

A Review on “Conditional Contextual Refinement”

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About the Paper

- **Title:** Conditional Contextual Refinement
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Program Verification

- *Implementation*: A program we wish to verify.
- *Specification*: A property we wish to show the program satisfies.
- *Precondition*: What should be true before the code runs?
- *Postcondition*: What is guaranteed to be true after the code runs?



Verification Method

Based on	Form of Specification	Aspect of Composition
Separation Logic	$\{P\} C \{Q\} \begin{cases} P: & \text{precondition,} \\ C: & \text{code,} \\ Q: & \text{postcondition.} \end{cases}$	modular reasoning about shared state
Refinement	$I \sqsubseteq S \begin{cases} I: & \text{implementation,} \\ S: & \text{specification.} \end{cases}$	transitive proof composition

Table 1: Based on Separation Logic vs. Based on Refinement.

Summary.

- *Separation logic* supports both features.
- *Refinement* supports both features.

Question: Can we marry the complementary benefits of refinement and separation logic in one framework?



Marrying Separation Logic and Refinement

1. Relational Separation Logic.

- Implemented in *Simuliris*.
- There are two judgments: $\{P\} I \lesssim S \{Q\}$ and $I \sqsubseteq_{\text{ctx}} S$.
 - **Relational Separation Logic** ($\{P\} I \lesssim S \{Q\}$): A simulation $I \lesssim S$ with pre/post-conditions P, Q . It does not enjoy transitive composability.
 - **Contextual Refinement** ($I \sqsubseteq_{\text{ctx}} S$): It is implied by $\{P\} I \lesssim S \{Q\}$ for certain restricted choices of P and Q . It means that I refines S when placed in an arbitrary program context. However, $I \sqsubseteq_{\text{ctx}} S$ is un-conditional.
- \therefore The benefits are kept *separate*!

2. Conditional Contextual Refinement. The first verification system to not only combine refinement and separation logic in a single framework but also *fuse* their complementary benefits together in a unified mechanism.



A Key-Value Storage

```

1 private data := NULL
2 def init(sz: int) =
3   data := calloc(sz)
4 def get(k: int): int =
5   return *(data + k)
6 def set(k: int, v: int) =
7   *(data + k) := v
8 def set_by_user(k: int) =
9   set(k, input())

```

Listing 1: Module I_{Map} .

```

1 private map := (fun k => 0)
2 def init(sz: int) =
3   skip
4 def get(k: int): int =
5   return map[k]
6 def set(k: int, v: int) =
7   map := map[k<-v]
8 def set_by_user(k: int) =
9   set(k, input())

```

Listing 2: Module A_{Map} .

- Unfortunately,

$$I_{\text{Map}} \not\sqsubseteq A_{\text{Map}}.$$

- It only holds *conditionally*:

`init` should be called at most once and before any other operation.



A Key-Value Storage

$$\begin{aligned}
 &\forall sz. \{ \overline{\text{pending}} \} \\
 &\quad \text{init}(sz) \\
 &\quad \{ *_{k \in [0, sz)} k \mapsto_{\text{Map}} 0 \} \\
 &\forall k v. \{ k \mapsto_{\text{Map}} v \} \\
 &\quad \text{get}(k) \\
 &\quad \{ r. r = v \wedge k \mapsto_{\text{Map}} v \} \\
 &\forall k w v. \{ k \mapsto_{\text{Map}} w \} \\
 &\quad \text{set}(k, v) \\
 &\quad \{ k \mapsto_{\text{Map}} v \} \\
 &\forall k w. \{ k \mapsto_{\text{Map}} w \} \\
 &\quad \text{set_by_user}(k) \\
 &\quad \{ \exists v. k \mapsto_{\text{Map}} v \}
 \end{aligned}$$

Figure 1: Pre/Post-conditions of S_{Map}

- **pending** is a unique, unforgeable token, and it gets consumed when calling **init**.
- Now, the following *conditional contextual refinement* holds:

$$S_{\text{Map}} \models I_{\text{Map}} \sqsubseteq A_{\text{Map}},$$

which means that the refinement

$$I \sqsubseteq A$$

holds under the separation logic conditions $S : \text{String} \rightarrow \text{Cond}$.

- **Cond** is the set of pre/post-conditions in separation logic.
- Enjoys benefits of both sides: modular reasoning on shared states and transitive composition.



Wrapper

In CCR, conditional refinement is defined as a contextual refinement:

$$S \models I \sqsubseteq A \quad \triangleq \quad I \sqsubseteq_{\text{ctx}} \langle S \vdash A \rangle,$$

where $\langle S \vdash A \rangle$ is called a (separation logic) **wrapper**, which converts A into a module that self-enforces the pre/post-conditions of S at the points where A interacts with its program context.

- **Good:**

- (1) the definition is simple and universal; and
- (2) we can exploit all the existing benefits of unconditional refinement: horizontal compositionality, vertical compositionality (i.e., transitivity).

- **Question:** Since A and $\langle S \vdash A \rangle$ are modules, the pre/post-conditions in A should be operationalized. Then, what should be the definition of

OPERATIONALIZED_CONDITIONS?



Stateless Conditional Refinement

```

1 def exp(x: int, n: int) =
2   if n == 0 then
3     return 1
4   else
5     return x * exp(x, n - 1)

```

Listing 3: Module I_{expn} .

```

1 def exp(x: int, n: int) =
2   assume(n >= 0)
3   var r := x ^ n
4   assert(r = x ^ n)
5   return r

```

Listing 4: Module $\langle S \vdash A_{\text{expn}} \rangle$.

$$I_{\text{expn}} \sqsubseteq_{\text{ctx}} \langle S \vdash A_{\text{expn}} \rangle.$$

$\frac{P \rightarrow (\mathbb{T} \lesssim \mathbb{S})}{\mathbb{T} \lesssim (\text{assume}(P); \mathbb{S})} \text{ ASMR}$	$\frac{P \wedge (\mathbb{T} \lesssim \mathbb{S})}{\mathbb{T} \lesssim (\text{assert}(P); \mathbb{S})} \text{ ASTR}$
$\frac{P \wedge (\mathbb{T} \lesssim \mathbb{S})}{(\text{assume}(P); \mathbb{T}) \lesssim \mathbb{S}} \text{ ASML}$	$\frac{P \rightarrow (\mathbb{T} \lesssim \mathbb{S})}{(\text{assert}(P); \mathbb{T}) \lesssim \mathbb{S}} \text{ ASTL}$

Table 2: Encoding conditional wrappers.



Stateless Conditional Refinement

```

1 def exp(x: int, n: int) =
2   if n == 0 then
3     return 1
4   else
5     return x * exp(x, n - 1)

```

Listing 5: Module I_{expn} .

```

1 def exp(x: int, n: int) =
2   assume(n >= 0)
3   var r := x ^ n
4   assert(r = x ^ n)
5   return r

```

Listing 6: Module $\langle S \vdash A_{\text{expn}} \rangle$.

$$I_{\text{expn}} \sqsubseteq_{\text{ctx}} \langle S \vdash A_{\text{expn}} \rangle.$$

```

1 def main() =
2   var r := exp(3, 2)
3   // ... r ...

```

Listing 7: Module I_{client} .

```

1 def main() =
2   assert(2 >= 0)
3   var r := exp(3, 2)
4   assume(r = 3 ^ 2)
5   // ... r ...

```

Listing 8: Module $\langle S \vdash A_{\text{client}} \rangle$.

$$I_{\text{client}} \sqsubseteq_{\text{ctx}} \langle S \vdash A_{\text{client}} \rangle.$$



Stateful Conditional Refinement

- What is an *ownership*?

An exclusive control of *resources*, clearly defining who can read or write memory at a given point.

- Why is it important?

\therefore Separation Logic = Hoare Logic + Ownership.

- **Question:** How do we transfer resources operationally?

- (i) First Attempt: **pass as arguments (and return)**

However, because $S \models I \sqsubseteq A$ is defined as

$$I \sqsubseteq_{\text{ctx}} \langle S \vdash A \rangle,$$

the un-conditionality of \sqsubseteq_{ctx} implies that the resources cannot be passed explicitly between $\langle S \vdash A \rangle$ and another module $\langle S \vdash A' \rangle$.

- (ii) Solution: **pass resources implicitly**, using the

dual non-determinism.



Interaction Tree

Let $E : \mathbf{Type} \rightarrow \mathbf{Type}$ be given, where $E(X)$ is called a type of *events* for each $X : \mathbf{Type}$. An *interaction tree* i of the type $\mathbf{itree} E T$ can be seen as an open small-step semantics that can:

- (i) take a silent deterministic step ($i = \mathbf{Tau} i'$);
- (ii) terminate with a return value r of the type T ($i = \mathbf{Ret} r$); or
- (iii) trigger an event e in $E(X)$ for some $X : \mathbf{Type}$, and resume execution with continuation k for each possible input value of the type X ($i = \mathbf{Vis} X e k$).

Since $\mathbf{itree} E$ forms a monad for any $E : \mathbf{Type} \rightarrow \mathbf{Type}$, we henceforth use the monad notations $x \leftarrow i; k x$ and $i \gg= k$ for *bind* and *ret* for *pure*:

$$\mathbf{ret} r \triangleq \mathbf{Ret} r.$$

$$\mathbf{Ret} r \gg= k \triangleq k r,$$

$$\mathbf{Tau} i \gg= k \triangleq \mathbf{Tau} (i \gg= k),$$

$$\mathbf{Vis} X e k \gg= k' \triangleq \mathbf{Vis} X e (\lambda x, k x \gg= k').$$



Trace

A **trace** is a finite or infinite sequence of **ObsEvents** (i.e., pairs of an observable event and its return value) that can possibly end one of the four cases:

- (i) **Normal termination** (**Term** v).
Normal termination with a value v of the type **Any**.
- (ii) **Silent divergence** (**Diverge**).
Silent divergence without producing any events.
- (iii) **Erroneous termination** (**Error**).
Termination due to an error in the program.
- (iv) **Partial termination** (**Partial**).
Partial termination due to the user interrupting execution.

Note that:

- **Any** can be understood as the set of all mathematical values;
 - the type of traces is denoted as **Trace**; and
- partial termination will serve as a dual of erroneous termination.



Behavior

- (1) The behavior of an itree i is defined as $\text{beh}(i)$, where the function $\text{beh} : \text{itree } \text{Ep Any} \rightarrow \wp(\text{Trace})$ has the following properties:
 - **Prefix-closed:** $t_0 \uparrow t_1 \in \text{beh}(i) \implies t_0 \uparrow \text{Partial} \in \text{beh}(i)$.
 - **Postfix-closed:** $t_0 \uparrow \text{Error} \in \text{beh}(i) \implies t_0 \uparrow t_1 \in \text{beh}(i)$.
- (2) The behavior of a function can be defined because its body can be represented as an itree.
- (3) The behavior of a module can be defined because it consists of initial values of local states and functions(which themselves are defined as itrees).
- (4) The behavior of a closed program can be defined because it consists of several modules.

Remarks.

- An itree is said to be **divergent** if its execution diverges silently without producing any events. If an itree i is divergent then $\text{Diverge} \in \text{beh}(i)$.
- Term $r \in \text{beh}(\text{Ret } r)$; $\text{beh}(i) \subseteq \text{beh}(\text{Tau } i)$; and $\text{Partial} \in \text{beh}(i)$.



Dual Non-determinism

- What is “dual non-determinism”?
It refers to either *demonic non-determinism* or its dual, *angelic non-determinism*.
- What do the terms “demonic non-determinism” and “angelic non-determinism” mean respectively?

In CCR, they refer to **choose** and **take** respectively, where:

Syntax	Semantics	Analogy
choose (X)	$\text{beh}(\text{choose}(X) \gg= k) \triangleq \bigcup_{x \in X} \text{beh}(k(x))$	assert (P)
take (X)	$\text{beh}(\text{take}(X) \gg= k) \triangleq \bigcap_{x \in X} \text{beh}(k(x))$	assume (P)

- Why does it resolve the problem?
 - The caller’s “**assert**” provides a resource at a call site.
 - The callee’s “**assume**” receives the resource provided by the caller.
 - At the point of **return**, the callee **asserts** that it is giving back a resource satisfying its postcondition.
 - Finally, the caller **assumes** the postcondition of the callee and receives the resource implicitly.



UB & NB

- What is **UB**?

In general, it refers to “undefined behavior”. In CCR,

$$\text{UB} \triangleq \text{take}(\emptyset).$$

In order to prove $\mathbb{T} \lesssim \text{UB}$, it is not required for \mathbb{T} to satisfy any particular property—that is, the behavior of the target \mathbb{T} is undefined.

Therefore, we can accept the definition of **UB** in CCR.

- What is **NB**?

Being different from “unspecified behavior”, **NB** is just the dual of **UB**:

$$\text{NB} \triangleq \text{choose}(\emptyset) = \{\text{Partial}\}.$$

Because it is rare to define the notion of “no behavior”, it is also hard to imagine **NB**. Hence, the only method to figure out **NB** is to understand the duality of **UB** and **NB**—e.g.,

$$\text{NB} \lesssim \mathbb{S} \iff \mathbb{T} \iff \mathbb{T} \lesssim \text{UB}.$$



WET (Wrapper Elimination Theorem)

- **Question:** How can we remove those operationalized conditions after proving an entire closed program—i.e., the result of inlining all functions of the program in the main function? We need a lemma of the following form:

$$\frac{I_1 \circ I_2 \circ \dots \circ I_n \sqsubseteq_{\text{beh}} \langle S \vdash A_1 \rangle \circ \langle S \vdash A_2 \rangle \circ \dots \circ \langle S \vdash A_n \rangle}{I_1 \circ I_2 \circ \dots \circ I_n \sqsubseteq_{\text{beh}} A_1 \circ A_2 \circ \dots \circ A_n}$$

- The ***Wrapper Elimination Theorem*** is a foundational soundness theorem for the CCR verification framework, which states as follows:

$$\langle S \vdash A_1 \rangle \circ \langle S \vdash A_2 \rangle \circ \dots \circ \langle S \vdash A_n \rangle \sqsubseteq_{\text{beh}} A_1 \circ A_2 \circ \dots \circ A_n.$$

It ensures that wrappers enforcing separation logic conditions can be safely removed after verifying a whole program. This makes conditional refinement practically useful—allowing conditions to be operationalized initially but eliminated safely and entirely at runtime.



Contribution

CCR:

- Is formalized in Coq.
- Includes challenging case studies:
 1. shared memory;
 2. mutual recursion;
 3. function pointers;
 4. termination/non-termination; and
 5. system calls.
- Is ready to be used:
 1. end-to-end verification (with CompCert), and
 2. executable (with Interaction Trees).
- Inspired “DimSum”.
- Extended to “Concurrency + CCR”.
- Is used by “Program logic for int2ptr casting”.

Motivated “Operationalizing liveness”.



Thank you for listening!

