

Future Conditions

Temporal Property guided Program Analysis, Repair and Verification

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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]

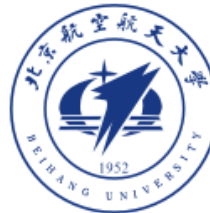
Specifying and Verifying Future Conditions [Under Submission]



ProveNFix: Temporal Property guided Program Repair

Yahui Song, Xiang Gao, Wenhua Li, Wei-Ngan Chin, Abhik Roychoudhury

17th July @ FSE 2024, Porto de Galinhas, Brazil



北京航空航天大学
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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 :

- ❑ 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  $\wedge$   $\epsilon$ )  $\vee$  (ptr $\neq$ null  $\wedge$  free(ptr))  
// future: true  $\wedge$   $\mathcal{G}$  (!_(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  $\wedge$  _★  
// post: (ret=null  $\wedge$   $\epsilon$ )  $\vee$  (ret $\neq$ null  $\wedge$  malloc(ret))  
// future: ret $\neq$ null  $\rightarrow$   $\mathcal{F}$  (free(ret))
```

Future-condition based compositional analysis

$$\begin{array}{c}
 f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \quad] \in \mathcal{E} \\
 \hline
 \Phi <: \Phi_{pre} \quad \{ \Phi \circ \Phi_{post} \} e \{ \Phi_e \} \\
 \{ \Phi \} f(\bar{x}); e \{ \Phi_{post} \circ \Phi_e \}
 \end{array}
 \quad \text{[FV-Call]}$$

Entailment Checking

A collection of specifications

Future-condition based compositional analysis

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

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  $\wedge \mathcal{G} (!\_(\text{ret}))$ )  $\vee$  (ret $\neq$ null  $\wedge \mathcal{F}$  (free(ret)))
```

```
void wrap_malloc_I (int* ptr)  
// future: ptr=null  $\wedge \mathcal{G} (!\_(\text{ptr}))$   
            $\vee$  ptr $\neq$ null  $\wedge \mathcal{F}$  (free(ptr))  
{ ptr = malloc (4); return;} 
```

```
int* wrap_malloc_II ()  
// future: ret=null  $\wedge \mathcal{G} (!\_(\text{ret}))$   
            $\vee$  ret $\neq$ null  $\wedge \mathcal{F}$  (free(ret))  
{ int* ptr = malloc (4); return ptr;}
```

Specification inference

```
void *malloc (size_t size);  
// future: (ret=null  $\wedge \mathcal{G} (!\_(\text{ret}))$ )  $\vee$  (ret $\neq$ null  $\wedge \mathcal{F}$  (free(ret)))
```

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

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

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

Can temporal property analysis be modular?

“Each function is analysed only once and
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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.

(IntRE)	Φ	$::=$	$\bigvee (\pi \wedge \theta)$
(Traces)	θ	$::=$	$\perp \mid \epsilon \mid \mathbf{I} \mid \theta_1 \cdot \theta_2 \mid \theta_1 \vee \theta_2 \mid \theta^\star$
(Events)	\mathbf{I}	$::=$	$\mathbf{A}(v) \mid \mathbf{A}(_) \mid !\mathbf{A}(v) \mid !__(v) \mid _ \mid \mathbf{I}_1 \wedge \mathbf{I}_2$
(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	$::=$	$v \mid t_1 + t_2 \mid t_1 - t_2$
(Values)	v	$::=$	$c \mid x \mid null$

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:

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

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

$$\text{true} \wedge E \not\sqsubseteq \text{true} \wedge (E . F)$$

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


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

$$a \cdot (a \vee b)^\star \sqsubseteq (a \vee b \vee bb)^\star \quad b \cdot (a \vee b)^\star \sqsubseteq \dots$$

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

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. **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”

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

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 ∧  $\star$   
// post: (ret=null ∧  $\epsilon$ ) ∨ (ret≠null ∧ malloc(ret))  
// future: ret≠null →  $\mathcal{F}$  (free(ret))
```

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

Three main limitations:

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- ❑ Handle loops via unrolling
- ❑ Bug-finding (no incorrectly flagged safe code) over soundness (no missed violations)

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);    Use-after-free!  
8     free(buf1); free(buf3); }
```

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

```
void *malloc (size_t size);  
// pre: size>0  $\wedge$   $\_*$   
// post: (ret=null  $\wedge$   $\epsilon$ )  $\vee$  (ret $\neq$ null  $\wedge$  malloc(ret))  
// future: ret $\neq$ null  $\rightarrow$   $\mathcal{F}$  (free(ret))
```

```
void free (void *ptr);  
// post: true  $\wedge$  free(ptr)  
// future: true  $\wedge$   $\mathcal{G}$  (!_(ptr))
```

```
char *strncpy(char *dest, const char *source, size_t num);  
// post: true  $\wedge$  strncpy(dest)
```

$f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E}$ [FV-Call]

$$\frac{\Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\} e \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\} f(\bar{x}); e \{\Phi_{post} \circ \Phi_e\}}$$

```
1 int main(int argc, char **argv) {  
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3     buf1 = malloc(1);  
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7     strncpy(buf2, argv[1], 1);    Use-after-free!  
8     free(buf1); free(buf3); }
```

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

```
void *malloc (size_t size);
// pre: size>0  $\wedge$   $\_*$ 
// post: (ret=null  $\wedge$   $\epsilon$ )  $\vee$  (ret!=null  $\wedge$  malloc(ret))
// future: ret!=null  $\rightarrow$   $\mathcal{F}$  (free(ret))
```

```
void free (void *ptr);
// post: true  $\wedge$  free(ptr)
// future: true  $\wedge$   $\mathcal{G}$  (!_(ptr))
```

```
char *strncpy(char *dest, const char *source, size_t num);
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$f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E}$ [FV-Call]

$$\frac{\Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\} e \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\} f(\bar{x}); e \{\Phi_{post} \circ \Phi_e\}}$$

```
1 int main(int argc, char **argv) {
2   char *buf1, *buf2, *buf3;
3   buf1 = malloc(1);  $\leftarrow$  malloc(buf2).free(buf2).malloc(buf3).strncpy(buf2).free(buf1).free(buf3)  $\sqsubseteq$  F(free(buf1))
4   buf2 = malloc(1);  $\leftarrow$  free(buf2).malloc(buf3).strncpy(buf2).free(buf1).free(buf3)  $\sqsubseteq$  F(free(buf2))
5   free(buf2);  $\leftarrow$  malloc(buf3).strncpy(buf2).free(buf1).free(buf3)  $\not\sqsubseteq$  G(!_ (buf2))
6   buf3 = malloc(1);  $\leftarrow$  strncpy(buf2).free(buf1).free(buf3)  $\sqsubseteq$  F(free(buf3))
7   strncpy(buf2, argv[1], 1); Use-after-free!
8   free(buf1); free(buf3); }  $\leftarrow$  free(buf3)  $\sqsubseteq$  G(!_ (buf1))
                                     empty  $\sqsubseteq$  G(!_ (buf3))
```


A new solution for reasoning FCs

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);`

A new solution for reasoning FCs

```
2. char *buf1, *buf2, *buf3;
{ (∃buf1, buf2, buf3. true ; ε ; _*) }
3. buf1 = malloc(1);
{ (∃buf1, buf2, buf3. buf1 ≠ null ; malloc(buf1) ; ℱ(free(buf1))) }
4. buf2 = malloc(1);
{ (∃buf1, buf2, buf3. buf1 ≠ null ∧ buf2 ≠ null ; malloc(buf1) · malloc(buf2) ;
  ℱ(free(buf1)) ∧ ℱ(free(buf2))) }
5. free(buf2);
{ (∃buf1, buf2, buf3. buf1 ≠ null ∧ buf2 ≠ null ; malloc(buf1) · malloc(buf2) · free(buf2) ;
  ℱ(free(buf1)) ∧ _* ∧ ℒ(!_ (buf2))) }
6. buf3 = malloc(1);
{ (∃buf1, buf2, buf3. buf1 ≠ null ∧ buf2 ≠ null ∧ buf3 ≠ null ; malloc(buf1) · malloc(buf2)
  · free(buf2) · malloc(buf3) ; ℱ(free(buf1)) ∧ ℒ(!_ (buf2)) ∧ ℱ(free(buf3))) }
7. strncpy(buf2, argv[1], 1);
{ (∃buf1, buf2, buf3. buf1 ≠ null ∧ buf2 ≠ null ∧ buf3 ≠ null ; malloc(buf1) · malloc(buf2)
  · free(buf2) · malloc(buf3) · strncpy(buf2) ; ℱ(free(buf1)) ∧ ⊥ ∧ ℱ(free(buf3))) ⇐ X }
FC Violation Found: subtracting “strncpy(buf2)” from “ℒ(!_ (buf2))” leads to false!
```

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

The existing solution

<pre>void *malloc (size_t size); // pre: size>0 ∧ _[★] // post: (ret=null ∧ ε) ∨ (ret≠null ∧ malloc(ret)) // future: ret≠null → \mathcal{F} (free(ret))</pre>	$\frac{f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E} \quad [\text{FV-Call}] \quad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\} e \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\} f(\bar{x}); e \{\Phi_{post} \circ \Phi_e\}}$
--	---

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;
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 */}

```



$mallocN(n, arr) \equiv \text{req: } length(arr) \geq n$

$\text{ens: } (\exists i. \text{true} ; \text{pred}_t([0..n), i) ; \text{pred}_f([0..n), i))$

$\text{pred}_t(B, i) \equiv \Lambda_i^B (arr[i] \neq \text{null} \wedge \text{malloc}(arr[i])) \vee (arr[i] = \text{null} \wedge \epsilon)$

$\text{pred}_f(B, i) \equiv \Lambda_i^B (arr[i] \neq \text{null} \wedge \mathcal{F}(\text{free}(arr[i])))$

When reasoning about main():

8. `void *arr[5]; mallocN (5, arr);`
 $\{(\exists arr, i. length(arr) = 5 ; \text{pred}_t([0..5), i) ; \text{pred}_f([0..5), i))\}$

9. `free(arr[0]);`
 $\{(\exists arr, i. length(arr) = 5 ; \text{pred}_t([0..5), i) \cdot \text{free}(arr[0]) ; \text{pred}_f([1..5), i) \wedge \mathcal{G}(!_ (arr[0])))\}$

FC Violation Found: empty trace “ ϵ ” does not satisfy the obligation “ $\text{pred}_f([1..5), arr)$ ”!

(Specification) $[\text{req: } \pi \text{ ens: } \Delta]$

(Post Summary) $\Delta ::= \bigvee (\pi ; \theta ; F)$

Predicates for Bags of Traces and Future Conditions

```

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 */}

```

When reasoning about mallocN():

$$\frac{[\text{FV-While}] \quad \{(\pi \wedge \pi_g; \theta; F)\} e \{(\pi; \theta; F)\}}{\{(\pi; \theta; F)\} \text{ while } \pi_g \text{ do } e \{(\pi \wedge \neg \pi_g; \theta; F)\}}$$



$\text{mallocN}(n, \text{arr}) \equiv \text{req: } \text{length}(\text{arr}) \geq n$

$\text{ens: } (\exists i. \text{true}; \text{pred}_t([0..n], i); \text{pred}_f([0..n], i))$

$\text{pred}_t(B, i) \equiv \Lambda_i^B (\text{arr}[i] \neq \text{null} \wedge \text{malloc}(\text{arr}[i])) \vee (\text{arr}[i] = \text{null} \wedge \epsilon)$

$\text{pred}_f(B, i) \equiv \Lambda_i^B (\text{arr}[i] \neq \text{null} \wedge \mathcal{F}(\text{free}(\text{arr}[i])))$

```

3. while (i < n){
  {(\exists i. \text{true}; \text{pred}_t([0..i], i); \text{pred}_f([0..i], i))}
  4.   arr[i] = malloc(4);
  {(\exists i. \text{true}; \text{pred}_t([0..i+1], i); \text{pred}_f([0..i+1], i))}
  5.   i = i+1;
  {(\exists i. \text{true}; \text{pred}_t([0..i+1], i+1); \text{pred}_f([0..i+1], i+1))}
  6. } {(\exists i. i = n; \text{pred}_t([0..i], i); \text{pred}_f([0..i], i))} \rightsquigarrow
  {(\exists i. \text{true}; \text{pred}_t([0..n], i); \text{pred}_f([0..n], i))}

```

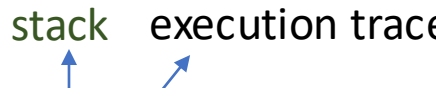
The existing solution

<pre>void *malloc (size_t size); // pre: size>0 ∧ _[★] // post: (ret=null ∧ ε) ∨ (ret≠null ∧ malloc(ret)) // future: ret≠null → \mathcal{F} (free(ret))</pre>	$\frac{f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E} \quad [\text{FV-Call}] \quad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\} e \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\} f(\bar{x}); e \{\Phi_{post} \circ \Phi_e\}}$
--	---


Three main limitations:

- ✓ 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: $[s, \rho, F, e] \longrightarrow [s', \rho', F', v]$

- 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

<pre>void *malloc (size_t size); // pre: size>0 ∧ _[★] // post: (ret=null ∧ ε) ∨ (ret≠null ∧ malloc(ret)) // future: ret≠null → \mathcal{F} (free(ret))</pre>	$\frac{f(\bar{x}) [\Phi_{pre}, \Phi_{post}, \Phi_{future}] \in \mathcal{E} \quad [\text{FV-Call}] \quad \Phi <: \Phi_{pre} \quad \{\Phi \circ \Phi_{post}\} e \{\Phi_e\} \quad \Phi_e <: \Phi_{future}}{\{\Phi\} f(\bar{x}); e \{\Phi_{post} \circ \Phi_e\}}$
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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

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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