Panini: Reconciling Concurrency and Modularity in Design

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Abstract
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Keywords
implicit-invocation languages, aspect-oriented programming languages, event types, event expressions, concurrent languages

Disciplines
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Abstract
Writing correct and efficient concurrent programs still remains a challenge. Explicit concurrency is difficult, error prone, and creates code which is hard to maintain and debug. This type of concurrency also treats modular program design and concurrency as separate goals, where modularity often suffers. To solve these problems, we are designing a new language that we call Păñini. In this paper, we focus on Păñini’s asynchronous, typed events which reconcile the modularity goal promoted by the implicit invocation design style with the concurrency goal of exposing potential concurrency between the execution of subjects and observers. Since modularity is improved and concurrency is implicit in Păñini, programs are easy to reason about and maintain. Furthermore, races and deadlocks are avoided entirely yielding programs with a guaranteed sequential semantics. To evaluate our language design and implementation we show several examples of its usage as well as an empirical study of program performance. We found that not only is developing and understanding Păñini programs significantly easier compared to standard concurrent object-oriented programs, but performance of Păñini programs is comparable to the equivalent programs written using Java’s fork-join framework.

1. Introduction

Coming together is a beginning. – Henry Ford

The idea behind Păñini’s design is that if programmers structure their system to improve modularity in its design, they should get concurrency for free.

1.1 Object-oriented (OO) Concurrency Features
It is widely accepted that multicore computing is becoming the norm. However, writing correct and efficient concurrent programs using concurrency-unsafe features remains a challenge [5, 33–35, 46]. A language feature is concurrency-unsafe if its usage may give rise to program execution sequences containing two or more memory accesses to the same location that are not ordered by a happens-before relation [25]. Several such language features exist in common language libraries, for example, threads, processes, Futures, and FutureTask are all examples from the Java programming language’s standard library [35, 46]1. Using such language features has advantages, e.g. they can encapsulate complex synchronization code and allow its reuse.

To illustrate, consider the implementation of a genetic algorithm in Java presented in Figure 1. The idea behind a genetic algorithm is to mimic the process of natural selection. Genetic algorithms are computationally intensive and are useful for many optimization problems [41]. The main concept is that searching for a desirable state is done by combining two parent states instead of modifying a single state [41]. An initial generation with n members is given to the algorithm. Next, a cross over function is used to combine different members of the generation in order to develop the next generation (lines 10–16 in Figure 1). Optionally, members of the offspring may randomly be mutated slightly (lines 18–23 in Figure 1). Finally, members of the generation (or an entire generation) are ranked using a fitness function (lines 25–29 in Figure 1).

Multiple Concerns of the Genetic Algorithm. In the OO implementation of the genetic algorithm in Figure 1 there are three concerns standard to the genetic algorithm: cross over (creating a new generation), mutation (random changes to children), and fitness calculation (how good is the new generation). Logging of each generation is another concern added here since it may be desirable to observe the space searched by the algorithm (lines 17 and 24). The final concern here is concurrency (lines 4, 7–9, and 30–33). In this example, production of a generation is run as a FutureTask. The different shading shows code corresponding to each concern as illustrated in the legend.

1.2 Problems with Explicit Concurrency Features

Explicit concurrency. With explicit concurrency, the programmer must divide the program into independent tasks.

1 Original proposal for futures in MultiLisp is concurrency-safe [40].
Next, the programmer must handle creating and managing the individual threads. A problem with the concurrency-unsafe language features described previously and illustrated in Figure 1 is that correctness is difficult to ensure since it relies on all objects obeying a usage policy [26]. Since such policies cannot automatically be enforced by a library based approach [26], the burden on the programmer is increased and errors arise (ex: deadlock, data races, etc.). Also, the non-determinism introduced by such mechanisms makes debugging hard since errors are difficult to reproduce [45]. Furthermore, this style of explicit parallelism can hurt the design and maintainability of the resulting code [39].

Separation of modular and concurrent design. Another significant shortcoming of these language features, or perhaps the discipline that they promote, is that they treat modular program design and concurrent program design as two separate and orthogonal goals.

From a quick glance at Figure 1, it is quite clear that the five concerns are tangled. For example, the code for concurrency (lines 4, 7-9, and 30-33) is interleaved with the logic of the algorithm (the other four concerns). Also, the code for logging occurs in two separate places (lines 17 and 24). This arises from implementing a standard well understood sequential approach and then afterward attempting to expose concurrency rather than pursuing modularity and con-
dleware, databases, and Internet-scale distribution frameworks [19].

In Pāñini, an event type is seen as a decoupling mechanism that is used to interface two sets of modules, so that they can be independent of each other. Below we briefly describe the syntax in the context of the genetic algorithm implementation in Pāñini shown in Figure 2 (a more detailed description appears in Section 2). In the listing we have omitted initializations of classes for brevity. In this listing an example of an event type appears on lines 1–3, whose name is GenAvailable and that declares to make one context g of type Generation available.

Certain classes, to which we refer to as subjects from here onward, declaratively and explicitly announce events. The class CrossOver (lines 4-19) is an example of such a subject. This class contains a probability for the cross over operation and a maximum depth at which the algorithm will quit producing offspring. The method cross for this class computes the new generation based on the current generation (lines 11-19). After the cross method creates a new generation, it announces an event of type GenAvailable (line 18) denoted by code announce GenAvailable(gl).

Another set of classes, which we refer to as observers from here onward, can provide methods, called handlers that are invoked (implicitly and potentially concurrently) when events are announced. The listing in Figure 2 has several examples of observers: CrossOver, Mutation, Logger and Fittest. A class can act as both subject and observer. For example, the classes CrossOver and Mutation are both subjects and observers for events of type GenAvailable.

In Pāñini classes statically express (potential) interest in an event by providing a binding declaration. For example, the Mutate concern (lines 20–35) wants to randomly mutate some of the population after it is created. So in the implementation of class Mutation there is a binding declaration (line 26) that says to run the method mutate (lines 27–35) when events of type GenAvailable are announced.

At runtime these interests in events can be made concrete using the register expressions. The class Mutation has a method on lines 22–25 that when called registers the current instance this to listen for events. After registration, when any event of type GenAvailable is announced the method mutate (lines 27–35) will run with the registered instance this as the receiver object.

Similarly, the method logit (line 39) will log each generation when events of type GenAvailable are announced. Finally, method check in class Fittest (lines 41-51) will determine the better fitness between the announced generation and the previously optimal generation when events of type GenAvailable are announced.

Benefits of Pāñini’s Version of Genetic Algorithm. At a quick glance, we can see from the shading that the four remaining concerns are no longer tangled and they are separated into individual modules. This separation not only makes reasoning about their behavior simple but also allows us to expose potential concurrency between them.

Furthermore, the concurrency concern has been removed entirely since the implementation of Pāñini encapsulates all the code for managing the concurrency. By not requiring users to write this code, Pāñini avoids any threat of incorrect or non-deterministic concurrency thus easing the burden on the programmer. This allows the programmer to focus on creating a good, maintainable modular design.

Finally, additional concurrency between these four modules is now automatically exposed. Thus, Pāñini reconciles modular program design and concurrent program design.

Advantages of Pāñini’s Design over Related Ideas. Pāñini is most similar to our previous work on Ptolemy [36], but Pāñini’s event types also have concurrency advantages.

It is also similar to implicit invocation (II) languages [12, 31] that also see events as a decoupling mechanism. The advantage of using Pāñini over an II language is that asynchronous, typed events in Pāñini allow developers to take advantage of the decoupling of subjects and observers to expose potential concurrency between their execution.

These events also relieve programmers from the burden of explicitly creating and maintaining threads, managing locks, and shared memory. Thus Pāñini avoids the burden of reasoning about the usage of locks, which has several benefits. First, incorrect use of locks may have safety problems. Second, locks may degrade performance since acquiring and releasing a lock has overhead. Third, threads are cooperatively managed by the language runtime, thus thrashing due to excessive threading is avoided. These benefits make Pāñini an interesting point in the design space of concurrent languages.

In summary, this work makes the following contributions:

1. Pāñini’s language design with a simple and flexible implicit concurrency model such that Pāñini programs are
   • free of data races,
   • free of deadlocks, and
   • have a guaranteed sequential semantics;

2. a precise operational semantics and type system for Pāñini’s novel constructs;

3. an efficient implementation of Pāñini’s design as an extension of the JastAdd compiler [13] that relies on:
   • a sound algorithm for finding inter-handler dependence at registration time to maximize concurrency,
   • a simple and efficient algorithm for scheduling concurrent tasks that builds on the fork/join framework [27];

4. a detailed analysis of Pāñini and closely related ideas;

5. and, an empirical performance analysis of Pāñini implementations using canonical concurrency examples.
1.4 Organization of this Paper

We have developed a small-step operational semantics, a type system and proved its soundness. Their details can be found in Appendix A (on page 14) and Appendix B (on page 16). The next section describes the design and implementation of the Pañini language in detail. So a theoretical roadmap might be to read the next section followed by Appendix A and Appendix B.

Section 3 gives more examples in Pañini and describes our performance evaluation and experimental results. So an alternative roadmap might be to read the next two sections.

Finally, Section 4 surveys related work, and Section 5 describes future directions and concludes.

2. Pañini’s Design

Pañini, fl. c.400 BC, Indian grammarian, known for his formulation of the Sanskrit grammar rules, the earliest work on linguistics.

In this section, we describe Pañini’s design. Pañini’s design builds on our previous work on the Ptolemy [36] and Eos [38] languages as well as implicitly parallel languages such as Jade [39]. Pañini achieves concurrent speedup by executing handler tasks (that do not conflict) concurrently. The novel features of Pañini are found in its concurrency model, event model and type system.

2.1 Pañini’s Abstract Syntax

\[
\begin{align*}
\text{prog} & ::= \text{dec}^* e \\
\text{dec} & ::= \text{class } e \text{ extends } f \{ \text{field } m \text{ binding } \} \\
\text{event} & ::= \{ \text{form} \} \\
\text{field} & ::= e f ; \\
\text{meth} & ::= e m ( \text{form} ) \{ e \} \\
t & ::= e \text{ void binding } ::= \text{when } p \text{ do } m ; \\
\text{form} & ::= e \text{ var, where var}\{\text{this}\} \\
e & ::= \text{new } c () | \text{var } \{ e, m \} | e.f | e.f = e \text{ cast } e \text{ c} \\
& | \text{form } = e | e | e \text{ [register } e | \text{ announce } p \} ; e \\
\text{where} & ::= c, d \in C, \text{ the set of class names} \\
p & \in P, \text{ the set of event type names} \\
f & \in F, \text{ the set of field names} \\
m & \in M, \text{ the set of method names} \\
\text{var} & \in \{ \text{this} \} \cup V, V \text{ is the set of variable names}
\end{align*}
\]

Figure 3. Pañini’s abstract syntax, based on [9, 36].

Pañini features new mechanisms for declaring events and for announcing these events. These features are inspired by implicit invocation (II) languages such as Rapide [12] and concurrent languages such as Erlang [4]. The technical presentation of Pañini builds upon previous object-oriented calculi [9, 10, 18, 22, 36]. The object-oriented part of Pañini has classes, objects, inheritance, and subtyping, but it does not have super interfaces, exception handling, built-in value types, privacy modifiers, or abstract methods.

The abstract syntax is shown in Figure 3. A Pañini program consists of a sequence of declarations followed by an expression, which can be thought of as the body of a “main” method. In this syntax, the novel features are: event type declarations (event), event announcement expressions (announce), and handler registration expressions (register). Since Pañini is an implicitly concurrent language, it does not feature any construct for spawning threads or for mutually exclusive access to shared memory. Rather, concurrent execution is facilitated by announcing events, using the announce expression, which may cause handlers to run concurrently. Examples of the syntax can be seen in Figure 2. This example is described thoroughly in Section 1.3.

Top-level Declarations. The two top-level declaration forms, classes and event type declarations, may not be nested. A class has exactly one superclass and may declare several fields, methods, and bindings. An event type (event) declaration has a name (p), and zero or more context variable declarations (form*). These context declarations specify the types and names of reflective information exposed by conforming events. An example is given in Figure 2 on lines 1-3 where event GenAvailable has one context variable Generation g which denotes the generation which is now available. The intention of this event type declaration is to provide a named abstraction for a set of events that result from a generation being ready.

Like Eos [37] classes in Pañini may also contain binding declarations. A binding declaration mainly consists of two parts: an event type name and a method name. For example, in Figure 2 line 10 the class CrossOver declares a binding such that the cross method is invoked whenever an event of type GenAvailable is announced. This method may run asynchronously with other handler methods.

2.2 Pañini’s Expressions

Registration. Like II languages, a module in Pañini can express interest in events, e.g. to implement the observer design pattern [19]. Just like II languages, where one has to write an expression for registering a handler with each event in a set, and similar to Ptolemy [36], such modules are defined using a binding inside a class declaration. Examples are shown on lines 7, 23, 38 and 44 in Figure 2.

Object-oriented Expressions. The formally specified version of Pañini is an expression language, thus the syntax for expressions includes several standard OO expressions [9, 10, 36]. These OO expressions include construction of an object (new c()), variable dereference (var, including this), field dereference (e.f), null, cast (cast t e), assignment to a field (e1.f = e2), a definition block (t var = e1; e2), and sequencing (e1; e2). Their semantics and typings are fairly standard [9, 10]. In the examples, we use conditionals of the form if e == null { e } else { e } and for (e ; e ; e) { e }, which has standard desugaring.

Concurrency in Pañini. The announce expression enables concurrency in Pañini. The expression announce p (e*) ; e signals an event of type p, which may run any handler bodies that are applicable to p asynchronously, and waits
for the handlers to finish. In Figure 2 the body of the cross method contains an announce expression on line 18. On evaluation of the announce expression, Pănini first looks for any applicable handlers. Here, the handlers CrossOver, Mutation, Logger, and Fittest, are declared to handle the events of type GenAvailable. Such handlers may run concurrently, depending on whether they interfere with each other. The type system of Pănini computes the potential effects of the handlers. Pănini will update the handlers’ potential effects when they register and decide which handlers conflict between each other. Pănini then schedules the handlers to maximize concurrency while maintaining the sequential semantics. The evaluation of the announce expression then continues with evaluating the sequence on line 18, which returns from the method. The announcement of the event allows for potential concurrent execution of the bodies of the cross (lines 11–19), mutate (lines 27–35), logit (line 38), and check (lines 45–51) methods.

The announce expression also binds values to the event type declaration’s context variables. For example, when announcing event GenAvailable on line 18, gl is bound to the context variable g on line 2. This binding makes the new generation available in the context variable g, which is needed by the context declared for the event type GenAvailable.

2.3 Pănini’s Registration Algorithm

Handlers’ abstract read/write set. To detect the dependency between any two handlers, two sets, namely the read and write set, are needed. The read set is a set of tuples of fields of classes that handler may read. Similarly, the write set stores tuples about fields that could be modified. Suppose we have two handlers, h1 and h2. For a handler h2 to depend on h1, there are two conditions: 1) handler h1 must register earlier than h2 in the program expression; 2) h2’s read set must conflict with h1’s write set (read after write [21]), or h2’s write set conflicts with either the read set of h1 (write after read [21]) or the write set of h1 (write after write [21]). That is because, in the sequential semantics, h2 should view the changes by h1, while h2’s changes are invisible to h1, neither should the changes of h2 be overwritten by the changes of h1.

Notice that a subscriber o could also be a publisher for an event, say p. Then the read/write set of o could be enlarged over time, because new handlers for p may register later and the effects of these new handlers should propagate to o. Pănini does these updates automatically when new handlers register for a certain event.

Event’s Subject list. Subjects are formed into a list for an event. Thus, when a handler registers, its changes could be passed to these subscribers, and these subscribers merge the changes and recursively pass changes to other events when necessary. This continues until a fix point is reached (that is, no more effects are added to the publishers).

Handlers’ Hierarchy. Pănini groups handlers into hierarchies. In the first level, all the handlers have no dependency between any other handlers, while any handler in the second level depends on a subset of the handlers in the first level and no other handlers. Similarly, handlers in the third level may depend on handlers on the first two level, but no handlers in any other level. It is possible that the effects of one handler will become larger (mentioned in the previous paragraph) and in response to this, Pănini will reorder the hierarchy dynamically.

Event registration. When an event handler, say h, registers, we first propagate its effects to the publishers in the publishers list, then the dependencies between h and the previous registered handlers are computed based on the read / write set. After dependencies are calculated, the handler is put into a proper level of the hierarchy.

Event announcement and task scheduling algorithm. When a publisher fires an event, Pănini executes the handlers in the first level concurrently. After all the handlers in this level are done, handlers in the next level are released and run in parallel until all the handlers are finished.

The computation of the dependency and the effect propagation is done when handlers register, based on the assumption that in a program, the number of announcements considerably outweighs the number of registrations. Therefore, the overhead of effects manipulation is amortized. More details can be found in Appendix A and Appendix B.

2.4 Properties of Pănini’s Design

In this subsection, we study the key properties of Pănini’s design. We show that our language design has the following desirable properties. Well-typed Pănini programs do not get stuck and are free of races and deadlocks. The proof of this uses a standard preservation and progress argument [47] and is presented in Appendix C.

2.5 Pănini’s Runtime System and Compiler

We designed an extension of Java to have asynchronous, typed events and implemented a compiler for this extension using the JastAddJ extensible compiler system [13]. As its backend, Pănini’s runtime system uses the fork/join framework [27]. This framework uses the work stealing algorithm [7] and works well for recursive work algorithms. We observed that handlers usually also act as subjects and recursively announce events, thus Pănini was built based on this framework. When an event is announced by a publisher, all handlers that are applicable are wrapped and put into the fork/join framework and may execute concurrently. Below we describe key parts of our implementation strategy.

---

2 This is similar with Jade [39], where the implementation tries to discover concurrency. But unlike Jade, Pănini does not require programmers to provide any information.

3 The type system is discussed in Appendix A.
class MethodDecl extends ASTNode {
  /* other fields and method elided */
  FieldDecl extends Expression{
      Effect computeEffect(){
          return body.computeEffect();
      }
  }
  class Expression extends ASTNode{
      Effect computeEffect( );
  }
  class Sequence extends Expression{
      class Expression extends ASTNode{
          FieldDecl extends Expression{
              Effect computeEffect(){
                  return body.computeEffect();
              }
          }
      }
  }
}

Figure 5. Snippets of an AST with an Effects System

3. Evaluation

In union there is strength. – Aesop

This section describes evaluation of design and performance benefits of Pāñīni’s design.

3.1 Analysis of Modularity and Concurrency Synergy

Pāñīni’s design can be seen as promoting both modularity and concurrency goals for a class of requirements that are typically modularized using behavioral design patterns [19]. The goal of this section is to analyze “if a program is modularized using Pāñīni’s features does that also expose potential concurrency in its execution?”

We have already presented one such case in Section 1, where modularization of various concerns in the implementation of a genetic algorithm exposed potential concurrency between these concerns. To further assess Pāñīni’s ability to achieve a synergy between modularity and concurrency goals, we have implemented several representative examples and they worked out beautifully. In the rest of this section, we present three examples. In these examples, we use Java extended with Pāñīni, which is supported by our compiler.

3.1.1 Concurrency in Compiler Implementations

In the art of writing compilers, performance often has higher priority than modularity. Compiler designers employ all kinds of techniques to optimize their compilers. For example, merging transformation passes which perform different transformation tasks in the same traversal, is a common practice in writing multi-pass compilers. However, the implementation of this technique usually suffers the problem of code-tangling: implementations of different concerns (i.e., transformation tasks) are all mixed together.
Figure 5 illustrates this via snippets from an abstract syntax tree (AST). It shows concerns for method declarations, expressions, and two concrete expressions: a sequence expression \((e; e)\) and a field get expression \((e.f)\). As an example compiler pass, we show computation of effects for these AST nodes. The effect computation concern is scattered and tangled with the AST nodes. This is a common problem in compiler design where the abstract syntax tree hierarchy imposes a modularization based on language features whereas compiler developers may also want another modularization based on passes, e.g., type checking, error reporting, code generation, etc [13]. The visitor design pattern solves this problem to a certain extent but it has other problems [13].

```java
class MethodDecl extends ASTNode{
    MethodDecl m; HashTable h;
    MethodVisited() {
        m = md;
        h = new HashTable();
    }
    start() {
        m = md;
        h.add( m, new EffectSet() );
    }
    when FieldGetVisited do add;
    void body() {
        h.add(m, new ReadField() );
    }
}

class FieldGet extends Expression{
    FieldGet() {
        announce FieldGetVisited(this);
        body.visit();
    }
    void visit(){ } }

FieldGetVisited { FieldGet fg; }
SequenceVisited { Sequence seq; }
Expression { Expression e; }
MethodDecl { MethodDecl md; }
MethodVisited { MethodDecl md; }

when a method \(m\) is declared and \(e\) is executed, the field \(f\) is possibly read and the computed effect is stored in a hashtable. When \(e\) continues, it is possible that another method \(m\) is declared and \(e\) is executed again, so the field \(f\) could be read again. In this case, the program would store the effect again, which is not desirable. This problem can be solved by a visitor pattern or a modularization based on language features. However, this solution may be too simplistic. A more general approach is to use a modularization based on passes, e.g., type checking, error reporting, code generation, etc.

3.1.2 Modular and Concurrent Image Processing

This example is adapted from and inspired by the ImageJ image processing toolkit [23]. For simplicity, assume that this library uses a class `List` and `Hashtable` similar to the classes in the `java.util` package. We have also omitted the irrelevant initializations of these classes. The class `Image` (lines 27-33) maintains a list of pixels. The method `set` for this class (lines 29–33) sets the value of a pixel at a given location to the specified integer value.

An example requirement for such a collection could be to signal changes of elements as an event. Other components may be interested in such events, e.g., for implementing incremental functionalities which rely on analyzing the increments. One such requirement for a list of pixels is to incrementally compute the Nonparametric Histogram-Base Thresholding [1, 20]. The threshold functionality may not be useful for all applications that use the image class, thus it would be sensible to keep its implementation separate from the image class to maximize reuse of the image class. Pānini’s implementation allows the threshold computation concerns to remain independent of the image concerns, while allowing their concurrent execution.

3.1.3 Overlapping Communication with Computation via Modularization of Concerns

Our next example presents a simple application for planning a trip. Planning requires finding available flights on the departure and return dates as well as a hotel and rental car for the duration of the trip. To find each of these items the program must communicate with services provided by other providers and each computation can be run independently.
In this example the context variable tripData is used to both provide the handlers with information and to give the handlers a place to store their results. As with the above example, initialization functions are elided. The FilterCars handler is also elided. The lists are filtered with an event since filtering the lists can be done independently and concurrently. In this example as well Pānini’s design shows the potential of reconciling modularity goals with concurrency goals. When an event of type PlanTrip is announced each of the three handlers can execute concurrently.

3.2 Performance Evaluation

The goal of this section is to analyze “how well do the Pānini programs perform compared to a hand-tuned concurrent implementation of equivalent functionality?”

We first describe our experimental setup and then analyze speedup realized by Pānini’s implementation as well as the overheads.

All experiments were performed on a system with a total of 12 cores (2x6-core AMD Opteron 2431 chips) running Fedora GNU/Linux.

3.2.1 Concurrency Benchmark Selection

To avoid bias in the performance measurement, we picked already implemented concurrent solutions of five computationally intensive kernels: Euler number, FFT, Fibonacci, integrate, and merge sort. Hand-tuned implementations of these kernels were already available [27].

Each program takes an input to vary the size of the workload (Euler: number of rows, FFT: size of matrix 2^n, Fibonacci: x^th Fibonacci number, integrate: number of exponentials, and merge sort: array size 2^n). For each example program, a sequential version was tested as well as concurrent versions ranging from 1 to 14 threads. Furthermore, three concurrent versions were tested:

1. an implementation using the fork/join framework [27],
2. a Pānini version with no conflict between handlers, and
3. a second Pānini’s implementation that was intentionally designed to have conflicts between handlers.

For example, calculating a Fibonacci number, fib(n), is done by recursively calculating two subproblems, fib(n−1) and fib(n−2). With the fork/join framework, each of these subproblems is done by a separate thread. When both of these threads are completed, the spawning thread adds them together. For Pānini, each of these subproblems is handled in separate handlers. In the case with no conflicts, these are the only two handlers. In the case with conflicts, a third handler takes the result of the two handlers for the subproblems and
adds them together. In all cases, when the problem size is small enough, computation continues sequentially.

### 3.2.2 Speedup over Sequential Implementation

We now analyze the speedup of parallel programs achieved by the Pānini’s implementation as compared to the standard fork/join model [27].

Figure 9 shows a summary comparison of speedup between the three versions. In this figure, the average speedup across all five benchmarks was taken. For each program, large input sets were used (Euler: 39, FFT: 24, Fibonacci: 55, integrate: 7, and merge sort: 25). The line in the figure represents optimal speedup.

This figure shows that the speedups between the three styles are comparable. Speedups for fork/join and Pānini without conflicts are nearly the same. A statistical analysis shows that for all benchmarks, we do not see a statistically significant difference ($p < 0.05$) between fork/join and Pānini with no conflicts.

From the figure, we can also see that Pānini with conflicts has slightly lower speedup than both fork/join and Pānini with conflicts, however, this decrease is rather small (average 6.5% decrease from fork/join). We found a statistically significant difference ($p < 0.05$) between fork/join and Pānini with conflicts. Note that since we are using a machine with 12 cores, performance levels off at 12 threads.

### 3.2.3 Overhead over the Sequential Implementation

We also measured the overhead involved with Pānini as compared to the standard fork/join model.

We first consider the average overhead across all benchmarks as shown in Figure 10. Overhead is calculated by determining the increase in runtime from the sequential version to the concurrent version with a single thread. For this figure, we use large input sizes.

This figure shows us that while Pānini increases the overhead over fork/join, it is not a prohibitive amount. For example, from fork/join to Pānini with no conflicts, we only see a 7.7% increase in overhead. Similarly, adding conflicts to Pānini only incurs an additional 6.1% overhead.

Figure 11 shows a summary comparison of overhead as program input size changes. In this figure, the overhead for the Fibonacci program is shown with a variety of input sizes. Again, overhead is calculated by determining the increase in runtime from the sequential version to the concurrent version with a single thread.

This figure shows that as input size increases, overhead decreases. In this case, overhead decreases to as low as 5.5% additional overhead for Pānini with no conflicts. Pānini with conflicts only incurs an additional 1.2% overhead for larger input sizes. Each of the differences in overhead (fork/join vs Pānini without conflicts, fork/join vs Pānini with conflicts, and Pānini with vs Pānini without conflicts) was statistically significant ($p < 0.05$) across all benchmarks.

### 3.3 Summary of Results

In summary, Pānini shows speedups which scale as well as the standard fork/join model. Even though Pānini has a higher overhead than fork/join, Pānini performs nearly as well as the fork/join model in terms of speedup for nearly all cases. This is all achieved without requiring explicit con-
currency and while encouraging good modular design and ensuring that programs are free of deadlocks and have sequential semantics.

4. Related Work

conciliate, mediate, harmonize, settle, accommodate, reunite – entry for "reconcile" in Roget's II

Like Jade [39], Pāṇini is an implicit concurrency language. Programmers in Jade supply information about the effect of tasks so that the implementation may discover concurrency. Pāṇini is different in that it relies on its type system to maximize its effects and removes the burden on the programmer to supply these effects by hand. Pāṇini also removes any errors which could be introduced by incorrect specification of effects. This is different from Grace [6] which is an explicit threading language. Grace executes threads speculatively. If a conflict is detected, it rolls back the changes. If no races are detected it commits the changes. Pāṇini detects conflict when handlers register.

Like X10 [8], Pāṇini does not feature any construct for explicit locking. However, X10 is an explicit concurrency language and it uses atomic blocks for lock-free synchronization and uses the concept clocks as synchronization between activities. The Task Parallel Library (TPL) [28], wraps computation into tasks and uses thread stealing as the underlying implementation. This is similar to Pāṇini’s runtime, but programmers in TPL have to explicitly account for races, whereas Pāṇini's effect system automatically avoids all races.

Events have a long history in both the software design [11, 17, 29, 31, 44] and distributed systems communities [16, 24, 32]. Pāṇini’s notion of asynchronous, typed events build on these notions, in particular recent work in programming languages focusing on event-driven design [14, 15, 36]. In software design, events and implicit-invocation have been seen as a decoupling mechanism for modules [31, 44], whereas in distributed systems, events are seen as a mechanism of decoupling component execution for location transparent deployment and extensibility [32]. New to Pāṇini’s design and its philosophy is the unification of design and execution decoupling.

Pāṇini’s design is also not the first to promote implicit concurrency. For example, in POOL [3], ABCL [48], Concurrent Smalltalk [49] and BETA [43], objects implicitly execute in the context of a local process. This is different from Pāṇini where only handler instances are run implicitly and concurrently. This allows smoother integration with mainstream programming languages such as Java. This also permits an easier integration of our event-based model with the thread-based explicit concurrency models as promoted by Li and Zdancewic [29]. In this work, we do not discuss the semantic issues with this integration, however.

Other recent work such as TaskJava [17] in the programming language design setting and Tame [24] and Tasks [11], in the distributed systems setting, have promoted similar integration with existing languages. Fischer et al. in their work on TaskJava [17] introduce task, similar to a handler in Pāṇini. An asynchronous method is marked with the keyword async, indicating that it could block and should be compiled into continuation-passing style. This method may use a primitive wait to express its interests in a set of events and this expression will block until one of them fires. Krohn et al. have promoted similar ideas in Tame [24] where they use a primitive twait to block on events. In both these approaches, running of the concurrent task is explicitly managed by the programmer. In Pāṇini, however, handlers are implicitly spawned and managed by the language runtime. As a result, programmers are relieved of reasoning about locking and data race problems. Such software engineering properties are becoming very important with the increasing presence of concurrent software, increasing interleaving of threads in concurrent software, and increasing number of under-prepared software developers writing code using concurrency unsafe features.

Figure 11. Average overhead for Fibonacci benchmark for varying input size and each scheduling strategy.
Unlike Multilisp [40], which has the future construct, Pānini uses different expressions as synchronization points. Moreover, unlike Java’s current adoption of Futures, which is unsafe [46], heap access expressions in Pānini are sound. Furthermore, unlike previous work [35, 46], our implementation doesn’t require modifications to the virtual machine.

5. Conclusion and Future Work

Faith is taking the first step even when you don’t see the whole staircase. – Martin Luther King Jr.

Language features that promote concurrency in program design have become important [2, 5]. Explicit concurrency features such as threads are hard to reason about and building correct software systems in their presence is difficult [33, 42]. There have been several proposals for concurrent language features, but none unifies program design for modularity with program design for concurrency. In the design of Pānini, we pursue this goal. In an effort to do so, we have developed the notion of events that are especially helpful for programs where modules are decoupled using implicit-invocation design style [12, 31, 32, 44]. Event announcements provide implicit concurrency in program designs when events are signaled and consumed. We have tried out several examples, where Pānini improves both program design and potential available concurrency.

For future work, we would like to apply Pānini’s design to large projects and to evaluate whether the reconciliation of modularity and concurrency goals that we saw in our examples is scalable to larger software projects.

Acknowledgments

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A. Pāṇini’s Type and Effect System

Type checking uses the attributes defined in Figure 12. Compared to Ptolemy [36] new to Pāṇini is its effect system. For example, the type attributes for expressions are represented as $(t, \rho)$, the type of the expression $(t)$ and its effect set $(\rho)$.

$$\theta ::= \text{OK}$$

$$\theta ::= \{ t_1 \times \ldots \times t_n \rightarrow t, \rho \} \text{ in } \mathfrak{c}$$

$$\theta ::= \{ \}$$

$$\rho ::= \epsilon$$

$$\rho ::= e + \rho \; | \; \ast$$

$$\epsilon ::= \text{read } c \; f$$

$$\epsilon ::= \text{write } c \; f$$

$$\epsilon ::= \text{reg } c$$

$$\epsilon ::= \text{create } c$$

$$\pi, \Pi ::= \{ t : \theta_i \}_{i \in K}, \text{ where } K \text{ is finite, } K \subseteq (\mathcal{C} \cup \{ \text{this} \} \cup \mathcal{V})$$

\(\text{“type environments”}\)

![Figure 12. Type and Effect Attributes.](image)

The effects are used to compute the potential conflicts between handlers. These effects include: 1) read effect: a class and a field to be read; 2) write effect, content is similar to read effect; 3) announce effect: what event a certain expression may announce; 4) register effect and 5) new object. The interference between the effects is shown in Figure 13.

<table>
<thead>
<tr>
<th>Effects</th>
<th>read</th>
<th>write</th>
<th>ann</th>
<th>reg</th>
<th>create</th>
</tr>
</thead>
<tbody>
<tr>
<td>read</td>
<td>√</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>write</td>
<td>√</td>
<td>√</td>
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<td></td>
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</tr>
<tr>
<td>ann</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>reg</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>create</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 13. Effect Interference. √: conflicts, ×: no conflicts](image)

Read effects will not interfere with each other. Write effects will conflict if either another read or write effect accesses the same field of the same object. Announce effects will interfere with register effects, because the order of registration affects the set of handlers running during announcement. Announce effect is also used later in the semantics because handlers could also act as publishers (refer to as handler/pub-

2. otherwise, assume that a newly created object ($o_n$) escapes the handler ($h_1$) and is referenced by another handler ($h_2$), then the program will have to change a field of another object (referred to as $o_n$) to point to $o_n$ to make it escape. On the other hand, $h_2$ will have to read the field of $o_n$, which will be detected by Pāṇini and reported as an interference (because $h_1$ changes the field of $o_n$ and $h_2$ reads the field of $o_n$). That is to say, it will not be the newly created object that causes data races.

Thanks to this observation, Pāṇini could safely remove the read/write effect of any newly created object and thus reduce false interferences to a considerable extent.

The type checking rules are shown in Figures 14 and 16. The notation $\nu' < \nu$ means $\nu'$ is a subtype of $\nu$. It is the reflexive-transitive closure of the declared subclass relationships [36]. We state the type checking rules using a fixed class table (list of declarations $CT$) as in Clifton’s work [9,10]. The class table can be thought of as an implicit inherited attribute used by the rules and auxiliary functions. We require that top-level names in the program are distinct and that the inheritance relation on classes is acyclic. The typing rules for expressions use a simple type environment, $\Pi$, which is a finite partial mapping from locations $loc$ or variable names $var$ to a type.

![Figure 14. Type and Effect Attributes](image)

The (T-PROGRAM) rule says that the entire program type checks if all the declarations type check and the expression $e$ has any type $t$ and any effect $\rho$.

The (T-EVENT) rule says that an event declaration type checks, if all the types of all the fields are declared properly. The auxiliary function $istype$ (shown in Figure 17), looks at the class table to check if a type has been defined or not.
Valid method overriding:

\[
\begin{align*}
CT(c) &= \text{class } c \text{ extends } d \{ \text{field}\^* \text{meth}_1 \ldots \text{meth}_p \text{ bind}_1 \ldots \text{bind}_q \} \\
\forall i \in \{1 \ldots p\} \text{. meth}_i &= t \text{m} \{t_1 \text{var}_1, \ldots, t_n \text{var}_n\} (e) \\
\text{override}(m, c, t_1 \times \ldots \times t_n \to t, \rho) \\
\text{methodType}(d, m) &= (t_1 \times \ldots \times t_n \to t', \rho') \quad \rho \subseteq \rho' \\
\text{override}(m, d, t_1 \times \ldots \times t_n \to t, \rho) \\
\end{align*}
\]

Figure 15. Auxiliary functions used in type rules [9, 10].

(T-NEW)

\[
\Pi \vdash \text{new } c() : (c, \{ \text{create } c \})
\]

(T-GET)

\[
\Pi \vdash e : (c, \rho) \quad \rho \neq \{ \text{create } c \} \\
\text{fieldsOf}(c)(f) = t \\
\Pi \vdash e, f : (t, \rho \cup \{ \text{read } e \})
\]

(T-SEQUENCE)

\[
\Pi \vdash e_1 : (t_1, \rho) \\
\Pi \vdash e_2 : (t_2, \rho') \\
\Pi \vdash e_1, e_2 : (t_2, \rho \cup \rho') \\
\Pi \vdash e_1, e_2 : (t_2, \rho \cup \rho') \\
\Pi \vdash e : (t, \rho \cup \rho')
\]

(T-ANNOUNCE)

\[
\begin{align*}
CT(p) &= \text{event } p \{ t_1 \text{var}_1 \ldots t_n \text{var}_n \} \\
\forall i \in \{1 \ldots n\} \quad \Pi \vdash e_i : (u_i, \rho_i) \quad \land u_i < t_i \\
\Pi \vdash \text{ann } p : (t, \rho) \cup \bigcup_{i=1}^{n} \rho_i \cup \rho
\end{align*}
\]

(T-CALL)

\[
\begin{align*}
(c_1, m \{t_1 \text{var}_1 \ldots t_n \text{var}_n\}, \text{exec}_{c+1}(p, m) &= \text{findMethod}(c_0, m) \\
\Pi \vdash e_0 : (c_0, \rho_0) \\
\forall i \in \{1 \ldots n\} \quad \Pi \vdash e_i : (u_i, \rho_i) \quad \land u_i < t_i \\
\Pi \vdash m_0, e_1, \ldots, e_n : (t, \rho \cup \bigcup_{i=1}^{n} \rho_i \cup \rho_0)
\end{align*}
\]

Figure 16. Type and Effect rules for expressions [9, 10, 36].

The (T-CLASS) rule says that a class declaration type checks if all the following constraints are satisfied. First, all the newly declared fields are not fields of its super class (this is checked by the omitted auxiliary function validF). Next, its super class d is defined in the Class Table. Finally, all the declared methods and bindings type check.

The (T-METHOD) rule says that a method declaration type checks if all the following constraints are satisfied. First, the return type is a class type. Next, if all the parameters have their corresponding declared types, the body of the method has type u and effect ρ. Also u is a subtype of t. This rule also uses an auxiliary function override, defined in Figure 15. In addition to standard conditions, this function enforces that the effect of an overriding method is the subset of the effect of overridden method.

The (T-BINDING) rule says that a binding declaration type checks, if the named method is properly defined; all the context variables are subtypes of their corresponding declared type in the method; and the annotated event type is declared.

The type rules for the expressions are shown in Figure 16. Most rules for typing expressions are straightforward.

The (T-NEW) rule says that a new expression has the type of the class being declared if the class c has been properly declared and has a single effect create to denote that this is a newly created object as mentioned previously to reduce false interferences.

The (T-CAST) rule says that for a cast expression, the cast type must be a class type, and its effect is the same as the expression’s.

The (T-GET) rule says that a field access expression returns the type of the field of the class, the effects of it will be the effect of the object expression plus a read effect.

The (T-GET-LOCAL) rule is similar to the previous rule, except that Paṇini knows that the object expression is pointing to a newly created object and thus the read effect is redundant and deleted.

The (T-SEQUENCE) rule states that the sequence expression has same type as the last expression and its effects are the union of the two expressions.

The (T-YIELD) rule says that a yield expression has the same type and same effect as the expression e.

The (T-VAR) rule checks that var is in the environment.

The (T-DEFINE) rule for declaration expressions is similar to the sequence expression except that the initial expression should be a subtype of the type of the new variable. Also, the type of the variable is placed in the environment. Finally, the sequence expression type checks properly.

The (T-NULL) rule says that the null expression will type check and has no effect.

The (T-REGISTER) rule says that a register expression has the same type as the object expression and the effects will be the effects of the object expression plus one register effect.

The (T-SET) rule says that a field assignment expression type checks if the object expression is of a class type and the type of the assignment expression e2 is a subtype of the type of the field of the class. The effects will be the union of

In practice, we enlarge the effect set of the method in the super class such that the effect of the overriding method is a subset of its super class.
the effects of its two subexpressions plus one write effect since this expression is to modify a field of an object.

The (T-SET-LOCAL) rule is similar to (T-SET) except that the type system can detect that it is changing a field of a new object thus the single write is not needed.

The (T-ANNOUNCE) rule says that an announcement expression type checks if the event was declared and the actual parameters are a subtype of the declared fields type in the event declaration. The entire expression has the type of the subsequent expression. The effects of the announce expression will be the union of all the parameters’ effects and the subsequent expression plus an announcement effect.

The (T-CALL) is similar to the announce expression. This rule says that for a method call expression it finds the method in the CT using the auxiliary function findMeth (not shown here) and this method is declared either in its own class or its super class. Each actual argument expression is of subtype of corresponding parameter type. This method call expression has the same type as the return type of the method.

Valid method overriding:

\[
\text{isType}(t) = (t \in \text{dom}(CT) \land CT(t) = \text{class } l \ldots)
\]

\[
\text{fieldsOf}(e) = \{t\} \cup \text{fieldsOf}(e')
\]

\[
\text{where } CT(t) = \text{class } \text{extends } c'(\{f_1 f_2 \ldots f_n \ldots\})
\]

\[
\text{validF}(\text{F}, c) = \forall i \in \{1 \ldots n\} : \text{isType}(t_i) \land f_i \in \text{dom}(\text{fieldsOf}(e))
\]

**Figure 17.** Auxiliary functions used in type rules [?].

### B. Pāṇini’s Operational Semantics

Here we give a small-step operational semantics for Pāṇini.

**Added Syntax:**

\[
e ::= \text{loc} | \text{yield } e | \text{NullPointerException} | \text{ClassCastException}
\]

where \(\text{loc} \in L\), a set of locations

**Evaluation relation:**

\[
\Sigma \rightsquigarrow \Sigma
\]

**Domains:**

\[
\Sigma ::= \langle \psi, \mu, \gamma \rangle
\]

"Program Configurations"

\[
\psi ::= \theta \cdot \psi
\]

"Task Configurations"

\[
\tau ::= \{\text{loc} \mapsto \text{loc} \} k \in K
\]

"Task Local Data"

\[
\mu ::= \{\text{loc} \mapsto \text{loc} \} + \mu
\]

"Stores"

\[
v ::= \text{null} | \text{loc}
\]

"Values"

\[
o ::= \{c, F\}
\]

"Object Records"

\[
F ::= \{f_k \mapsto v_k\} k \in K
\]

"Field Maps"

where \(K\) is finite

\[
\gamma ::= \text{loc} + \gamma
\]

"Subscriber List"

**Evaluation contexts:**

\[
E ::= - | E \cdot m(e \ldots) | v.m(v \ldots E e \ldots) | \text{cast } t E | E.f | E.f e | v.f = E | t \text{ var} = E | e | E | e | E\text{.register()}
\]

**Figure 18.** Added syntax, domains, and evaluation contexts used in the semantics, based on [9, 36].
namic dispatch, which starts from the dynamic class (c) of the record, and may look up the super class of the object if needed. The method body is to be evaluated with the arguments replaced by the actual values as well as the this variable by loc. It then yields control by calling (yield) to model concurrency, which will be discussed later.

The (Sequence) rule says that the current task may yield control after the evaluation of the first expression. The (Cast) rule is used only when the loc is a valid record in the store and when the type of object record pointed to by loc is subtype of the cast type. The (Define) rule allows for local definitions. It binds the variable given to the value and evaluates the subsequent expressions with the new binding.

The (Get) or get field read rule gets an object record from the store and retrieves the corresponding field value as the result. The semantics for (Set) uses ⊕ as an overriding operator for finite functions. That is, if µ′ = µ ⊕ (loc → v), then µ′(loc′) = v if loc′ = loc and otherwise µ′(loc′) = µ(loc′). The operation first fetches the object from the store and overrides the field.

Semantics for Yielding Control. In Pānini’s semantics, like Abadi and Plotkin [2], the running task may implicitly relinquish control to other tasks. The rules for yielding control are given in Figure 20.

The (Yield) rule says to put the current task configuration in the end of the task-queue and to start evaluating the next active task configuration from the current task queue. Finding an active task is done by the auxiliary function active (not shown). It searches the items (task configuration) from the head of the queue until it finds the first item that could be run and returns it. A task configuration is ready to run if the tasks in its dependence set are done.

The (Yield-Done) rule is applied when there are no other task configurations in the queue. Since there are no other tasks in the queue, it continues to evaluate the current task configuration. The (Yield-End) rule says that the current running task is done (it evaluates to a single value v), thus this task configuration is removed from the queue and next active task will be scheduled.

Semantics for Event registration. We now describe the semantics for subscribing to an event (Figure 21).

Figure 20. Semantics of yielding control in Pānini
spawn(p, ψ, γ, p, μ) = buildconf(s, H, ψ, ω, •, γ, μ)
where H = hfind(γ, p, μ) and CT is the program’s list of declarations

hfind(•, •, p, μ) = •

hfind(loc + γ, •, p, μ) = hfind(γ, p, μ)
where p(loc) = [c.F] and hmatch(c, p, CT) = •

hfind(loc + γ, •, p, μ) = concat(hfind(γ, p, μ), (loc, m))

where p(loc) = [c.F] and hmatch(c, p, CT) = m
and CT is the program’s list of declarations

hmatch(c, p, •) = •

hmatch(c, p, (event p (…)) + CT') = hmatch(c, p, CT')
hmatch(c, p, (class e (…)) + CT') = hmatch(c, p, CT') where e ≠ e'
hmatch(c, p, (class extends d (…)) + binding1, … + bindingn) + CT' =
= exc(match(binding1 +…+ bindingn, p), hmatch(d, p, CT'))
where exc(•, H) = id and exc(e, H) = e

match(•, p) = •

match((when p' do m) + B, p) = match(H, p) where p' ≠ p

match((when p' do m) + B, p) = m

car(•) = 0
car((loc, m) + H) = 1 + car(H)

max(•, id) = id

max('e', 'id', I')) + ψ, id) = max('e', id) where id' < id

max('e', 'id', I')) + ψ, id) = max('e', id') where id' > id

getE(•, γ, μ) = •

getE((loc, m) + H, γ, μ) = concat(update(ρ, γ, μ), getE(H, γ, μ))
where loc = [c.F] and (e, t, m, …, (p, ψ, ν, H, c, p, CT) = findMeth(c, m)

diff(•, p) = true
diff(e + ρ', p) = diff(e', p) where true = differ(e, p)
diff(e + ρ', p) = false where false = differ(e, p)

differ(e, •) = true
differ(e, e + ρ) = differ(e, p) where ϵ and c' have no conflict
differ(e, e' + ρ) = false where ϵ and c' have conflicts

Figure 24. Miscellaneous helper functions.

effect sets with the effect set of this task. Pāñini does this to get more accurate information about the potential effect sets of a task to reduce false conflicts. The functions differ and differ are used to actually compared the effects. The table in Figure 13 is used to compare effects. A read effect will conflict with a write effect if they access the same field of the same class or a subclass of another class. A read effect also conflicts with the register effect. A write effect will conflict with another write effect similar to the read effect discussed above. An announce effect conflicts with only register effects and register effects will conflict with any effect except for the create effect.

C. Properties of Pāñini’s Design

Definition C.1. [Blocked Configurations.] An expression e and its task local τ = ⟨τ, {nk}⟩ in a configuration ⟨⟨e, τ⟩, ψ, μ, γ⟩ may block if any one of its predecessors is still in execution.

Theorem C.2. [Liveness.] Let ⟨⟨e, τ⟩, ψ, μ, γ⟩ be an arbitrary program configuration, where e is a well-typed expression τ is a task local, μ is the store, ψ is a task queue and γ is a handler queue. Then either e is not blocked or there is some task configuration in ψ that is not blocked.

Figure 23. Functions for building handler configurations.

for each handler task, and configures the dependent set of this handler (discussed in 2.3). These task configurations are used to run the handler bodies and they are appended to the end of the queue ψ. The auxiliary function max is used to give the newly-born task a global unique ID.

The auxiliary function pre is used to find all the tasks that this task depends on. It first calls another auxiliary function update to update the effects of the task. The function update is used because the handler may signal events, say e, thus this function searches the handler queue γ to union their
C.1 Proof of Type Soundness

A standard preservation and progress argument [47] is used to prove the soundness of Panini’s type system. The details are adapted from previous work [9, 10, 18]. Throughout this section we assume a fixed, well-typed program with a fixed class table, CT. A type environment \( \Pi \) maps variables and store locations to types and effect sets. The effect set was used in the semantics to compute the dependency between handlers and will not be used in the following section. For simplicity, we omit \( \rho \) in subsequent discussion. The key definition of consistency is as follows.

Definition C.3. [Environment-Store Consistency] Suppose we have a type environment \( \Pi \) and \( \mu \) a store. Then \( \Pi \) is consistent with \( \mu \), written \( \Pi \approx \mu \), if and only if all the followings hold:

1. \( \forall \text{loc} \cdot \mu(\text{loc}) = [t,F] \Rightarrow \)
   (a) \( \Pi(\text{loc}) = t \) and
   (b) \( \text{dom}(F) = \text{dom}(\text{fieldsOf}(t)) \) and
   (c) \( \text{rng}(F) \subseteq \text{dom}(\mu) \cup \{\text{null}\} \) and
   (d) \( \forall f \in \text{dom}(F) \cdot F(f) = \text{loc}', \text{fieldOf}(t)(f) = u \) and \( \mu(\text{loc}') = [t',F'] \Rightarrow t' < u \).
2. \( \forall \text{loc} \cdot \text{loc} \in \text{dom}(\Pi) \Rightarrow \text{loc} \in \text{dom}(\mu) \).

Lemma C.4. [Substitution.] If \( \Pi, \text{var}_1 : t_1, \ldots, \text{var}_n : t_n \vdash e : t \) and \( \forall i \in \{1..n\} \cdot \Pi \vdash e_i : s_i \) where \( s_i < t_i \) then \( \Pi \vdash [\text{var}_1/e_1, \ldots, \text{var}_n/e_n] e : s \) for some \( s < t \).

Proof Sketch: Let \( \Pi' = \Pi, \text{var}_1 : t_1, \ldots, \text{var}_n : t_n \) and \( [\text{var}'/e'] = [\text{var}_1/e_1, \ldots, \text{var}_n/e_n] \). The proof proceeds by structural induction on the derivation of \( \Pi \vdash e : t \) and by cases based on the last step in that derivation. The base cases are (T-NEW) and (T-NULL)(T-VAR), which have no variables and \( s = t \). Other cases can be proved by adaptations of MiniMAO₀ [9]. The induction hypothesis is that the lemma holds for all sub-derivations of the derivation. The cases for (T-CAST), (T-SEQUENCE), (T-SET), (T-SET-LOCAL), (T-CALL), (T-GET) and (T-GET-LOCAL) are similar to Clifton’s proofs. We now consider the case for (T-REGISTER), (T-ANNOUNCE) and (T-YIELD).

For \( \text{announce} p (e_1, \ldots, e_n); e_{n+1} \), we do the same substitution for each argument \( e_i, 1 \leq i \leq n \). By IH each of these has a subtype of the argument. Also, by IH, the substitution of \( e_{n+1}, [\text{var}'/e']e_{n+1} \) has the subtype of \( e_{n+1} \). Therefore, since the whole expression has the same type, \( e_{n+1} \), consistency holds.

The cases for \( \text{yield} e \) and \( \text{register}(e) \) are straightforward, because the type of \( \text{yield} e \) and \( \text{register}(e) \) is the same as \( e \).

We now state standard lemmas for environment contraction, replacement and replacement with subtyping. These lemmas can be proved by adaptations of Clifton’s proofs for MiniMAO₀ [9]. We omit these here.

Lemma C.5. [Environment Extension.] If \( \Pi \vdash e : t \) and \( a \notin \text{dom}(\Pi) \), then \( \Pi, a : t' \vdash e : t \).

Lemma C.6. [Environment Contraction.] If \( \Pi, a : t' \vdash e : t \) and \( a \) is not free in \( e \), then \( \Pi \vdash e : t \).

Lemma C.7. [Replacement.] If \( \Pi \vdash e[c] : t \), \( \Pi \vdash e : t' \), and \( \Pi \vdash e' : t' \), then \( \Pi \vdash e'[c] : t \).

Lemma C.8. [Replacement with Subtyping.] If \( \Pi \vdash e[c] : t \), \( \Pi \vdash e : u \), and \( \Pi \vdash e' : u' \) where \( u' < u \), then \( \Pi \vdash e'[c] : t' \) where \( t' < t \).

Theorem C.9. [Progress.] For a well-typed expression \( e \), a task local \( \tau \), a task queue \( \psi \), a store \( \mu \), and a handler queue \( \gamma \). If \( \Pi \vdash e : t \) and \( \Pi \approx \mu \), then either

- \( e = \text{loc} \) or
- \( e = \text{null} \) or \( e = \text{NullPointerException} \) or \( e = \text{ClassCastException} \) or
- \( \langle \langle e, \tau \rangle, \psi, \mu, \gamma \rangle \rightarrow \langle \langle e', \tau' \rangle, \psi', \mu', \gamma' \rangle \).

Proof Sketch:

(a) If \( e = \text{loc} \) or \( e = \text{null} \), it is trivial.
(b) Cases \( e = \text{NullPointerException} \) or \( e = \text{ClassCastException} \) result from the semantics rules null.f.null.f = v, null.m(v1, ..., vn), register(null) and cast e (we omitted these rules where standard exceptions happen). These values serve as the base cases.
(c) In the case where the expression \( e \) is not a value, evaluation rules are considered case by case for the proof. We proceed with the induction of derivation of expression \( e \). Induction hypothesis (IH) assumes that all sub-terms of \( e \) progress and are well-typed.

Cases \( e = \text{E}[\text{new} c[]] \), \( e = \text{E}[\text{loc}.m(v_1, ..., v_n)] \), \( e = \text{E}[\text{loc}.f] \), \( e = \text{E}[\text{loc}.f = v] \), \( e = \text{E}[\text{cast} t \text{ loc}] \), \( e = \text{E}[t \text{ var} = v; e] \) and \( e = \text{E}[v; e_1] \) are similar to Clifton’s work [9, 10] and are omitted.

Case \( e = \text{E}[\text{register} e] \). Based on the IH, \( e \) is well typed. Thus, it evolves by (MULTI-REGISTER) or (REGISTER).

Case \( e = \text{E}[\text{announce} p (v_1, ..., v_n); \{e\}] \). Based on the IH, \( p \) is well typed and is defined. Each parameter is well typed and is a subtype of the type of the field in event \( p \). Thus, it evolves by (ANNOUNCE).

Case \( e = \text{E}[\text{yield} e] \). This case has no constraint and evolves based on different rules.

Theorem C.10. [Subject-reduction.] Let \( e \) be an expression and \( e \neq \text{yield} e_1 \) for any \( e_1, \tau \) task local, \( \psi \) a task queue, \( \mu \) a store, and \( \gamma \) a handler queue. Let \( \Pi \approx \mu \) be a type environment and \( t \) a type. If \( \Pi \vdash e : t \) and \( \langle \langle e, \tau \rangle, \psi, \mu, \gamma \rangle \rightarrow \langle \langle e', \tau' \rangle, \psi', \mu', \gamma' \rangle \), then there is some \( \Pi' \approx \mu' \) and \( t' \) such that \( \Pi' \vdash e' : t' \) and \( t' < t \).

Proof Sketch: The proof is by cases on the definition of \( \rightarrow \) separately. The cases for object oriented parts (rules (NEW), (NULL), (CAST), (GET), (SET), (VAR) and (CALL)) can be proved by adaptations of Clifton’s proofs for MiniMAO₀ [9, Section 3.1.3].
The rule for (SEQUENCE) is similar to Clifton’s work, except that \( e' = E[yield e] \) instead of \( e' = E[e] \). Since the type of \( yield \ e \) has the same type as \( e \), this case holds.

For (DEFINE), \( e = E[t \ var = v ; e_1] \) and \( e' = E[\var[v]e_1] \):

let \( \tau' = \tau, \ \mu' = \mu, \ \psi' = \psi, \ \gamma' = \gamma \) and \( \Pi' = \Pi \). We now show that \( \Pi \vdash e' : t' \) for some \( t' <: t \). \( \Pi \vdash e : t \) implies that \( t \ var = v ; e_1 \) and all its subterms are well typed in \( \Pi \). Let \( \Pi \vdash (t \ var = v ; e_1) : u \). By (T-Define), \( \Pi, \var : t \vdash e_1 : u' \). By Lemma C.4, \( \Pi \vdash [\var[v]e_1] : u'' \) for some \( u'' <: u' <: u \). Therefore, by lemma C.8, \( \Pi \vdash e' : t' \) for some \( t' <: t \).

The (IF-TRUE) and (IF-FALSE) rules hold because the stack and the store do not change. Also the type of the entire expression is the same as both the \( if \) expression and the \( else \) expression.

For the (MULTI-REGISTER) rule, \( e = E[\operatorname{register}(v)] \) and \( e' = E[v] \). Let \( \tau' = \tau, \ \mu' = \mu, \ \psi' = \psi, \ \gamma' = \gamma \) and \( \Pi' = \Pi \). Obviously, \( t' = t \).

For the (REGISTER) rule, \( e = E[\operatorname{register}(v)] \) and \( e' = E[v] \). Let \( \tau' = \tau, \ \mu' = \mu, \ \psi' = \psi, \ \gamma' = v + \gamma \) and \( \Pi' = \Pi \). Clearly, \( t' = t \).

For the (ANNOUNCE) rule, \( e' = E[e_2] \) and \( e = E[\text{announce } p (v_1, \ldots, v_n) ; e_2] \). Let \( \mu' = \mu, \ \gamma' = \gamma, \ \Pi' = \Pi \) and \( t' = t \). Thus \( \Pi \vdash e_2 : t \), has the same type as \( \Pi \vdash yield e_2 : t \).

**Definition C.11.** [Thread-interleaving.] If

\[
\langle \langle E[yield e], \tau \rangle + \psi, \mu, \gamma \rangle \rightarrow \langle \langle E[e_1], \tau_1 \rangle + \psi_1, \mu_1, \gamma_1 \rangle
\]

\[
\vdots
\]

\[
\rightarrow \langle \langle E_n[e_n], \tau_n \rangle + \psi_n, \mu_n, \gamma_n \rangle \rightarrow \langle \langle E[e], \tau \rangle + \psi', \mu', \gamma' \rangle
\]

or

\[
\langle \langle E[yield e], \tau \rangle + \psi, \mu, \gamma \rangle \rightarrow^* \langle \langle E[e], \tau \rangle + \psi', \mu', \gamma' \rangle,
\]

we denote this as \( \langle \langle E[yield e], \tau \rangle + \psi, \mu, \gamma \rangle \rightarrow^* \langle \langle e', \tau' \rangle + \psi', \mu', \gamma' \rangle \), where \( \forall i \in \{1 \leq i \leq n\} E_i[e_i] \neq E[e] \).

**Theorem C.12.** [Subject-reduction-Thread-interleaving] For an expression \( e = E[yield e_1] \) for any \( e_1 \), \( \tau \) task local, and \( \psi \) a task queue, \( \mu \) a store and \( \gamma \) a handler queue. Let \( \Pi \approx \mu \) be a type environment and \( t \) a type. If \( \Pi \vdash e : t \) and \( \langle \langle e, \tau \rangle + \psi, \mu, \gamma \rangle \rightarrow^* \langle \langle e', \tau' \rangle + \psi', \mu', \gamma' \rangle \), then \( \Pi \approx \mu' \) and \( \Pi \vdash e' : t' \) and \( t' <: t \).

**Proof Sketch:** The proof is based on the observation that Pāṇini does not have data race and thus, 1 of Definition C.3 holds. Since the store \( \mu \) does not shrink, 2 of Definition C.3 holds. Clearly, \( yield e_1 \) and \( e_1 \) have the same type in \( \Pi \), and therefore, by Lemma C.7, if \( \Pi \vdash e : t \), then \( \Pi \vdash e' : t' \).

**Theorem C.13.** [Soundness.] Given a program

\( P = \text{decl} \ldots \text{decl} \ n \ e \), if \( \vdash P : (t, \rho) \) for some \( t \) and \( \rho \), then either the evaluation of \( e \) diverges or else \( \langle \langle e, (0, 0) \rangle \rangle \rightarrow^* \langle \langle e', \tau' \rangle + \psi', \mu', \gamma' \rangle \) where one of the following holds for \( v \):

- \( e = \text{null} \)
- \( e = \text{NullPointerException} \)
- \( e = \text{ClassCastException} \).

**Proof Sketch:** If \( e \) diverges, then this case is trivial. Otherwise if \( e \) converges, then because the empty environment is consistent with the empty store. This case is proved by Theorem C.9, Theorem C.10 and Theorem C.12. ■