	

* Gu, Zuxing, et al. "SSLDoc: Automatically Diagnosing Incorrect SSL API Usages in C Programs." *SEKE*. 2019.

Summary

- Compositional static analyzer via temporal properties.
- Specified 17 APIs; found 515 bugs from 1 million LOC; (on average) 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.

Take away

❖ Specify a small set of properties once and analyse/repair a large number of programs

❖ Specification inference enabled by projecting global spec to local spec.