Separation Logic and the Mashup Isolation Problem

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Phd Qualifier Exam Talk
Outline

1 Background
   • Hoare Logic
   • Intuition behind Separation Logic

2 The Mashup Isolation problem?
   • Formal Definition of Mashups
   • Isolation Property
   • How does Separation Logic help?

3 Basic Separation Logic
   • Assertion language and Inference rules
   • Solving the Isolation Problem

4 Separation Logic with Permissions
   • Assertion language and Inference rules
   • Solving the Isolation Problem

5 Ongoing and Future Work
While Programs

Expressions $E$ : $x \mid n \mid E + E \mid E \ast E$

Boolean Expressions $B$ : $true \mid false \mid E = E \mid B \implies B$

Commands $C, D$ : $x := E \mid \text{if } B \text{ then } C \text{ else } C \mid$
\hspace{1cm} $\text{while } B \text{ then } C \mid C; C$

Store

$Vars$ : Set of Variables
$StoreValues$ : $Nat$

Stores $A, B : Vars \rightarrow StoreValues$

Each program $C$ evaluates with respect to store: $A_1, C_1 \rightarrow A_2, C_2$
Hoare Logic

- **Axiomatic method for proving properties of while-programs, invented by Hoare in 1969.**
- **Central Idea:** Assign meaning to a program $C$ using a Hoare triple $\{P\} C \{Q\}$
  - $P$: Assertion on variables before $C$ begins execution.
  - $Q$: Assertion on variables after $C$ finishes execution
- **Example:**
  - $\{x = 10\} y = x + 1 \{y = 11\}$.
  - $\{x = y\} \text{while } x = 10 \text{ then } x = x + 1; y = y + 1 \{x = y\}$.

Validity of triples

A Hoare triple $\{P\} C \{Q\}$ is valid IFF:

*IF* $P$ holds initially and $C$ terminates *THEN* $Q$ holds finally.
The assertions \( P, Q \) in the triple \( \{ P \} C \{ Q \} \) are predicates on the store.

\[
\{ P[E/x] \}_{x} := E\{ P \} \tag{S-ASSIGNMENT}
\]

\[
\{ P \} C_1 \{ P' \} \quad \{ P' \} C_2 \{ Q \} \quad \frac{}{\{ P \} C_1; C_2 \{ Q \}} \tag{S-SEQ}
\]

\[
\{ P \land B \} C_1 \{ Q \} \quad \{ P \land \neg B \} C_2 \{ Q \} \quad \frac{}{\{ P \} \text{if } B \text{ then } C_1 \text{ else } C_2 \{ Q \}} \tag{S-IF}
\]

\[
\models P \quad \models P' \quad \{ P' \} C \{ Q' \} \quad \models Q' \quad \models Q \quad \frac{}{\{ P \} C \{ Q \}} \tag{S-CONSEQ}
\]

- Notice the simplicity of the assignment axiom.
- Assignment axiom also provides Weakest-pre-condition.
$\mathcal{L}$: While-programs + references and records

Introduce Heaps: Mappings from locations to records

- Variables can be locations or numbers.
- Two new boolean expressions: $isNat? (x)$, $isLoc? (x)$.
- Three new commands:
  - $x.p := E$ Update property $p$ of record at location $x$.
  - $x_1 := x_2.p$ Lookup property $p$ of records at location $x_2$.
  - $x := \{p_i : E_i\}_{i \in \{1, \ldots, n\}}$ Record Creation.

Heaps and Stores

$Loc$ : Set of locations  \hspace{1cm} \mathbb{P}$ : Set of Property names

$StoreValues : Loc \cup \text{Nat}$

$Stores A, B : Vars \rightarrow StoreValues$

$Heaps H, C : Loc \rightarrow \mathbb{P} \rightarrow StoreValues$

Each program $C$ evaluates with respect to a heap and a store.
Hoare logic for $\mathcal{L}$

- We need assertions on heap-stores now: $\text{cont } x.p = E$
  - Meaning: Property $p$ of record at location $x$ has value of expression $E$.
  - Think of $\text{cont}$ as the function $\text{Loc} \rightarrow \mathbb{P} \rightarrow \text{StoreValues}$.
- Is $\{\text{cont } y.p = 10\} x.p = 11 \{\text{cont } y.p = 10\}$ valid?
  - No, $x$ and $y$ may contain same location.
  - Rule of Constancy does not hold.
- Correct Triple: $\{\text{cont}_{x.p := 11} y.p = 10\} x.p = 11 \{\text{cont } y.p = 10\}$
  - $\text{cont}_{x.p := 11} = \lambda l, q : \text{If } (l = x) \land (p = q) \text{ then } 10 \text{ else } \text{cont } l.q$
  - This is too complex, imagine multiple assignments to $x.p$.
- Intuitively, $\text{cont } y.p = E$ is preserved during execution of $C$ if $y$ is disjoint from location-properties touched by $C$.
- Can I prove that $\text{cont } y.p = E$ is preserved without threading it through the entire analysis of $C$?

This is where Separation Logic comes in!...
Hoare logic for $\mathcal{L}$

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Separation Logic

History:

1. Burstall, 1972: *separate program texts which work on separated sections of the store can be reasoned about independently.*

2. Reynolds, MPC 2000: An Intuitionistic logic based on Burstall’s observation. Introduced \(^*\).

3. Ishtiaq and O’Hearn, POPL 2001: A classical version of Reynold’s logic. Introduced \(\rightarrow^*\).

4. Reynolds, LICS 2002: Generalized the above logic to arbitrary pointer arithmatic.

5. Several variants for specific domains have been discovered:
   - Many more . . .
Basic Separation Logic

Change of Notation: \( x.p \leftrightarrow E \) instead of \( \text{cont } x \ p \ E \).

- **Separating conjunction** \( \ast: (x.p \leftrightarrow 10) \ast (y.p \leftrightarrow 10) \) means
  - Field \( p \) of locations \( x \) and \( y \), contains 10.
  - \( x \) and \( y \) are different locations.
  - Therefore
    \[
    \{x.p \leftrightarrow 10 \ast y.p \leftrightarrow 10\}x.p := 11\{x.p \leftrightarrow 11 \ast y.p \leftrightarrow 10\}
    \]
    is valid.

- **Local Reasoning**: A specification should *only* reason about the heap locations and variables accessed.
  - Assignment axiom for \( x.p := E \) is simply
    \[
    \{x.p \leftrightarrow \_\}x.p := E\{x.p \leftrightarrow E\}
    \]
  - How do we derive that \( y.p \leftrightarrow 10 \) is preserved under the assignment \( x.p := 11 \) if \( x \neq y \)?

- **Frame Rule**:
  \[
  \frac{\{P\}C\{Q\}}{\{P \ast R\}C\{Q \ast R\}}
  \]
  - Helps in going from local specifications to global specifications.
  - Soundness of frame rule \( \implies \) A specified program never looks beyond what is present in its pre-condition!
Basic Separation Logic

Change of Notation: \( x.p \mapsto E \) instead of \( \text{cont } x.p E \).

- **Separating conjunction** \( \ast \): \( (x.p \mapsto 10) \ast (y.p \mapsto 10) \) means
  - Field \( p \) of locations \( x \) and \( y \), contains 10.
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\frac{\{P\}C\{Q\}}{\{P*R\}C\{Q*R\}}
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Separation Logic and the Mashup Isolation Problem
Run-time Safety

- **Robin Milner**: *Well specified programs never go wrong.*
- Any specification $\{P\}C\{Q\}$ is such that for any heap-store $H, A$ which satisfies $P$, executing $C$ on $H, A$ will never lead to a run-time error. This means:
  - All locations and variables accessed are mentioned by $P$ so that there are no memory errors (*critical for frame rule*).
  - $P$ includes sufficient conditions on the values of variables so that there are no type errors.
- Therefore a specification $\{x.p \mapsto 5\}C\{x. \mapsto 10\}$ means that $C$ only accesses property $p$ of location contained in $x$.
- This was the main motivation behind using separation logic for proving mashup isolation.
Separation Logic with Permissions

- Invented by Bornat et al in 2005 by incorporating fractional permissions in Separation logic.
- Main motivation was to track permissions in threads.
- We consider it in a sequential setting with 3 permissions - \( \{r\}, \{w\}, \{r, w\} \).

Key Ideas:

- Add more information in the specification to reason about what is read-only.
- Read \( x.p \leftrightarrow v \) as “program has permission to read/write property \( p \) of record at \( x \)”.
- Three new assertions: \( x.p \overset{r}{\leftrightarrow} E \), \( x.p \overset{w}{\leftrightarrow} E \), \( x.p \overset{r,w}{\leftrightarrow} E \).
- Modified \( \ast: x.p \overset{r}{\leftrightarrow} 10 \ast y.p \overset{r}{\leftrightarrow} 10 \) can hold even if \( x = y \).
- Frame rule stays the same!
The Mashup Isolation Problem?

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5. Ongoing and Future Work
Web 2.0

All about mixing and merging content (data and code) from multiple content providers in the users browser, to provide high-value applications known as **mashups**

- **Notation:**
  - Individual contents being mixed - *Components*.
  - Content Providers - *Principals*.
  - Publisher of the mashup - *Host*.

- **Examples:**
  - Basic Mashup: Any web page with advertisements, Facebook page with applications
  - More complex mashups: Yelp, Yahoo Newsglobe ...
Security Issues in Mashups

- Principals participating in a mashup are usually mutually untrusting.
- Each component must be protected from malicious behavior of other components.
  - Each Facebook application wants to make sure that its variables are not over-written by other applications.
  - Current FBJS mechanism not sufficient for ensuring this.

This Work:
- Focus on non-interacting basic mashups.
- Verify complete inter-component isolation.
Our Model

Basic Mashups (defined first in our Oakland 2010 paper):
- Components are programs in some sequential prog. language
- Mashup is a sequential composition of the components after variable renaming: $Rn(C_1); \ldots; Rn(C_n)$.
- Reasonable model for a web page with multiple advertisements.

Isolation Property: Behavior of each component as part of the mashup should be similar to the behavior obtained by executing it independently.
- Isolation property in Oakland paper is a special case of the above.
- This work focusses on verifying the property whereas the Oakland paper focusses on enforcing it.

Prog. Language: Simple Imperative language with references and records. Far from JavaScript, but good starting point for testing out new theoretical techniques.
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Formal Definition of Mashups

- Principals: $id_1, \ldots, id_n$.
- Components $(C_1, id_1), \ldots, (C_n, id_n)$: Programs from $\mathcal{L}$.
- Initial execution environment: Heap-store $H, A$
- $Rn(C, a)$: Command obtained by replacing all $x \in C$ with $a.x$.
- $Rn(A, a)$: Store obtained by replacing all $x$ in $A$ with $a.x$.

Variable-separated mashup

A variable-separated mashup $M(H, A, (C_1, id_1), \ldots, (C_n, id_n))$ is defined as the state $H_{mash}, A_{mash}, D_1; \ldots; D_n$ where

- $H_{mash} := H$.
- $A_{mash} := Rn(A, id_1) \ldots \ldots Rn(A, id_n)$.
- $D_i := Rn(C_i, id_i)$.

Variable renaming is done so that components cannot influence each other via the store.
Formal Definition of Mashups

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- Components $(C_1, id_1), \ldots, (C_n, id_n)$: Programs from $\mathcal{L}$.
- Initial execution environment: Heap-store $H$, $A$
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Variable renaming is done so that components cannot influence each other via the store.
Operational Semantics of $\mathcal{L}$

- Expressions $\llbracket E \rrbracket_{\text{Exp}} : \text{Stores} \rightarrow \text{StoreValues} \cup \{\text{error}\}$.
- Boolean Expr $\llbracket B \rrbracket_{\text{Bexp}} : \text{Stores} \rightarrow \{\text{true}, \text{false}, \text{error}\}$.
- Program states $S, T$ are formalized as triples $(H, A, C)$
- Commands: $\frac{\langle \text{premise} \rangle}{H_1, A_1, C_1 \rightarrow H_2, A_2, C_2}$ (small step)

Example rules:

\[
\frac{H, A, C_1 \longrightarrow K, B, C'_1}{H, A, C_1; C_2 \rightarrow K, B, C'_1; C_2} \quad \text{[C-SEQUENCECONTINUE]}
\]

\[
\frac{l \in \text{dom}(H) \text{ AND } x \in \text{dom}(A)}{H, A, x := l.p \rightarrow H, A[x \rightarrow H(l).p], \text{normal}} \quad \text{[C-LOOKUPNORMAL]}
\]

\[
\frac{l \notin \text{dom}(H) \text{ OR } x \notin \text{dom}(A)}{H, A, x := l.p \rightarrow H, A, \text{abort}} \quad \text{[C-LOOKUPABORT]}
\]
\textit{Notations and Definitions}

\textit{dom}(H): \{(l, p) \mid H(l)(p) \text{ is defined}\}.
\textit{dom}(A): \{x \mid A(x) \text{ is defined}\}.

Given states \( S, T \):
- \( \mathcal{H}(S), S(S), C(S) \) denote the heap store and term part of the trace.
- \( S \rightsquigarrow T \): \( S \) goes to \( T \) in zero or more steps.
- \( \text{Traces}(S) \): Set of reduction traces of \( S \).
- \( S \uparrow \overset{\text{def}}{=} \neg \exists T : S \rightsquigarrow T \not\rightarrow \).
- \( \text{Safe}(S) \overset{\text{def}}{=} \forall T : S \rightsquigarrow T \implies C(T) \neq \text{abort} \).
The Simulation Relation

Heap Actions: \((l, p, a, v)\) where \(a \in \{r, w\}\) and \(v \in \text{StoreValues}\)

Store Actions: \((x, a, v)\) where \(a \in \{r, w\}\) and \(v \in \text{StoreValues}\)

- Given a trace \(\tau\), \(\text{Acc}(\tau)\) is the action sequence corresponding to the trace

State simulation \(S \sim T\)

There exists a variable renaming \(\text{ren} : \text{Vars} \to \text{Vars}\):

1. **Safe Monotonicity.** \(\text{Safe}(S) \implies \text{Safe}(T)\)
2. **Termination Monotonicity.**
   \(\neg S \uparrow \wedge \text{Safe}(S) \implies \neg T \uparrow \wedge \text{Safe}(S)\)
3. **Access Similarity** If \(\text{Safe}(S)\) holds then for all \(\tau_T \in \text{Traces}(T)\), there exists \(\tau_S \in \text{Traces}(S)\) such that \(\text{ren}(\text{Acc}(\tau_S)) = \text{Acc}(\tau_T)\)
Isolation Property

Let \( M(H, A, (C_1, id_1), ... , (C_n, id_n)) = H, A_{mash}, D_1; \ldots; D_n \), where \( D_i \) is a renamed version of \( C_i \).

Pick any \( \tau \in Traces(H, A_{mash}, D_1; \ldots; D_n) \).

- By semantics of sequential compositions, starting heap-store for \( D_{i+1} \) is the final heap-store for \( D_i \).
- Define \( States(\tau, id_i) \) as the sub-trace of \( \tau \) corresponding to execution of \( D_i \).
- \( States(\tau, id_i) = \emptyset \) if for some \( j < i \), \( D_j \) doesn’t terminate normally.
Isolation Property, formally

\[ \mathcal{M}(H, A, (C_1, id_1), \ldots, (C_n, id_n)) \text{ is isolated IFF:} \]
for all traces \( \tau \in \text{Traces}(\mathcal{M}((C_1, id_1), \ldots, (C_n, id_n))) \),

\[ \forall i : \text{States}(\tau, id_i) \neq \emptyset \implies (H, A, C_i) \sim (H_i, A_i, D_i) \]

where \( H_i, A_i = \mathcal{H}_S(\text{States}(\tau, id_i)) \)
How does Separation Logic help?

Consider heap store $H, A$ and two components $C_1, C_2$.

$\mathcal{M}(H, A, (C_1, id_1), (C_2, id_2)) = H, A_{mash}, D_1; D_2$:  
Let $H_1, A_1$ be such that $H, A_{mash}, D_1 \leadsto H_1, A_1, normal$ (assuming termination).

**Result**

$Isolation(\mathcal{M}(H, A, (C_1, id_1), (C_2, id_2)))$ IFF:

$$\forall l, p : l, p \in \text{Read}(H, A_{mash}, D_2) \cap \text{dom}(H) \implies H(l).p = H_1(l).p$$
How does separation logic help

∀l, p : l, p ∈ Read(H, A_{mash}, D_2) ∩ dom(H) \implies H(l).p = H_1(l).p

IFF: one of the following holds:
Any location-property pair that is read during the reduction of D_2 on H, A_{mash} is:

A. Not accessed during the reduction of D_1 on H, A
   - Basic Separation logic can tell me what is accessed and whether it is disjoint from a certain portion of the heap.

B. At most read during the reduction of D_1 on H, A
   - Definition of isolation in Oakland paper.
   - Separation logic with permissions - modified separating conjunction allows overlap on read-only portion.

C. At most written and restored during the reduction of D_1 on H, A
   - Tricky, I have a naive solution.
   - Separation logic and Information hiding.
How does separation logic help

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Basic Separation Logic $SL_1$

### Assertion language $A_1$

$$P ::= B \mid \text{emp} \mid x.p \mapsto E \mid P \times P \mid P \rightarrow P \mid P \Rightarrow P \mid \exists x. P$$

### Satisfaction of Assertions: $H, A \models_{A_1} P$

- **Boolean Exp:** $H, A \models_{A_1} B$ iff $\llbracket B \rrbracket_{BexpA} = \text{true}$
- **Points-to:** $H, A \models_{A_1} E_1.p \mapsto E_2$ iff
  1. $\text{dom}(H) = \{(\llbracket E_1 \rrbracket_{ExpA}, p)\}$
  2. $H(\llbracket E_1 \rrbracket_{ExpA}).p = \llbracket E_2 \rrbracket_{ExpA}$

- Notice that the points-to relation is exact.
Satisfaction of Assertions

Separating Conjunction: \( H, A \models_{A_2} P_1 \ast P_2 \) iff

\[ \exists H_1, H_2 : \]
- \( \text{dom}(H_1) \cap \text{dom}(H_2) = \emptyset \)
- \( H_1 \cdot H_2 = H \)
- \( H_1, A \models_{A_1} P_1 \land H_2, A \models_{A_1} P_2 \)

Remarks:
- No store separation, we can write \((l_1.p \rightarrow x) \ast (l_2.p \rightarrow x)\).
- Semantics is exact.

Empty Heap: \( H, A \models_{A_1} \text{emp} \) iff \( \text{dom}(H) = \emptyset \)

Implication: \( H, A \models_{A_1} P_1 \Rightarrow P_2 \) iff

\[ H, A \models_{A_1} P_1 \Rightarrow H, A \models_{A_1} P_2 \]
Satisfaction of Assertions

We have local specifications and frame rule, but how do we express pre-conditions for an arbitrary assertion $P$?

$$\{??\} x.p = 10\{P\}$$

Separating Implication ($\rightarrow^*$):

- $x.p \rightarrow 10 \rightarrow^* P$ holds for heaps to which if a heap satisfying $x.p \rightarrow 10$ is concatenated then assertion $P$ holds.
- Therefore, $\{x.p \rightarrow \_ \rightarrow^* (x.p \rightarrow 10 \rightarrow^* P)\} x.p = 10\{P\}$ is valid.

Formally, $H, A \models_{\mathcal{A}_1} P_1 \rightarrow^* P_2$ iff

$\forall H_1, H_2:$

- $\text{dom}(H_1) \cap \text{dom}(H) = \emptyset$
- $H.H_1 = H_2$
- $H, A \models_{\mathcal{A}_1} P_1 \land H_2, A \models_{\mathcal{A}_1} P_2$
Satisfaction of Assertions

We have local specifications and frame rule, but how do we express pre-conditions for an arbitrary assertion $P$?

\[{x.p = 10} P\]

**Separating Implication ($\rightarrow^*$):**

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Formally, $H, A \models A_1 P_1 \rightarrow^* P_2$ iff

\[\forall H_1, H_2: \]

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- $H.H_1 = H_2$
- $H, A \models A_1 P_1 \land H_2, A \models A_1 P_2$
Satisfaction of Assertions

We have local specifications and frame rule, but how do we express pre-conditions for an arbitrary assertion $P$?

$\{x.p = 10\} P$

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- $x.p \mapsto 10 \rightarrow^* P$ holds for heaps to which if a heap satisfying $x.p \mapsto 10$ is concatenated then assertion $P$ holds.
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Formally, $H, A \models A_1 P_1 \rightarrow^* P_2$ iff

$\forall H_1, H_2:
- \text{dom}(H_1) \cap \text{dom}(H) = \emptyset$
- $H.H_1 = H_2$
- $H, A \models A_1 P_1 \land H_2, A \models A_1 P_2$
Hoare logic rules apply. In addition:

\[
\{E_1.p \leftrightarrow \_ \land Wt(E_2)\} E_1.p = E_2\{E_1.p \leftrightarrow E_2 \land Wt(E_2)\} \]

\[y \text{ not free in } E\]

\[
\{\text{present}(x) \land \exists y : E.p \leftrightarrow y\} x = E.p\{\exists y : E[y/x].p \leftrightarrow x\}
\]

\[y \text{ not free in any } E_i\]

\[
\{\text{present}(x) \land Wt(E_i) \land \text{emp}\} x := \{\tilde{p}_i : \tilde{E}_i\}\{\exists y : (x : \{p_i \leftrightarrow E_i[y/x]\})\}
\]

- “Backwords” rules for arbitrary post-conditions can be written for each of the above commands.
- Ishtiaq and O’Hearn (POPL 2001) proved that the backwords axioms express weakest-pre-conditions.
Frame rule

\[
\frac{\{ P \} C \{ Q \}}{\{ P \ast R \} C \{ Q \ast R \}} \quad \text{[modifies}(C) \cap \text{free}(R) = \emptyset]\]

\textit{modifies}(C) can be syntactically derived from } C.

**Proposition**

For \( H, A \) and \( K, B \) such that \( H \subseteq K \) and \( A \subseteq B \), for all commands \( C \)

1. **Safe Monotonicity.** \( \text{Safe}(H, A, C) \implies \text{Safe}(K, B, C) \)
2. **Frame Property.** If \( \text{Safe}(H, A, C) \) holds then:
   For all \( K', B', C' \) such that \( K, B, C \leadsto K', B', C' \), exists \( H', A'' \):
   \[
   H, A, C \leadsto H', A', C' \land K' - H' = K - H \land B - A = B' - A'
   \]

Soundness of frame rule follows from above proposition.
Frame rule

\[
\frac{\{P\} C \{Q\}}{\{P \ast R\} C \{Q \ast R\}} \quad [modifies(C) \cap free(R) = \emptyset]
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**Proposition**

For \(H, A\) and \(K, B\) such that \(H \subseteq K\) and \(A \subseteq B\), for all commands \(C\)

1. **Safe Monotonicity.** \(\text{Safe}(H, A, C) \implies \text{Safe}(K, B, C)\)
2. **Frame Property.** If \(\text{Safe}(H, A, C)\) holds then:
   
   For all \(K', B', C'\) such that \(K, B, C \leadsto K', B', C', \) exists \(H', A''\):

   \[H, A, C \leadsto H', A', C' \land K' - H' = K - H \land B - A = B' - A'\]

Soundness of frame rule follows from above proposition.
Soundness

\[ [P]_{A_1} \overset{\text{def}}{=} \{ H, A \mid H, A \models_{A_1} P \} \]

Validity \( \models_{SL_1} \)

\( \{ P \} C \{ Q \} \) is \( SL_1 \)-valid IFF: for all heap-stores \( H, A \in [P]_{A_1} \),

1. \( \text{Safe}(H, A, C) \)
2. For all \( K, B: H, A, C \leadsto K, B, \text{normal} \implies K, B \in [Q]_{A_1} \)

Provability \( \vdash_{SL_1} \)

\( \{ P \} C \{ Q \} \) is \( SL_1 \)-provable IFF: it can be derived using the inference rules of Separation logic and \( A_1 \)-valid assertions.

Soundness

\( \vdash_{SL_1} \{ P \} C \{ Q \} \implies \models_{SL_1} \{ P \} C \{ Q \} \)
Solving the Isolation Problem

\[ M(H, A, (C_1, id_1), \ldots, (C_n, id_n)) = H, A_{mash}, D_1; \ldots; D_n \]

**Case A:** Any location-property pair that is read during the reduction of \( D_i \) on \( H, A_{mash} \) is **not accessed** during the reduction of \( D_j \) on \( H, A_{mash} \)

**Procedure 1 (sufficient for case A)**

1. Deduce specifications \( \{P_1\} C_1\{Q_1\}, \ldots, \{P_n\} C_n\{Q_n\} \) in \( SL_1 \).
2. Show that \( H, A \in \llbracket P_1 \ast \ldots \ast P_n \ast \text{true} \rrbracket_{A_1} \) holds.

**Theorem**

Procedure 1 is sound.

Spent most of my time proving the above theorem.
Example: Tree access

\[ H \triangleq \begin{cases} l & : \{ \text{val : 1, fone : } l_1, \text{ftwo : } l_2 \} \\ l_1 & : \{ \text{val : 2, fone : } l_3, \text{par : } l \} \\ l_2 & : \{ \text{val : 3, fone : } l_4, \text{par : } l \} \\ l_3 & : \{ \text{val : 4, par : } l_1 \} \end{cases} \]
Example: Tree access

\[
A_{\text{mash}} := \{ c_{\text{win}} : l_1, c_{\text{tmp1}} : 0, c_{\text{tmp2}} : 0, c_{\text{win}} : l_2, c_{\text{tmp1}} : 0, c_{\text{tmp2}} : 0 \}
\]
\[
C_1 := c_{\text{tmp1}} = c_{\text{win}.\text{par}}; c_{\text{tmp2}} = c_{\text{tmp1}.\text{val}}; c_{\text{win}.\text{val}} = c_{\text{tmp2}+};
\]
\[
C_2 := c_{\text{tmp1}} = c_{\text{win}.\text{val}}; c_{\text{win}.\text{val}} = c_{\text{tmp1}} + 1;
\]

Prove Isolation.

Solution

1. \( \{ \exists x. c_{\text{win}.\text{val}} \mapsto 2 \ast c_{\text{win}.\text{par}} \mapsto x \ast x.\text{val} \mapsto 1 \} C_1 \{ \text{true} \} \)
   \{ c_{\text{win}.\text{val}} \mapsto 3 \} C_2 \{ \text{true} \} \)

2. \( H, A_{\text{mash}} \in \llbracket (\exists x. c_{\text{win}.\text{val}} \mapsto 2 \ast c_{\text{win}.\text{par}} \mapsto x \ast x.\text{val} \mapsto 1) \ast c_{\text{win}.\text{val}} \mapsto 3 \ast \text{true} \rrbracket \llbracket A_1 \)
Issues

- Not in Algorithmic form
- Validity of $A_1$ assertions is not decidable in general.
  - Yang and Calcagno (FSTTCS 2001 and a few others) have found decidable subsets of the assertion language.
  - I will explore these and their implications on procedure 1 in future.
- Nevertheless, we can carry out hand-proofs of isolation.
Outline

1. Background
   - Hoare Logic
   - Intuition behind Separation Logic

2. The Mashup Isolation problem?
   - Formal Definition of Mashups
   - Isolation Property
   - How does Separation Logic help?

3. Basic Separation Logic
   - Assertion language and Inference rules
   - Solving the Isolation Problem

4. Separation Logic with Permissions
   - Assertion language and Inference rules
   - Solving the Isolation Problem

5. Ongoing and Future Work

Ankur Taly
Separation Logic and the Mashup Isolation Problem
Separation Logic with Permissions $SL_2$

**Assertion language $\mathcal{A}_2$**

$$P := B \mid emp \mid x.p \xleftarrow{a} E \mid P \ast P \mid P \rightarrow P \mid P \Rightarrow P \mid \exists x.P$$

where $a \subseteq \{r, w\}$.

**Satisfaction of Assertions**

- Assertions are on heap-stores and also on actions performed by programs.
- Define permission maps $\Sigma$ as $Loc \rightarrow \mathbb{P} \rightarrow \{\{r\}, \{w\}, \{r, w\}\}$
- General form: $H, A, \Sigma \models_{\mathcal{A}_2} P$
Satisfaction of Assertions ($\mathcal{A}_2$)

- **Points-to:** $H, A, \Sigma \models_{\mathcal{A}_2} E_1.p \xrightarrow{a} E_2$ iff
  - $\text{dom}(H) = \{(\llbracket E_1 \rrbracket_{\Sigma} A, p)\} = \text{dom}(\Sigma)$
  - $H(\llbracket E_1 \rrbracket_{\Sigma} A).p = \llbracket E_2 \rrbracket_{\Sigma} A$
  - $a = \Sigma(\llbracket E_1 \rrbracket_{\Sigma} A).p$

- **Separating-Conjunction:**
  $H, A, \Sigma \models_{\mathcal{A}_2} P_1 \cdot P_2$ iff $\exists H_1, \Sigma_1, H_2, \Sigma_2:
  - H_1, A, \Sigma_1 \models_{\mathcal{A}_2} P_1$
  - H_2, A, \Sigma_2 \models_{\mathcal{A}_2} P_2
  - $H_1 \triangleleft H_2, \Sigma_2$
  - $H_1 \cup H_2 = H \land \Sigma_1 \cup \Sigma_2 = \Sigma$
  where $\text{dom}(H_1), \Sigma_1 \triangleleft \text{dom}(H_2), \Sigma_2$ means that
  - $H_1 \cup H_2, \Sigma_1 \cup \Sigma_2$ are defined
  - $\forall l, p \in \text{dom}(\Sigma_1) \cap \text{dom}(\Sigma_2) : \Sigma_1(l) = \Sigma_2(l) = \{r\}$

Observe that $(x.p \xleftrightarrow{\ell} E) \cdot (x.p \xleftrightarrow{\ell} E) \Leftrightarrow x.p \xleftrightarrow{\ell} E.$
Satisfaction of Assertions ($A_2$)

- **Points-to:** $H, A, \Sigma \models_{A_2} E_1 \cdot p \rightarrow^a E_2$ \iff
  
  - $\text{dom}(H) = \{(\llbracket E_1 \rrbracket_{Exp} A, p)\} = \text{dom}(\Sigma)$
  - $H(\llbracket E_1 \rrbracket_{Exp} A).p = \llbracket E_2 \rrbracket_{Exp} A$
  - $a = \Sigma(\llbracket E_1 \rrbracket_{Exp} A).p$

- **Separating-Conjunction:**
  $H, A, \Sigma \models_{A_2} P_1 \ast P_2$ \iff
  $\exists H_1, \Sigma_1, H_2, \Sigma_2$

  - $H_1, A, \Sigma_1 \models_{A_2} P_1$
  - $H_2, A, \Sigma_2 \models_{A_2} P_2$
  - $H_1, \Sigma_1 \ast H_2, \Sigma_2$
  - $H_1 \cup H_2 = H \land \Sigma_1 \cup \Sigma_2 = \Sigma$

  where $\text{dom}(H_1), \Sigma_1 \ast \text{dom}(H_2), \Sigma_2$ means that

  - $H_1 \cup H_2, \Sigma_1 \cup \Sigma_2$ are defined
  - $\forall l, p \in \text{dom}(\Sigma_1) \cap \text{dom}(\Sigma_2) : \Sigma_1(l) = \Sigma_2(l) = \{r\}$

Observe that $(x.p \rightarrow^a E) \ast (x.p \rightarrow^a E) \Leftrightarrow x.p \rightarrow^a E$. 
Satisfaction of Assertions ($\mathcal{A}_2$)

- **Points-to:** $H, A, \Sigma \models_{\mathcal{A}_2} E_1.p \xrightarrow{a} E_2$ iff
  
  - $\text{dom}(H) = \{(\llbracket E_1 \rrbracket_{\text{Exp}A}, p)\} = \text{dom}(\Sigma)$
  
  - $H(\llbracket E_1 \rrbracket_{\text{Exp}A}).p = \llbracket E_2 \rrbracket_{\text{Exp}A}$
  
  - $a = \Sigma(\llbracket E_1 \rrbracket_{\text{Exp}A}).p$

- **Separating-Conjunction:** $H, A, \Sigma \models_{\mathcal{A}_2} P_1 \ast P_2$ iff $\exists H_1, \Sigma_1, H_2, \Sigma_2$:
  
  - $H_1, A, \Sigma_1 \models_{\mathcal{A}_2} P_1$
  
  - $H_2, A, \Sigma_2 \models_{\mathcal{A}_2} P_2$
  
  - $H_1, \Sigma_1 \not\sqsubset H_2, \Sigma_2$
  
  - $H_1 \cup H_2 = H \land \Sigma_1 \cup \Sigma_2 = \Sigma$

  where $\text{dom}(H_1), \Sigma_1 \not\sqsubset \text{dom}(H_2), \Sigma_2$ means that
  
  - $H_1 \cup H_2, \Sigma_1 \cup \Sigma_2$ are defined
  
  - $\forall l, p \in \text{dom}(\Sigma_1) \cap \text{dom}(\Sigma_2) : \Sigma_1(l) = \Sigma_2(l) = \{r\}$

  Observe that $(x.p \xrightarrow{r} E) \ast (x.p \xrightarrow{r} E) \iff x.p \xrightarrow{r} E$. 
Axioms and Inference rules ($SL_2$)

\[ y \text{ not free in } E \]

\[ \{ \text{present}(x) \land \exists y : E.p \xrightarrow{r} y \} x = E.p \{ \exists y : E[y/x].p \xrightarrow{r} x \} \]

\[ \{ E_1.p \xrightarrow{w} \land Wt(E_2) \} E_1.p = E_2 \{ E_1.p \xrightarrow{w} E_2 \land Wt(E_2) \} \]

\[ y \text{ not free in any } E_i \]

\[ \{ \text{present}(x) \land Wt(\tilde{E}_i) \land \text{emp} \} x := \{ \tilde{p}_i : \tilde{E}_i \} \{ \exists y : (x : \{ p_i \xrightarrow{r,w} E_i[y/x] \}) \} \]

- There are “backwards” version for each these using $\xrightarrow{\ast}$.
- All other rules stay the same.
Soundness

\[ \llbracket P \rrbracket_{A_2} \overset{def}{=} \{ H, A \mid \exists \Sigma : H, A, \Sigma \models A_2 P \} \]

Validity \( \models_{SL_1} \)

\{ P \} C \{ Q \} is \( SL_1 \)-valid IFF: for all \( H, A, \Sigma, H, A, \Sigma \models A_2 P \),

1. Safe\((H, A, C)\)
2. For all \( K, B, D \) such that \( H, A, C \leadsto K, B, D \),
   a. \( K, B \in \llbracket Q \rrbracket_{A_2} \) if \( D = \text{normal} \).
   b. For all \((l, p, a, v)\) IF \((l, p, a, v) \in \text{Acc}^{heap}((H, A, C), (K, B, D))\)
      and \( l, p \in \text{dom}(H) \) THEN \( a \in \Sigma(l).p \)

Provability \( \vdash_{SL_2} \)

\{ P \} C \{ Q \} is \( SL_2 \)-provable IFF: it can be derived using the inference rules of Separation logic and \( A_2 \)-valid assertions.

Soundness: \( \vdash_{SL_2} \{ P \} C \{ Q \} \implies \models_{SL_2} \{ P \} C \{ Q \} \).
Case B: Any location-property pair that is read during the reduction of $D_i$ on $H, A_{mash}$ is at most read during the reduction of on $D_j$ on $H, A_{mash}$

Procedure 2 (sufficient for case $B$)

1. Deduce specifications $\{P_1\}C_1\{Q_1\}, \ldots, \{P_n\}C_n\{Q_n\}$ in $SL_2$.
2. Show that $H, A \in [\{P_1 \ast \ldots \ast P_n \ast true\}]_{A_2}$ holds.

Theorem

Procedure 2 is sound.
Handling Case C

Case C: Any location-property pair that is read during the reduction of $D_i$ on $H$, $A_{mash}$ is at most written and restored during the reduction of on $D_j$ on $H$, $A_{mash}$

- Difficult to handle using permissions, we have an invariant which is temporarily broken and then restored.

Separation Logic with Information Hiding: POPL 2004

- Main Idea: Consider a program using multiple procedures.
  - Each procedure will have certain internal resources only managed by it.
  - The program should be reasoned about independent of these internal resources.
- Introduced the “hypothetical frame rule”
  \[
  \vdash \{P_1 \ast R\} C_1 \{Q_1 \ast R\}
  \]
  \[
  \vdots
  \]
  \[
  \vdash \{P_n \ast R\} C_n \{Q_n \ast R\}
  \]
  \[
  \{P_1\}k\{Q_1\}[X_1],\ldots,\{P_n\}k\{Q_n\} \vdash \{P\} C\{Q\}
  \]
  \[
  \vdash \{P \ast R\} \text{let } k_1 = C_1, \ldots, k_n = C_n \text{ in } C\{Q \ast R\}
  \]
Handling Case C

**Case C:** Any location-property pair that is read during the reduction of $D_i$ on $H$, $A_{mash}$ is at most written and restored during the reduction of on $D_j$ on $H$, $A_{mash}$

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$$
\vdash \{P_1 * R\} C_1 \{Q_1 * R\} \\
\vdots \\
\vdash \{P_n * R\} C_n \{Q_n * R\} \\
\{P_1\}k\{Q_1\}[X_1], \ldots, \{P_n\}k\{Q_n\} \vdash \{P\}C\{Q\} \implies [] \\
\vdash \{P * R\} \text{let } k_1 = C_1, \ldots, k_n = C_n \text{ in } C\{Q * R\}
$$
Our Procedure

- Our procedure is inspired by the hypothetical frame rule.
- Exact Assertion: $R$ is exact iff for all stores $S$ there is unique heap $H$ such that $H, A \in [R]_{A_1}$.

Procedure 3 (sufficient for case $C$)

1. Deduce specifications of the form 
   \[ \{P_1 \ast R\}C_1\{Q_1 \ast R\}, \ldots, \{P_n \ast R\}C_n\{Q_n \ast R\} \] in $SL_1$.
2. Show that $R$ is exact.
3. Show that $H, A \in [P_1 \ast \ldots \ast P_n \ast R \ast true]_{A_1}$ holds.

Theorem

Procedure 3 is sound.

- Soundness of hypothetical frame rule used in the proof.
- Ownership transfer of $R$ from $C_1$ to $\ldots$ to $C_n$. 
Comparison with Authority Safety

Oakland 2010 paper:

- \textit{Auth}(H, A, C): Over-approximations of the set of actions performed during the reduction of C on H, A
- \textit{AuthIsolation}(H, A, C_1, \ldots, C_n): For all \( i,j \), authority map of \( C_i \) does not contain a write action to a location where \( C_j \) reads from.

\textbf{Theorem:}

\begin{align*}
\text{AuthIsolation}(H, A, C_1, \ldots, C_n) & \implies \\
\text{Isolation}(\mathcal{M}(H, A, C_1, \ldots, C_n))
\end{align*}

How does this relate to what we have done?

- Semantically relates to solving Case B.
- Authority maps are usually computed by heap reachability analysis.
- Specifications are “more informative authority maps”: More closely related to what is actually reached.
Comparison with Authority Safety

Oakland 2010 paper:

- **Auth(H, A, C)**: Over-approximations of the set of actions performed during the reduction of C on H, A
- **AuthIsolation(H, A, C₁, ..., Cₙ)**: For all \(i, j\), authority map of \(C_i\) does not contain a write action to a location where \(C_j\) reads from.

**Theorem:**

\[ AuthIsolation(H, A, C₁, ..., Cₙ) \implies Isolation(\mathcal{M}(H, A, C₁, ..., Cₙ)) \]

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- Semantically relates to solving Case B.
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- Specifications are “more informative authority maps”: More closely related to what is actually reached.
Future Work: Migrating to *JavaScript*

Hopeful about the following features:

1. **Deleting record properties**: There are rules for *dispose*
2. **Computable Properties x[E]**: There are rules for handling pointer arithmetic (Reynolds, 2002).

Following seem tricky:

1. **Dynamic addition of properties**: Tempting to think of them as “resource allocation”, but they are subtly different.
   - This is allocation of a particular resource and not a non-deterministically chosen one.
   - Frame rule might break!
   - May be some kind of “existence permissions” can help.
2. **Prototype chains**: How do we express what part of the chain is reached during property access?
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   - Frame rule might break!
   - May be some kind of “existence permissions” can help.
2. **Prototype chains**: How do we express what part of the chain is reached during property access?
Other Future directions

1. Think of better solutions for handling case $C$.
   - Explore if a permission based approach exists.

2. Formalize the notion of **defensive consistency** using separation logic.
   - Informally, defensively consistent functions are ones that are incorruptible by their clients.
   - Hypothetical frame rule can be useful.

3. Explore **capability systems** where meaning of a capability is specified using a specification rather than an authority map.

4. Formalize the right isolation property for mashups where each component is allowed to call methods defined by other components. Example: Yelp
Thank You