

Towards Complete Specifications with an Error Calculus

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Specification and Verification

Specification provides formal documentation and can guide *code verification*.

```
data node { int val;  node next;}
```

```
1  int get_data(node ptr){  
2    return ptr.val;  
3  }
```

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Specification provides formal documentation and can guide *code verification*.

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1  int get_data(node ptr){  
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```

Method Specification:

```
requires ptr ↦ node⟨d,p⟩  
ensures  res=d;
```

Code can be modular but complex.

```
4  int ll_sum(node ll){
5      if (ll ≠ null){
6          int d = get_data(ll);
7          return (d + ll_sum(ll.next));
8      }
9      else return 0;
10 }
```

Example above requires acyclic list with summation.

What specification to provide?

- Predicate for Acyclic List with Sum

```
pred llist⟨root,S⟩ ≡  
  (root=null ∧ S=0)  
  ∨ (∃d,q,S1 · root↦node⟨d,q⟩* llist⟨q,S1⟩ ∧ S=S1+d)
```

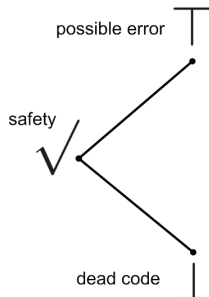
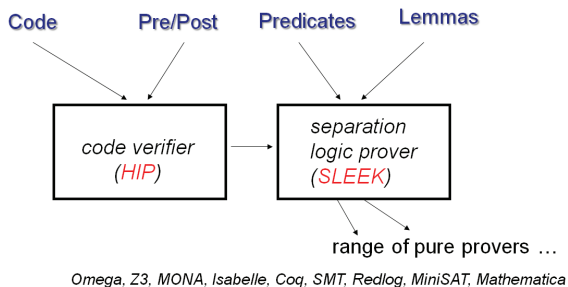
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```

- Pre/Post Safety Specification

```
int ll_sum (node ll)  
  requires  llist⟨ll,s⟩  
  ensures  llist⟨ll,s⟩ ∧ res=s;
```

HIP/SLEEK for Safety Verification



- symbolic execution based on separation logic
- safety guarantee : no memory errors, safe pre-conditions met, safe post-condition ensured.
- modularity: each function call captured via pre/post

Key Idea 1: Complete Specifications

Apart from safety verification, we are also interested in error scenarios to facilitate bug-finding.

```
1 int get_data(node ptr){  
2     return ptr.val;  
3 }
```

```
int get_data(node ptr)  
  requires ptr → node(d, -)  
  ensures res = d;
```


Key Idea 1: Complete Specifications

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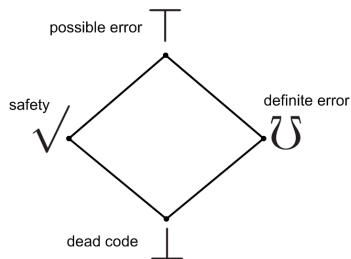
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int get_data(node ptr)  
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```

ptr = null?



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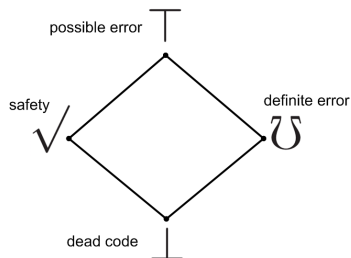
We introduce new status \cup to enable

- error scenarios be explicitly expressed



Key Idea 1: Complete Specifications

Apart from safety verification, we are also interested in error scenarios to facilitate bug-finding.



We introduce new status \cup to enable

- error scenarios be explicitly expressed
- definite errors be detected by verification.



Key Idea 1: Complete Specifications

```
1 int get_data(node ptr){  
2     return ptr.val;  
3 }
```

```
int get_data(node ptr)  
  requires ptr → node(d, -)  
  ensures res = d;
```

```
int get_data(node ptr)  
  requires ptr = null  
  ensures (true)  $\cup$ ;
```

Key Idea 1: Complete Specifications

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1 int get_data(node ptr){
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```

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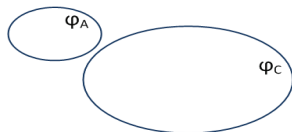
```
int get_data(node ptr)
  requires ptr = null
  ensures (true)  $\mathcal{U}$ ;
```

Complete Specification

```
int get_data(node ptr)
  case {
    ptr ≠ null → requires ptr → node⟨d, -⟩
                 ensures (res=d)  $\checkmark$ ;
    ptr = null → ensures (true)  $\mathcal{U}$ ;
  }
```



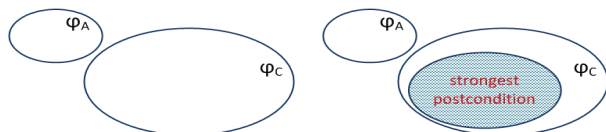
Key Idea 2: Two Entailment Procedures for The Lattice



- Entailment Procedure for Checking: $\varphi_A \vdash \varphi_C$
- φ_C are postconditions or preconditions and may **NOT** be the best

Observation: in the scenarios that φ_A contradicts with φ_C

Key Idea 2: Two Entailment Procedures for The Lattice

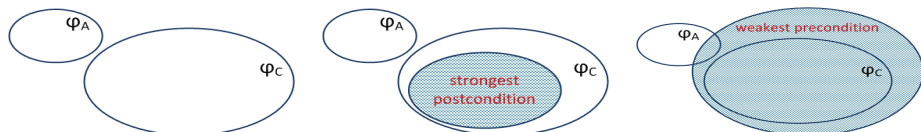


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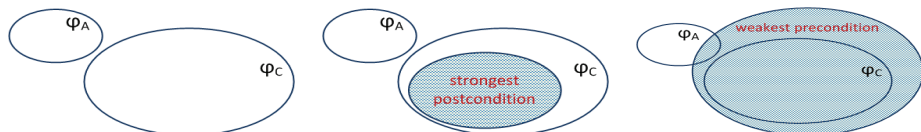


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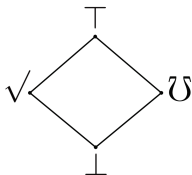
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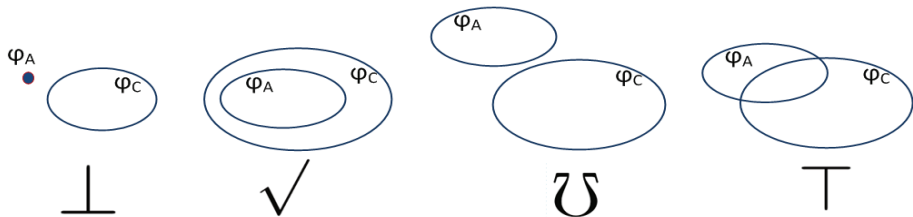
- when φ_C is a postcondition, it is **sound** to return an \perp status
- when φ_C is precondition, it is **unsound** to return an \perp status

We propose **two entailment procedures**: one for postconditions checking (\vdash_{post}) and another for precondition checking (\vdash_{pre}).

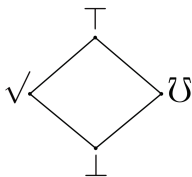
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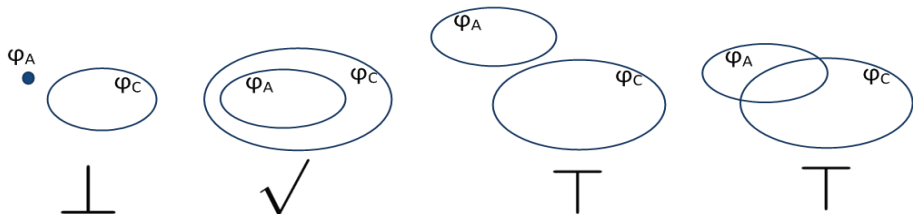
Entailment Procedure for Postcondition Checking: $\varphi_A \vdash_{post} \varphi_C$



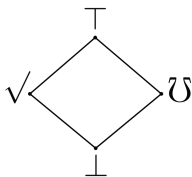
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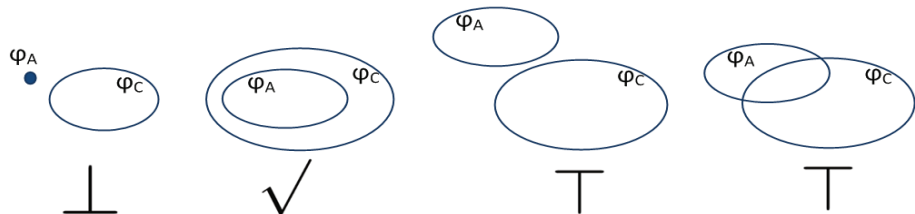
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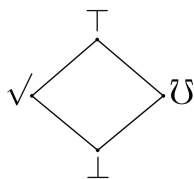


Entailment Procedure for Precondition Checking: $\varphi_A \vdash_{pre} \varphi_C$



How to get \emptyset for preconditions proving at function calls?

Key Idea 2: Two Entailment Procedures for The Lattice



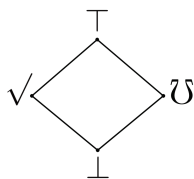
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2.   return ptr.val;
3.}
4. int ll_sum(node x){
   .....
6.   int d = get_data(x);
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```
int get_data(node ptr)
case {
  ptr ≠ null → requires ptr→node(d,-)
               ensures (res=d) ✓;
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```

Safety Proving and Bugs Finding for Function Calls

- two statuses

Key Idea 2: Two Entailment Procedures for The Lattice



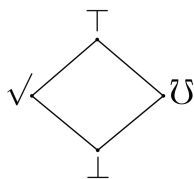
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 - ① come from postconditions

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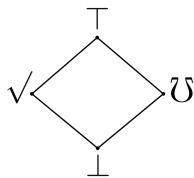
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   .....
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```

```
int get_data(node ptr)
case {
  ptr != null → requires ptr→node(d,-)
               ensures (res=d) ✓;
  ptr = null → ensures (true) ✗;
}
```

Safety Proving and Bugs Finding for Function Calls

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 - 1 come from postconditions
 - 2 produced by entailment procedure for precondition checking

Key Idea 2: Two Entailment Procedures for The Lattice



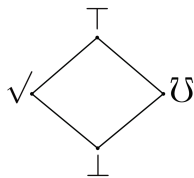
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- need operators to combine two statuses

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Safety Proving and Bugs Finding for Function Calls

- two statuses
 - 1 come from postconditions
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- need operators to combine two statuses

\cup status can be obtained from the combination

Key Idea 3: Operators for Error Calculus

Separation Logic Entailment:

$$\Delta_a \vdash \Delta_c$$

Δ_a and Δ_c are of conjunction form

However:

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produce more complex entailment:

$$\Delta_1 \vee \Delta_2 \vdash \Delta_3 \vee \Delta_4$$

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produce more complex entailment:

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need operators to combine error statuses

Key Idea 3: Operators for Error Calculus

SEARCH - \oplus

Search for success:

[SE- $[\oplus$ SEARCH]]

$$\pi \vdash \pi_1 \rightsquigarrow \tau_1$$

$$\pi \vdash \pi_2 \rightsquigarrow \tau_2$$

$$\pi \vdash \pi_1 \vee \pi_2 \rightsquigarrow \tau_1 \oplus \tau_2$$

\oplus	\top	\perp	\checkmark	\perp
\top	\top	\top	\checkmark	\perp
\perp	\top	\perp	\checkmark	\perp
\checkmark	\checkmark	\checkmark	\checkmark	\perp
\perp	\perp	\perp	\perp	\perp

SEARCH - \oplus

Search for success. Example:

$$x=\text{null} \vdash_{\text{post}} (x=\text{null}) \vee (\exists q. x \mapsto \text{node}\langle -, q \rangle * \text{llist}\langle q, - \rangle)$$

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$$\begin{aligned} x=\text{null} \vdash_{\text{post}} (x=\text{null}) \vee (\exists q \cdot x \mapsto \text{node}\langle -, q \rangle * \text{l1ist}\langle q, - \rangle) \\ \rightsquigarrow \checkmark \oplus \mathcal{U} = \checkmark \end{aligned}$$

Key Idea 3: Operators for Error Calculus

JOIN - \sqcup

Least upper bound

[SE- \sqcup JOIN]

$\pi_1 \vdash \pi \rightsquigarrow \tau_1$

$\pi_2 \vdash \pi \rightsquigarrow \tau_2$

$\pi_1 \vee \pi_2 \vdash \pi \rightsquigarrow \tau_1 \sqcup \tau_2$

\sqcup	T	\cup	\checkmark	\perp
T	T	T	T	T
\cup	T	\cup	T	\cup
\checkmark	T	T	\checkmark	\checkmark
\perp	T	\cup	\checkmark	\perp

Key idea 3: Operators for Error Calculus

JOIN - \sqcup

Least upper bound

For example, join statuses for path traces:

$(x > 0 \wedge \text{res} = x) \vee (\neg(x > 0) \wedge \text{res} = x) \vdash_{\text{post}} \text{res} > 0$

```
int foo (int x)
  requires true;
  ensures res > 0;
{
  if (x > 0) {
    .....//not change x
  }
  else {
    .....//not change x
  }
  return x;
}
```

Key idea 3: Operators for Error Calculus

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- $x > 0 \wedge \text{res} = x \vdash_{\text{post}} \text{res} > 0 \rightsquigarrow \checkmark$

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$$(x > 0 \wedge \text{res} = x) \vee (\neg(x > 0) \wedge \text{res} = x) \vdash_{\text{post}} \text{res} > 0 \rightsquigarrow \checkmark \sqcup \text{✗} = \top$$

Key idea 3: Operators for Error Calculus

COMPOSE - \otimes

Group relevant sub-formulas:

[SE- \otimes COMPOSE]

$$\pi \vdash \pi_1 \rightsquigarrow \tau_1$$

$$\pi \vdash \pi_2 \rightsquigarrow \tau_2$$

$$\pi \vdash \pi_1 \wedge \pi_2 \rightsquigarrow \tau_1 \otimes \tau_2$$

\otimes	\top	\cup	\checkmark	\perp
\top	\top	\cup	\top	\perp
\cup	\cup	\cup	\cup	\perp
\checkmark	\top	\cup	\checkmark	\perp
\perp	\perp	\perp	\perp	\perp

Key idea 3: Operators for Error Calculus

COMPOSE - \otimes

Group relevant sub-formulas:

Example:

$$x > 3 \wedge y > 7 \vdash_{post} x < 0 \wedge y > 3$$

Key idea 3: Operators for Error Calculus

COMPOSE - \otimes

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- $x > 3 \wedge y > 7 \vdash_{post} x < 0 \rightsquigarrow \top$
 - do slice: $x > 3 \vdash_{post} x < 0 \rightsquigarrow \top$

Key idea 3: Operators for Error Calculus

COMPOSE - \otimes

Group relevant sub-formulas:

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- $x > 3 \wedge y > 7 \vdash_{post} x < 0 \rightsquigarrow \text{U}$
 - do slice: $x > 3 \vdash_{post} x < 0 \rightsquigarrow \text{U}$
- $x > 3 \wedge y > 7 \vdash_{post} y > 3 \rightsquigarrow \checkmark$

Key idea 3: Operators for Error Calculus

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- $x > 3 \wedge y > 7 \vdash_{post} y > 3 \rightsquigarrow \checkmark$

$$x > 3 \wedge y > 7 \vdash_{post} x < 0 \wedge y > 3 \rightsquigarrow \top \otimes \checkmark = \top$$

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- Soundness proof of structural entailment procedure
- Extend the calculus
 - with error messages
 - with error localization
 - for separation logic

Experiment

Calculus Performance for Heap-Based (bug-free) Programs:
overhead around 1.62 seconds (8%)

Programs (specified props)	Size		Proc #	Time(sec.)		Invo.(#)	
	LOC	LOS		wo	w	wo	w
Linked list (size,interval)	327	50	26	0.44	0.46	2738	3202
Linked list (size,sets)	157	27	13	0.58	0.6	1520	1724
Sorted llist (size,sness,sets)	98	11	6	0.46	0.49	955	1060
Doubly llist (size,interval)	186	23	13	0.34	0.34	1864	2083
Doubly llist (size,sets)	91	13	5	0.5	0.5	1309	1429
CompleteT (size,minheight)	106	12	5	0.87	0.94	2149	2533
Heap trees (size,maxelem)	179	13	5	1.9	1.91	4540	4954
AVL (height, size)	313	27	12	3.44	3.59	7863	8585
AVL2 (height,size,bal)	152	37	7	2.83	3	6959	7876
BST (size,height)	177	18	9	0.35	0.37	1883	2192
BST (size,height,interval)	153	12	6	0.3	0.31	1581	1836
RBT (size,blackheight)	508	48	19	3.32	3.38	13069	16687
Bubble sort (size)	75	9	4	0.21	0.21	1092	1254
Quick sort (size, sets)	82	10	4	0.27	0.28	778	832
Merge sort (size,sets)	109	11	6	0.47	0.5	1035	1074
Quick sort - queue (size)	127	4	2	4.25	5.27	13218	21139
Total	2840	325	142	20.53	22.15	62553	78460

Experiment: Calculus Usability

- 1 taken from Siemens/SIR benchmark
- 2 T^* results from JOIN (\sqcup) of one safety and one must error:

$$T^* = \cup \sqcup \checkmark$$

Programs	LOC	Pr.#	Ver.#	F#	\cup	T^*	T	LOE	time(s)
tcas	173	9	41	48	31	14	3	3.48	3.06
schedule2	374	16	10	10	5	0	3	3	8.25
schedule1a	412	18	10	16	15	0	1	4.38	18.13
schedule1b	413	18	9	8	7	0	1	4.25	32.29
replace	564	21	24	24	18	0	6	4.21	17.89
print_tokens2	570	19	10	10	7	0	1	4.88	20.42
print_tokens	726	18	7	9	8	0	1	3.67	6.73
Total/(Average)	3232	119	111	125	91	14	16	(3.98)	(15.25)

HiPEE detected **97%** of real bugs: 73%, 11% and 13% of \cup , T^* and T errors, respectively.

We have presented

- a lattice domain with four distinct statuses on possible program states.

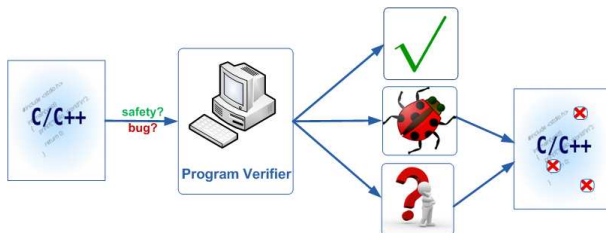
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- a mechanism for complete specifications
- a calculus (for the 4-point lattice domain)

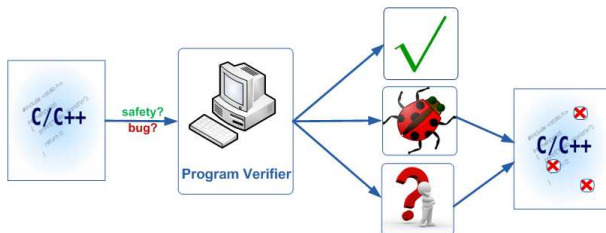
Conclusions



We have implemented an automatic *modular* verification system

① for safety proving and bugs finding

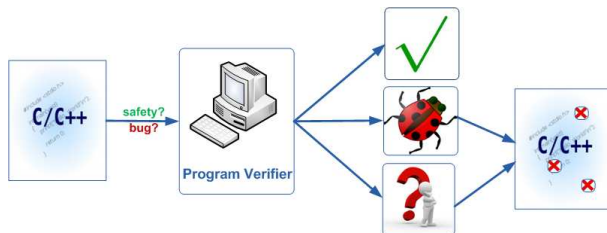
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Conclusions



We have implemented an automatic *modular* verification system

- 1 for safety proving and bugs finding
- 2 and further assist users through errors localization.
- 3 on **heap-manipulating** programs through separation logic.

Stronger specifications inference and Counterexample generation

- abduction (Calcagno et. al. POPL09, Aiken et. al. PLDI12).
- the weakest precondition (Snugglebug Chandra et. al. PLDI09) and negation on separation logic.
- CEGAR based (Berdine et. al. CAV12)

Thank you!

Specs with Sound and Complete Requirements

```
1.  bool ischedule(int prio){
2.    if (prio>3) return true; /*run it */
3.    else if (prio<0) abort();
4.    else{
5.      printf("Allow this task to run? y or n");
6.      char c=getc();
7.      if (c =' y') return true; /*run it */
8.      if (c =' n') abort();
9.      printf("input must be y or n! Please try again");
10.     return ischedule(prio);
11.   }
12. }
```

requires prio>3
ensures (res=true);

prio = 0

```
case{
  prio>3 → ensures(res=true)√;
  prio<0 → ensures (true)∪;
  0≤prio≤3 → ensures (true)∇;
}
```