Future Conditions

Temporal Property guided Program Analysis, Repair and Verification

Yahui Song

Research Fellow @ National University of Singapore (NUS)

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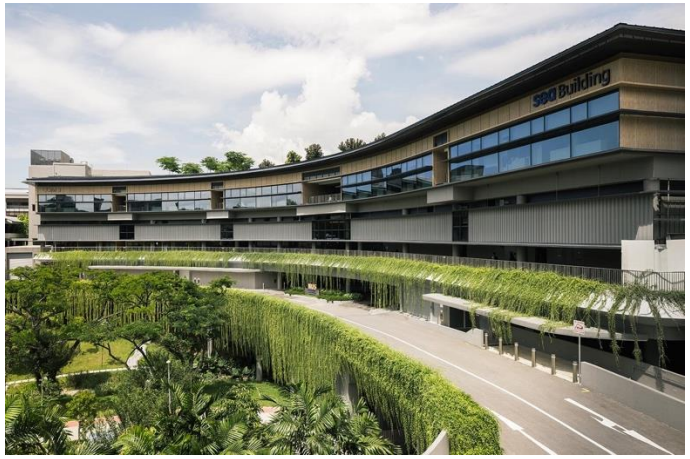

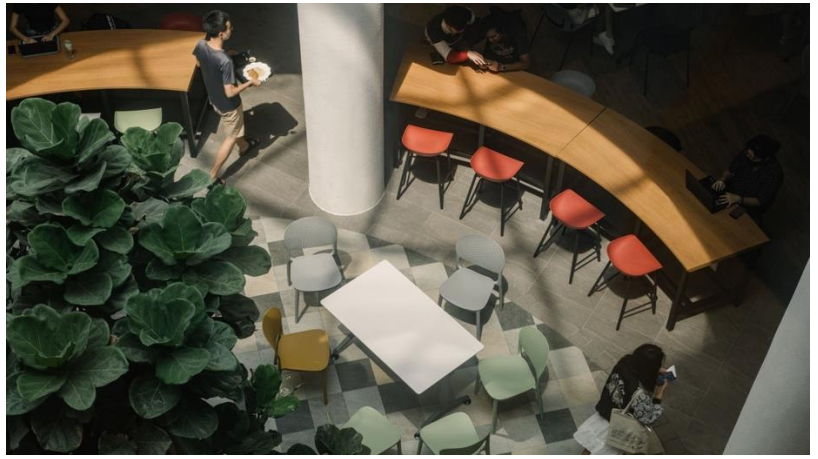

My Research

- PhD (2018 Aug – 2022 Dec)

  Thesis: Symbolic Temporal Verification Techniques with Extended Regular Expressions

  Keywords: Modularly (Scalability), Expressive Specification, Hoare-style Verification (source code level)

  Applications
  - Event-based reactive systems [ICFEM 2020]
  - Synchronous languages like Esterel [VMCAI 2021]
  - User-defined algebraic effects and handlers [APLAS 2022]
  - Real-time systems [TACAS 2023]

- Research Fellow (2023 Jan – now)

  Staged Specification Logic (Regular expression + Separation logic):

  Higher-order Imperative Programs [FM 2024]; Algebraic Effects and Handlers [ICFP 2024]

  Temporal Property guided Program Analysis, Repair and Verification:

  ProveNFix: Temporal Property guided Program Repair [FSE 2024]

  Specifying and Verifying Future Conditions [Under Submission]

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:

- ❑ Temporal logic entailment checker.
- ❑ Writing temporal specifications for each function is tedious and challenging.
- ❑ 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`).

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 based compositional analysis

$$\frac{\Phi <: \Phi_{pre} \qquad \{\Phi \circ \Phi_{post}\}\ e\ \{\Phi_e\} \qquad f\,(\overline{x})\,[\Phi_{pre}, \Phi_{post}, \quad\ ] \in \mathcal{E}}{\{\Phi\}\ f(\overline{x})\,;\ e\ \{\Phi_{post} \circ \Phi_e\}}\ \text{[FV-Call]}$$

Entailment Checking

A collection of specifications

Future-condition based compositional analysis

$$\frac{f\,(\overline{x})\,[\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E} \qquad \Phi <: \Phi_{pre} \qquad \{\Phi \circ \Phi_{post}\}\ e\ \{\Phi_e\} \qquad \Phi_e <: \Phi_{future}}{\{\Phi\}\ f(\overline{x})\,;\ e\ \{\Phi_{post} \circ \Phi_e\}}\ [\text{FV-Call}]$$

Entailment Checking

A collection of specifications

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

Specification inference

```
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

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

Can temporal property analysis be modular?

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Three main difficulties:

❑ Temporal logic entailment checker.

Primitive spec + spec inference!

✓ Writing temporal specifications for each function is tedious and challenging.

✓ 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”

Term rewriting system for regular expressions

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

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

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

Term rewriting system for regular expressions

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

Examples:

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

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

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

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

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

✓ Temporal logic entailment checker.

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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
`free`	✓	✓	✓	(Leak, Use-After-Free, Double 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 $\mathcal{E} \vdash \{T \wedge \epsilon\}\ e_R\ \{\pi \wedge \theta_{target}\}$

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

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

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

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9: **end for**
10: **return** without any suitable patches

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

Example: `true` ∧ $\mathcal{E} \not\vdash$ `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	✓	✓	

Summary

Contributions

- ✓ A novel *future-condition*
- ✓ Compositional temporal analysis
- ✓ Light-weight specification inference
- ✓ Fast and most-automated
- ✓ Proof guided repair
- ✓ Large-scale usability

Limitations

- ❑ Handle loops via unrolling
- ❑ Inefficient ($O(n^2)$) entailment checking
- ❑ On-demand path pruning
- ❑ False negatives
- ❑ No machine checkable certification
- ❑ Limited expressiveness

Specifying and Verifying Future Conditions (FCs)

Yahui Song, Darius Foo, Wei-Ngan Chin

(Under Submission)

The existing solution

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

$$\frac{f\,(\overline{x})\,[\Phi_{pre},\Phi_{post},\Phi_{future}] \in \mathcal{E} \quad \text{[FV-Call]} \qquad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\}\ e\ \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\}\ f(\overline{x})\,;\ e\ \{\Phi_{post} \circ \Phi_e\}}$$

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Inefficient ($O(n^2)$) entailment checking

A use-after-free bug recorded from CWE-416

```
1 int main(int argc, char **argv) {
2   char *buf1, *buf2, *buf3;
3   buf1 = malloc(1);
4   buf2 = malloc(1);
5   free(buf2);
6   buf3 = malloc(1);
7   strncpy(buf2,argv[1],1);
8   free(buf1); free(buf3); }
```

Use-after-free!

A new solution for reasoning FCs

2. `char *buf1, *buf2, *buf3;`

$\{(\exists buf1, buf2, buf3.\ true\ ;\ \epsilon\ ;\ \_^{\star})\}$

3. `buf1 = malloc(1);`

$\{(\exists buf1, buf2, buf3.\ buf1 \neq null\ ;\ malloc(buf1)\ ;\ \mathcal{F}(free(buf1)))\}$

4. `buf2 = malloc(1);`

$\{(\exists buf1, buf2, buf3.\ buf1 \neq null \wedge buf2 \neq null\ ;\ malloc(buf1) \cdot malloc(buf2)\ ;$
$\mathcal{F}(free(buf1)) \wedge \mathcal{F}(free(buf2)))\}$

5. `free(buf2);`

$\{(\exists buf1, buf2, buf3.\ buf1 \neq null \wedge buf2 \neq null\ ;\ malloc(buf1) \cdot malloc(buf2) \cdot free(buf2)\ ;$
$\mathcal{F}(free(buf1)) \wedge \_^{\star} \wedge \mathcal{G}(!\_(buf2)))\}$

6. `buf3 = malloc(1);`

$\{(\exists buf1, buf2, buf3.\ buf1 \neq null \wedge buf2 \neq null \wedge buf3 \neq null\ ;\ malloc(buf1) \cdot malloc(buf2)$
$\cdot free(buf2) \cdot malloc(buf3)\ ;\ \mathcal{F}(free(buf1)) \wedge \mathcal{G}(!\_(buf2)) \wedge \mathcal{F}(free(buf3)))\}$

7. `strncpy(buf2,argv[1],1);`

$\{(\exists buf1, buf2, buf3.\ buf1 \neq null \wedge buf2 \neq null \wedge buf3 \neq null\ ;\ malloc(buf1) \cdot malloc(buf2)$
$\cdot free(buf2) \cdot malloc(buf3) \cdot strncpy(buf2)\ ;\ \mathcal{F}(free(buf1)) \wedge \bot \wedge \mathcal{F}(free(buf3))) \Leftarrow \text{✗}\}$

FC Violation Found: subtracting "$strncpy(buf2)$" from "$\mathcal{G}(!\_(buf2))$" leads to false!

- ❖ Linear trace processing
- ❖ Embed FCs into program states
- ❖ Trace conjunction + subtraction

The existing solution

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

$$\frac{f\,(\overline{x})\,[\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E} \quad \text{[FV-Call]} \qquad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\}\ e\ \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\}\ f(\overline{x})\,;\ e\ \{\Phi_{post} \circ \Phi_e\}}$$

Three main limitations:

- ✓ Inefficient entailment checking **Embed FCs into the states + Trace subtraction**
- ❑ Handle loops via unrolling
- ❑ Bug-finding (no incorrectly flagged safe code) over soundness (no missed violations)

Predicates for Bags of Traces and Future Conditions

A false negative example from ProveNFix

```
1 void* mallocN(int n,void **arr,){
2   int i = 0;
3   while (i < n) {
4     arr[i] = malloc(4); i = i+1;}
5   return *arr;}
6
7 void main () {
8   void *arr[5]; mallocN (5, arr);
9   free(arr[0]);/* memory leak */}
```

Predicates for Bags of Traces and Future Conditions

```
1 void* mallocN(int n,void **arr,){
2   int i = 0;
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4     arr[i] = malloc(4); i = i+1;}
5   return *arr;}
6
7 void main () {
8   void *arr[5]; mallocN (5, arr);
9   free(arr[0]);/* memory leak */}
```

$$mallocN(n, arr) \equiv \textbf{req}: length(arr) \geq n$$
$$\textbf{ens}: (\exists i.\ true\ ;\ pred_t([0..n), i)\ ;\ pred_f([0..n), i))$$
$$pred_t(B, i) \equiv \Lambda_i^B(arr[i] \neq null \wedge malloc(arr[i])) \vee (arr[i] = null \wedge \epsilon)$$
$$pred_f(B, i) \equiv \Lambda_i^B(arr[i] \neq null \wedge \mathcal{F}(free(arr[i])))$$

$$(Specification) \quad [\textbf{req}: \pi\ \textbf{ens}: \Delta]$$
$$(Post\ Summary) \quad \Delta ::= \bigvee(\pi\ ;\ \theta\ ;\ F)$$

When reasoning about main():

8. `void *arr[5]; mallocN (5, arr);`

$$\{(\exists arr, i.\ length(arr) = 5\ ;\ pred_t([0..5), i)\ ;\ pred_f([0..5), i))\}$$

9. `free(arr[0]);`

$$\{(\exists arr, i.\ length(arr) = 5\ ;\ pred_t([0..5), i) \cdot free(arr[0])\ ;\ pred_f([1..5), i) \wedge \mathcal{G}(!\_(arr[0])))\}$$

FC Violation Found: empty trace "ϵ" does not satisfy the obligation "$pred_f([1..5), arr)$"!

The existing solution

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

$$\frac{f\,(\overline{x})\,[\Phi_{pre},\Phi_{post},\Phi_{future}] \in \mathcal{E} \quad \text{[FV-Call]} \qquad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\}\ e\ \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\}\ f(\overline{x})\,;\ e\ \{\Phi_{post} \circ \Phi_e\}}$$

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✓ Inefficient entailment checking — **Embed FCs into the states + Trace subtraction**

✓ Handle loops via unrolling — **Predicates for bags of traces and FCs**

❑ Bug-finding (no incorrectly flagged safe code) over soundness (no missed violations)

Soundness Formalization

- An instrumented semantics for the target language: $[s, \rho, F, e] \longrightarrow [s', \rho', F', v]$

  stack execution trace

- Semantic model of trace specifications: $s, \rho \models \pi \wedge \theta$

- A set of forward verification rules: $\{(P\,;\theta_1\,;F_1)\}\ e\ \{(Q\,;\theta_2\,;F_2)\}$

```
Theorem soundness : forall P e Q t1 t2 rho1 rho2 s1 v s2 f1 f2 f3,
  forward P t1 f1 e Q t2 f2 ->
  P s1 ->
  trace_model rho1 t1 ->
  bigstep s1 rho1 f1 e s2 rho2 f3 v ->
  Q v s2 /\ trace_model rho2 t2 /\ futureCondEntail f2 f3.
```

It only sound to strengthen the future conditions, so that we do not miss any violations.

The existing solution

```
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Coq formalization

Experimental Results

Category	Example APIs	Future Conditions
1. File Ops	fopen, open fclose, close	Finally to close the file descriptor Globally do not access the file descriptor Read-only files cannot be written to
2. Threads	pthread_create pthread_mutex_lock	Finally to pthread_join or detach the thread Finally to pthread_mutex_unlock
3. Memory	free malloc realloc	Globally do not access the pointer Finally free the new pointer Globally the old pointer is not accessed & finally free the new pointer
4. Sockets	socket	Finally to close the socket
5. Database	sqlite3_open	Finally to sqlite3_close the connection
6. URV/NPD	fgets, gethostbyaddr	Check the return value immediately after calls

Write these future conditions manually

Experimental Results

Category	LoC	PrimS	InferredS	InferredInv	Report/Exp.	Time(s)
1	656	8	29	7	14/12	10.05
2	330	4	25	1	4/4	1.97
3	424	6	30	11	25/23	8.87
4	103	2	6	1	3/3	1.76
5	108	4	6	0	4/4	1.97
6	67	10	5	0	5/5	0.56
Total	1,688	34	101	20	55/51	25.18

Category	Example APIs	Future Conditions
1. File Ops	fopen, open fclose, close	Finally to close the file descriptor Globally do not access the file descriptor Read-only files cannot be written to
2. Threads	pthread_create pthread_mutex_lock	Finally to pthread_join or detach the thread Finally to pthread_mutex_unlock
3. Memory	free malloc realloc	Globally do not access the pointer Finally free the new pointer Globally the old pointer is not accessed & finally free the new pointer
4. Sockets	socket	Finally to close the socket
5. Database	sqlite3_open	Finally to sqlite3_close the connection
6. URV/NPD	fgets, gethostbyaddr	Check the return value immediately after calls

False positive due to the limited expressiveness:

```
1 void false_positive1() {
2   int** ptr1= malloc(4);
3   int*  ptr2= malloc(4);
4   *ptr1 = ptr2;
5   free(*ptr1);
6   free(ptr1); }
7 False positive: Memory Leak!
```

Future Conditions

Thanks for listening!

Bug Finding and Repair

- ✓ A novel *future-condition*
- ✓ Compositional temporal analysis
- ✓ Light-weight specification inference
- ✓ Fast and most-automated
- ✓ Proof guided repair
- ✓ Large-scale usability

Verification

- ✓ Handle loops via recursive predicates
- ✓ Efficient (linear) entailment checking
- ✓ Sound weakening when path explosion
- ✓ No false negatives
- ❑ No machine checkable certification
- ❑ Limited expressiveness