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ABSTRACT

We present OOlong, an object calculus with interface inheritance, structured concurrency and locks. The goal of the calculus is extensibility and reuse. The semantics are therefore available in a version for \LaTeX\ typesetting (written in Ott), and a mechanised version for doing rigorous proofs in Coq.

KEYWORDS

Object Calculi, Semantics, Mechanisation, Concurrency

1 INTRODUCTION

When reasoning about object-oriented programming, object calculi are a useful tool for abstracting away many of the complicated details of a full-blown programming language. They provide a context for prototyping in which proving soundness or other interesting properties of a language is doable with reasonable effort.

The level of detail depends on which concepts are under study. One of the most used calculi is Featherweight Java, which models inheritance but completely abstracts away mutable state [12]. The lack of state makes it unsuitable for reasoning about any language feature which entails object mutation, and many later extensions of the calculus re-adds state as a first step. Other proposals have also arisen as contenders for having "just the right level of detail" [3, 15, 21].

This paper introduces OOlong, a small, imperative object calculus for the multi-core age. Rather than modelling a specific language, OOlong aims to model object-oriented programming in general, with the goal of being extensible and reusable. To keep subtyping simple, OOlong uses interfaces and omits class inheritance and method overriding. This avoids tying the language to a specific model of class inheritance (e.g., Java’s), while still maintaining an object-oriented style of programming. Concurrency is modeled in a finish/async style, and synchronisation is handled via locks.

The semantics are provided both on paper and in a mechanised version written in Coq. The paper version of OOlong is defined in Ott [20], and all type rules in this paper are generated from this definition. To make it easy for other researchers to build on OOlong, we are making the sources of both versions of the semantics publicly available.

With the goal of extensibility and re-usability, we make the following contributions:

- We define the formal semantics of OOlong, motivate the choice of features, and prove type soundness (§2–5).
- We provide a mechanised version of the full semantics and soundness proof, written in Coq (§6).
- We provide Ott sources for easily extending the paper version of the semantics and generating type rules in \LaTeX\ (§7).
- We give two examples of how OOlong can be extended; support for assertions, and more fine-grained locking based on regions (§8).

2 RELATED WORK

The main source of inspiration for OOlong is Welterweight Java by Östlund and Wrigstad [15], a concurrent core calculus for Java with ease of reuse as an explicit goal. Welterweight Java is also defined in Ott, which facilitates simple extension and \LaTeX\ typesetting, but only exists as a calculus on paper. There is no online resource for accessing the Ott sources, and no published proofs except for the sketches in the original treatise. OOlong provides Ott sources and is also fully mechanised in Coq, increasing reliability. Having a proof that can be extended along with the semantics also improves re-usability. Both the Ott sources and the mechanised semantics are publicly available online [5]. OOlong is more lightweight than Welterweight Java by omitting mutable variables and using a single flat stack frame instead of modelling the call stack. Also, OOlong is expression-based whereas Welterweight Java is statement-based, making the OOlong syntax more flexible. We believe that all these things make OOlong easier to reason and prove things about, and more suitable for extension than Welterweight Java.

Object calculi are used regularly as a means of exploring and proving properties about language semantics. These calculi are often tailored for some special purpose, e.g., the calculus of dependent object types [1], which aims to act as a core calculus for Scala, or OrcO [16], which adds objects to the concurrent-by-default language Orc. While these calculi serve their purposes well, their tailoring also make them fit less well as a basis for extension when reasoning about languages which do not build upon the same features. OOlong aims to act as a calculus for common object-oriented languages in order to facilitate reasoning about extensions for such languages.
While this is enough for reasoning about Java's type system, the weight Java, Welterweight Java and OOlong. The original Java-specific. To the best of our knowledge, Middleweight Java was Java programs are also valid Java programs. The high level of detail however makes it unattractive for extensions which are not highly instructors and Java's block structure and call stack. Middleweight core calculus which also models object identity, null mechanised.

ConcurrentJava

Interfaces and Java's block structure and call stack. Middleweight core calculus which also models object identity, null mechanised.

ClassicJava

Flanagan et al. define Lightweight Java [8, 22]), Flanagan and Freund later added concurrency and locks to ClassicJava in ConcurrentJava [10], but omitted interfaces. To the best of our knowledge, neither ClassicJava nor ConcurrentJava have been mechanised.

Bierman et al. define Middleweight Java [3], another imperative core calculus which also models object identity, null pointers, constructors and Java’s block structure and call stack. Middleweight Java is also a true subset of Java, meaning that all valid Middleweight Java programs are also valid Java programs. The high level of detail however makes it unattractive for extensions which are not highly Java-specific. To the best of our knowledge, Middleweight Java was never mechanised. Strniša proposes Lightweight Java as a simplification of Middleweight Java [21], omitting block scoping, type casts, constructors, expressions, and modelling of the call stack, while still being a proper subset of Java. Like Welterweight Java it is purely based on statements, and does not include interfaces. Like OOLong, Lightweight Java is defined in Ott, but additionally uses Ott to generate a mechanised formalism in Isabelle/HOL. A later extension of Lightweight Java was also mechanised in Coq (∼800 lines generated from Ott, and another ∼5800 lines of proofs) [9].

Last, some language models go beyond the surface language and execution. One such model is Jinja by Klein and Nipkow [13], which models (parts of) the entire Java architecture, including the virtual machine and compilation from Java to byte code. To handle the complexity of such a system, Jinja is fully mechanised in Isabelle/HOL. The focus of Jinja is different than that of calculi like OOLong, and is therefore not practical for exploring language extensions which do not alter the underlying runtime.

2.2 Background

OOLong started out as a target language acting as dynamic semantics for a type system for concurrency control [6]. The proof schema for this system involved translating the source language into OOLong, establishing a mapping between the types of the two languages, and reasoning about the behaviour of a running OOLong program. In this context, OOLong was extended with several features, including assertions, readers–writer locks, regions, destructive reads and mechanisms for tracking which variables belong to which stack frames (§ 8 outlines the addition of assertions and regions). By having a machine checked proof of soundness for OOLong that we could trust, the proof of progress and preservation of the source language followed from showing that translation preserves well-formedness of programs.
3 STATIC SEMANTICS OF OOLONG

In this section, we describe the formal semantics of OOlong. The semantics are also available as Coq sources, together with a full soundness proof. The main differences between the paper version and the mechanised one are outlined in §6.

Figure 2 shows the syntax of OOlong. The meta-syntactic variables are \( x, y \) and \( \text{this} \) for variable names, \( f \) for field names, \( C \) for class names, \( I \) for interface names, and \( m \) for method names. For simplicity we assume that all names are unique. OOlong defines objects through classes, which implement some interface. Interfaces are in turn defined either as a collection of method signatures, or as an “inheriting” interface which joins two other interfaces. There is no inheritance between classes, and no overriding of methods. A program is a collection of interfaces and classes together with a starting expression \( e \).

Most expressions are standard: values (null or abstract object locations \( i \)), variables, field accesses, field assignments, method calls, object instantiation and type casts. For simplicity, targets of field and method lookups must be variables, and method calls have exactly one parameter (multiple parameters can be simulated through method indirection). We also use let-bindings rather than sequences and variables. Sequencing can be achieved through the standard trick of translating \( e_1; e_2 \) into let \( \_ = e_1 \) in \( e_2 \) (due to eager evaluation of \( e_1 \)). Parallel threads are spawned with the expression finish(\( \text{async}(e_1) \) \( \text{async}(e_2) \)); \( e_3 \), which runs \( e_1 \) and \( e_2 \) in parallel, waits for their completion, and then continues with \( e_3 \).

The expression lock(\( x \)) in \( e \) locks the object pointed to by \( x \) for the duration of \( e \). While an expression locking \( t \) is executed in the dynamic semantics, it appears as locked, \{\( e \}\}. This way, locks are automatically released at the end of the expression \( e \). It also allows tracking which field accesses are protected by locks and not.

Types are class or interface names, or Unit (used as the type of assignments). The typing environment \( \Gamma \) maps variables to types and abstract locations to classes.

3.1 Well-Formed Program (Figure 3)

A well-formed program consists of well-formed interfaces and well-formed classes, plus a well-typed starting expression. A non-empty interface is well-formed if its method signatures only mention well-formed types (WF-INTERFACE), and an inheriting interface is well-formed if the interfaces it extends are well-formed (WF-INTERFACE-EXTENDS). A class is well-formed if it implements all the methods in its interface. Further, all fields and methods must be well-formed (WF-CLASS). A field is well-formed if its type is well-formed (WF-FIELD). A method is well-formed if its body has the type specified as the method’s return type under an environment containing the single parameter and the type of the current this (WF-METHOD).

3.2 Types and Subtyping (Figure 4)

Each class or interface in the program corresponds to a well-formed type (T-WF-‘). Subtyping is transitive and reflexive, and is nominally defined by the interface hierarchy of the current program (T-SUB-‘). A well-formed environment \( \Gamma \) has variables of well-formed types and locations of valid class types (WF-ENV). Finally, the frame rule splits an environment \( \Gamma_1 \) into two sub-environments \( \Gamma_2 \) and \( \Gamma_3 \) whose variable domains are disjoint (but which may share locations \( i \)).

This is used when spawning new threads to prevent them from sharing variables1.

3.3 Expression Typing (Figure 5)

Most typing rules for expressions are simple. Variables are looked up in the environment (WF-VAR) and introduced using let bindings (WF-LET). Method calls require the argument to exactly match the parameter type of the method signature (WF-CALL). We require explicit casts, and only support upcasts (WF-CAST). Fields are looked up with the helper function fields (WF-SELECT). Fields may only be looked up in class types (as interfaces do not define fields). Field updates have the Unit type (WF-UPDATE). Any class in the program can be instantiated (WF-NEW). Locations can be given any super type of their class type given in the environment (WF-LOC). The constant null can be given any well-formed type, including Unit (WF-NULL).

Forking new threads requires that the accessed variables are disjoint, which is enforced by the frame rule \( \Gamma = \Gamma_1 + \Gamma_2 \) (WF-FJ). Locks can be taken on any well-formed target (WF-LOCK*).

4 DYNAMIC SEMANTICS OF OOLONG

Figure 6 shows the structure of the run-time constructs of OOlong. A configuration \( \langle H; V; T \rangle \) contains a heap \( H \), a variable map \( V \), and a collection of threads \( T \). A heap \( H \) maps abstract locations to objects. Objects store their class, a map \( F \) from field names to values, and a lock status \( L \) which is either locked or unlocked. A stack map \( V \) maps variable names to values. As variables are never updated, OOlong could use a simple variable substitution scheme instead of tracking the values of variables in a map. However, the current design gives us a simple way of reasoning about object references on the stack as well as on the heap.

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1Since variables are immutable in OOlong, this kind of sharing would not be a problem in practice, but for extensions requiring mutable variables, we believe having this in place makes sense.
Figure 4: Typing, subtyping, typing environment and the frame rule. In the latter, \( \gamma \) abstracts over variables \( x \) and locations \( \iota \) to reduce clutter. The helper function \( \text{vardom} \) abstracts over variables \( \iota \) and locations \( \iota \).

Figure 5: Typing of expressions

Figure 6: Run-time constructs of OoLong. \( \mathcal{L} \) is a set of locations whose locks are held by the current thread.

4.1 Well-Formedness Rules (Figure 7)

An OoLong configuration is well-formed if its heap \( H \) and stack \( V \) are well-formed, its collection of threads \( T \) is well-typed, and the current lock situation in the system is well-formed (WF-CFG). A heap \( H \) is well-formed under a \( \Gamma \) if all locations in \( \Gamma \) correspond to objects in \( H \), all objects in the heap have an entry in \( \Gamma \), and the fields of all objects are well-formed under \( \Gamma \) (WF-HEAP). The fields of an object of class \( C \) are well-formed if each name of the static fields of \( C \) maps to a value of the corresponding type (WF-FIELDS). A stack \( V \) is well-formed under a \( \Gamma \) if each variable in \( \Gamma \) maps to a value of the corresponding type in \( V \), and each variable in \( V \) has an entry in \( \Gamma \) (WF-VARS). A well-formed thread collection requires all sub-threads and expressions to be well-formed (WF-T-*). An exceptional state can have any well-formed type (WF-T-EXN).

The current lock situation is well-formed for a thread if all locations in its set of held locks \( \mathcal{L} \) correspond to objects whose lock status is \text{locked}. Locks must be taken at most once in \( e \) (captured by \text{distinct}\{locks\}(e), cf §A.3), and for each \text{locked}, in the current expression, \( t \) must be in the set of held locks \( \mathcal{L} \). The parallel case propagates these properties, and additionally requires that two parallel threads do not hold the same locks in their respective \( \mathcal{L} \). Any locks held in the continuation \( e \) must be held by the first thread of

A thread collection \( T \) has one of three forms: \( T_1 || T_2 \triangleright e \) denotes two parallel asyncs \( T_1 \) and \( T_2 \) which must reduce fully before evaluation proceeds to \( e \). (\( \mathcal{L}, e \)) is a single thread evaluating expression \( e \). (\( \mathcal{L}, e \)) is the set of locations of all the objects whose locks are currently being held by the thread. The initial configuration is \((e; e; (0, e))\), where \( e \) is the initial expression of the program. A thread can also be in an exceptional state \text{EXN}. The current semantics only supports the \text{NullPointer}Exception.
4.2 Evaluation of Expressions (Figure 8)

OOlong uses a small-step dynamic semantics, with the standard technique of evaluation contexts to decide the order of evaluation and reduce the number of rules (DYN-EVAL-CONTEXT). We use a single stack frame for the entire program and employ renaming to make sure that variables have unique names\(^2\). Evaluating a variable simply looks it up in the stack (DYN-EVAL-VAR). A let-expression introduces a fresh variable that substitutes for the static name (DYN-EVAL-LET). Similarly, calling a method introduces two new fresh variables—one for this and one for the parameter of the method. The method is dynamically dispatched on the type of the target object (DYN-EVAL-CALL).

Casts will always succeed and are therefore no-ops dynamically (DYN-EVAL-CAST). Adding support for downcasts is possible with the

```
\begin{align*}
\text{DYN-EVAL-CAST} & : (H; V; (\mathcal{L}, x)) \rightarrow (H; V; (\mathcal{L}, v)) \\
V(x) & = v \\
\text{DYN-EVAL-LET} & : x' \text{ fresh} \quad V' = V[x' \mapsto v] \quad e' = e[x \mapsto x'] \\
\langle H; V; (\mathcal{L}, \text{let } x = \text{ in } e) \rangle & \rightarrow \langle H; V'; (\mathcal{L}, e') \rangle \\
\end{align*}
```

\(^2\) This sacrifices reasoning about properties of the stack size in favour of simpler dynamic semantics.

Figure 8: Dynamic semantics (1/2). Expressions. The evaluation context \(E\) is defined as

\[E[\bullet] ::= x.f = \bullet | x.(m怀念) | \text{let } x = \bullet \text{ in } e | (t) \bullet | \text{locked}, \{\bullet\}\]
We have omitted constructors from this treatise. A new object has what thread to evaluate. The hole of the evaluation context forces the full reduction of the parallel expressions to the left of \( \triangleright \) before continuing with \( \varepsilon_3 \), which is the expression placed in the hole of the evaluation context. When two asyncs have finished, the second thread is removed along with all its locks, and the first thread continues with the expression to the right of \( \triangleright \) (DYN-EVAL-ASYNC-JOIN).

5 TYPE SOUNDNESS OF OOLONG

We prove type soundness as usual by proving progress and preservation. This section only states the theorems and sketches the proofs. We refer to the mechanised semantics for the full proofs (cf. §6).

Since well-formed programs are allowed to deadlock, we must formulate the progress theorem so that this is handled. The Blocked predicate on configurations is defined in the appendix (cf. §A.1).

**Progress.** A well-formed configuration is either done, has thrown an exception, has deadlocked, or can take one additional step:

\[ \forall \Gamma, H, V, T, t. \Gamma \vdash (H; V; T) : t \Rightarrow T = (L, e) \vee T = \text{EXN} \vee \text{Blocked}(H; V; T) \vee \exists \text{cfg}^e, (H; V; T) \rightarrow \text{cfg}^e \]

**Proof sketch.** Proved by induction over the thread structure \( T \). The single threaded case is proved by induction over the typing relation over the current expression.

To show preservation of well-formedness we first define a subsumption relation \( \Gamma_1 \subseteq \Gamma_2 \) between environments. \( \Gamma_2 \) subsumes \( \Gamma_1 \) if all mappings \( \gamma : t \) in \( \Gamma_1 \) are also in \( \Gamma_2 \):

\[ \Gamma_1 \subseteq \Gamma_2 \]

\[ \forall \gamma : t. \Gamma, \Gamma'(\gamma) = t \]

\[ \Gamma \subseteq \Gamma' \]

**Preservation.** If \((H; V; T)\) types to \( t \) under some environment \( \Gamma \), and \((H; V; T)\) steps to some \((H'; V'; T')\), there exists an environment subsuming \( \Gamma \) which types \((H'; V'; T')\) to \( t \).

\[ \forall \Gamma, H, V, T, T', t. \Gamma \vdash (H; V; T) : t \wedge (H; V; T) \rightarrow (H'; V'; T') \Rightarrow \exists \Gamma', (H'; V'; T') : t \wedge \Gamma \subseteq \Gamma' \]

**Proof sketch.** Proved by induction over the thread structure \( T \). The single threaded case is proved by induction over the typing relation over the current expression. There are also a number of lemmas regarding locking that needs proving (e.g., that a thread can never steal a lock held by another thread). We refer to the mechanised proofs for details.

6 MECHANISED SEMANTICS

We have fully mechanised the semantics of OOLong in Coq, including the proofs of soundness. The source code weighs in at \( \approx 4700 \) lines of Coq, \( \approx 1100 \) of which are definitions and \( \approx 3600 \) of which are properties and proofs. In the proof code, \( \approx 300 \) lines are extra lemmas about lists and \( \approx 200 \) lines are tactics specific to this formalism used for automating often re-occurring reasoning steps. The proofs also make use of the LibTactics library [17], as well as the crush tactic [7]. We use Coq bullets together with Aaron Bohannon’s "Case" tactic to structure the proofs and make refactoring simpler; when a definition changes and a proof needs to be rewritten, it is immediately clear which cases need to be updated.

\( ^2 \)In practice, since locking is structured these locks will already have been released.
The mechanised semantics are the same as the semantics presented here, modulo uninteresting representation differences such as modelling the typing environment \( \Gamma \) as a function rather than a sequence. It explicitly deals with details such as how to generate fresh names and separating static and dynamic constructs (e.g., when calling a method, the body of the method will not contain any dynamic expressions, such as \( \text{locked}(e) \)). It also defines helper functions like field and method lookup.

The Coq sources are available in a public repository so that the semantics can be easily obtained and extended [5]. The source files compile under Coq 8.6.1, the latest version at the time of writing.

7 TYPESETTING OOlong

The paper version of OOlong is written in Ott [20], which lets a user define the grammar and type rules of their semantics using ASCII-syntax. The rules are checked against the grammar to make sure that the syntax is consistent. Ott can then generate B\&Y\&C code for these rules, which when typeset appear as in this paper. The Ott sources are available in the same repo as the Coq sources [5].

It is also possible to have Ott generate B\&Y\&C code for the grammar, but these require more whitespace than one typically has to spare in an article. We therefore include B\&Y\&C code for a more compact version of the grammar, as well as the definitions of progress and preservation [5]. Ott also supports generating Coq and Isabelle/HOL code from the same definitions that generate B\&Y\&C code. We have not used this feature as we think it is useful to let the paper version of the semantics abstract away some of the details that a mechanised version requires.

8 EXTENSIONS TO THE SEMANTICS

This section demonstrates the extensibility of OOlong by adding assertions and region based locking to the semantics. Here we only describe the additions necessary, but these features have also been added to the mechanised version of the semantics with little added complexity to the code. They are available as examples on how to extend the semantics [5].

8.1 Supporting Assertions

Assertions are a common way to enforce pre- and postconditions and to fail fast if some condition is not met. We add support for assertions in OOlong by adding an expression \( \text{assert}(x \Rightarrow y) \), which asserts that two variables are aliases (if we added richer support for primitives we could let the argument of the assertion be an arbitrary boolean expression). If an assertion fails, we throw an \text{AssertionException}. The type rule for assertions states that the two variables are of the same type. The type of an assertion is Unit:

\[
\text{DYN-EVAL-ASSERT} \quad \text{V}(x) = \text{V}(y) \\
\langle H; V; (\mathcal{L}, \text{assert}(x \Rightarrow y)) \rangle \iff \langle H; V; \text{null} \rangle
\]

In the dynamic semantics, we have two outcomes of evaluating an assertion: if successful, the program continues; if not, the program should crash.

8.2 Supporting Region-based Locking

Having a single lock per object prevents threads from concurrently updating disjoint parts of an object, even though this is benign from a data-race perspective. Many effect-systems divide the fields of an object into regions in order to reason about effect disjointness on a single object (e.g., [4]). Similarly, we can add regions to OOlong, let each field belong to a region and let each region have a lock of its own. Syntactically, we add a region annotation to field declarations (\( f : t \in \mathcal{r} \)) and require that taking a lock specifies which region is being locked (\( \text{lock}(x, r) \in e \)). Here we omit declaring regions and simply consider all region names valid. This means that the rules for checking well-formedness of fields do not need updating (other than the syntax).

Dynamically, locks are now identified not only by the location \( i \) of their owning object, but also by their region \( r \). Objects need to be extended from having one lock to having multiple locks, each with its own lock status. We model this by replacing the lock status of an object with a region map \( RL \) from region names to lock statuses. As an example, the dynamic rule for grabbing a lock for a region is updated thusly:

\[
\text{DYN-EVAL-LOCK-REGION} \quad \text{V}(x) = t \quad H(i) = (C, F, RL) \quad RL(r) = \text{unlocked} \quad (i, r) \notin \mathcal{L} \\
H^* = H[i \mapsto (C, F, RL[r \mapsto \text{locked}])] \quad \mathcal{L}' \equiv \mathcal{L} \cup \{(i, r)\} \\
\langle H; V; (\mathcal{L}, \text{lock}(x, r) \in e) \rangle \iff \langle H^*; V; (\mathcal{L}', \text{locked}(i, r) \in e) \rangle
\]

Similarly, the well-formedness rules for locking need to be updated to refer to region maps of objects instead of just objects. A region map must contain a mapping for each region used in the object:

\[
\text{WF-REGIONS} \quad \forall f : t \in \text{fields}(C), r \in \text{dom}(RL) \quad C \mapsto RL
\]

The changes can mostly be summarised as adding one extra level of indirection each time a lock status is looked up on the heap. This extension increases the mechanised semantics by ~130 lines.

9 CONCLUSION

We have presented OOlong, an object calculus with concurrency and locks, with a focus on extensibility. OOlong aims to model the most important details of concurrent object-oriented programming, but also lends itself to extension and modification to cover other topics. A good language calculus should be both reliable and reusable. By providing a mechanised formalisation of the semantics, we reduce the leap of faith needed to trust the calculus, and also give a solid starting point for anyone wanting to extend the calculus in a rigorous way. Using Ott makes it easy to extend the calculus...
We thank the anonymous reviewers for helpful feedback and suggestions.

REFERENCES


A.1 Blocking

The blocking property of a configuration holds if all its threads are either blocking on a lock or are done (i.e., have reduced to a value). This property is necessary to distinguish deadlocks from stuck states.

\[
\text{Blocked}(cfg) \iff (\text{Configuration is blocked})
\]

\[
\begin{align*}
\text{BLOCKED-LOCKED} & : \forall L, e. V(x) = \nu \rightarrow (H; V; \langle L, \text{lock}(x) \in e \rangle) \\
\text{BLOCKED-DEADLOCK} & : \forall L, e. \text{Blocked}(H; V; \langle L, \text{lock}(x) \in e \rangle) \rightarrow \text{Blocked}(H; V; T_i) \quad (T_i \ni T_2 \ni T_2 \ni e) \\
\text{BLOCKED-LEFT} & : \text{Blocked}(H; V; T_i) \rightarrow \text{Blocked}(H; V; \langle L, v \ni e \rangle) \\
\text{BLOCKED-RIGHT} & : \text{Blocked}(H; V; T_j) \rightarrow \text{Blocked}(H; V; \langle L, e \in \text{EXN} \rangle)
\end{align*}
\]

A.2 Exceptions

Exceptions terminate the entire program and cannot be caught. The only rule that warrants clarification is the rule for exceptions in evaluation contexts which abstracts the nature of an underlying exception to avoid rule duplication (dyne-exception-context). For readability we abbreviate NullPointerException as NPE. When we don’t care about the kind of exception we write EXN.

\[
\text{EXN} \rightsquigarrow \text{EXN}
\]

\[
\begin{align*}
\text{DYNE-NPE-SELECT} & : (H; V; \langle L, x, f \rangle) \rightsquigarrow (H; V; \text{NPE}) \\
\text{DYNE-NPE-CALL} & : (H; V; L, m; v)) \rightsquigarrow (H; V; \text{NPE}) \\
\text{DYNE-NPE-LOCK} & : (H; V; L, \text{lock}(x) \ni e) \rightsquigarrow (H; V; \text{NPE}) \\
\text{DYNE-EXCEPTION-ASYNC-LEFT} & : (H; V; \text{EXN}) \ni T_2 \ni e) \rightsquigarrow (H; V; \text{EXN}) \rightsquigarrow (H'; V'; \text{EXN})
\end{align*}
\]

A.3 Helper Functions

This section presents the helper functions used in the formalism. Helpers methods and fields are analogous to msigs, and we refer to the mechanised semantics for details [5].

\[
v\text{ardom}(T) = \{ x \mid x \in \text{dom}(T) \}
\]

\[
\begin{align*}
\text{msigs}(I) & = \{ \text{Msigs} \mid \text{if} \text{I}(\text{Msigs}) \in P \} \\
\text{msigs}(I) & = \{ \text{Msigs} \mid \text{if} \text{extends I}, I \in P \}
\end{align*}
\]

\[
\begin{align*}
\text{msigs}(C) & = \{ \text{Msigs} \mid \text{if} \text{class C} \ni \text{Md}s \ni P \} \\
\text{msigs}(t(m)) & = \{ t \mid \text{if} \text{m : I(t) : T_2} \in \text{msigs}(t) \}
\end{align*}
\]

\[
\begin{align*}
\text{heldLocks}(T) & = \{ L : \text{heldLocks}(T_i) \in \text{heldLocks}(T_2) \ni \text{if} \text{T} = (L, e) \} \\
\text{heldLocks}(e) & = \{ \text{if} \text{t = locked(e)} \ni \text{in e} \}
\end{align*}
\]

\[
\begin{align*}
\text{distinctLocks}(e) & = \text{null} \text{LockList}(e) \\
\text{where LockList}(e) & = \{ \text{if} \text{t = locked(e)} \ni \text{in e} \}
\end{align*}
\]

A. Omitted Rules

This appendix lists the rules for deadlocked states, exception propagation, and the helper functions used in the main article. They should all be unsurprising but are included for completeness.