The P# Tutorial

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1. Introduction

P# is an actor-based programming language for develoPing highly-reliable event-driven asynchronous .NET applications. The computational model underlying a P# program is *communicating state-machines* (similar concept to actors). P# machines communicate by sending and receiving *events*, an approach commonly used in building embedded, networked, and distributed systems. P# is an extension of the C# language: it provides new language primitives for creating machines and sending events from a machine to another. Because P# is built on top of C#, the programmer can blend P# and C# code: this not only lowers the overhead of learning a new language, but also allows P# to easily integrate with existing .NET projects.

In P#, machines are first class citizens of the language (similar to how classes are first class citizens in C#). Each machine has an input queue, states, transitions, event handlers, fields and methods. Machines run concurrently with each other, each executing an event handling loop that dequeues an event from the input queue and handles it by executing a sequence of operations. Each operation might update a field, create a new machine, or send an event to another machine. In P#, a send operation is non-blocking; the message is simply enqueued into the input queue of the target machine.

In the rest of this tutorial, we will introduce the features of P# through a series of examples. We will first present a simple program (Section 2) that illustrates the basic features of the P# state-machine programming model. Next, we present a more advanced example (Section 3) that illustrates advanced features of the P# language. Finally, we will provide an overview of the tools for compiling and systematically testing a P# program (Section 4) and conclude with a glossary of all P#-specific features in our language (Section 5).

2. A simple P# program

A P# program is a collection of `event`, `machine` and, optionally, other top-level C# declarations (e.g. `class`). Events and machines must be declared inside a `.psharp` file, while C# top-level declarations must be declared in a typical `.cs` file. Similar to C#, all top-level declarations must be declared inside a `namespace`. The following example contains a `Client` machine and a `Server` machine communicating with each other via `Ping` and `Pong` events.

```
// PingPong.psharp
namespace PingPong {
  event Ping;
  event Pong;
  event Unit;

  machine Server {
    machine client;

    start state Init {
      entry {
        this.client = create(Client, this);
        raise(Unit);
      }

      on Unit goto Playing;
    }

    state Playing {
      entry {
        send(this.client, Pong);
      }

      on Unit do SendPong;
      on Ping do SendPong;
    }

    void SendPong() {
      send(this.client, Pong);
    }
  }

  machine Client {
    machine server;
    int counter;

    start state Init {
      entry {
        this.server = (machine)payload;
        this.counter = 0;
        raise(Unit);
      }

      on Unit goto Playing;
    }

    state Playing {
      entry {
        if (this.counter = 5) {
          send(this.server, halt);
          raise(halt);
        }
      }

      on Unit goto Playing;

      on Pong do {
        this.counter++;
        send(this.server, Ping);
        raise(Unit);
      };
    }
  }

  public class Program {
    static void Main(string[] args) {
      PSharpRuntime.CreateMachine(typeof(Server));
      Console.ReadLine();
    }
  }
}
```

A machine declaration contains a collection of field, state and method declarations. For example, the machine Server has a client field, two states, Init and Playing, and a method SendPong declared inside it. The fields and methods of a machine *cannot* be public; they can only be accessed locally from a particular instance of the machine. The start modifier in the Init state declaration indicates that an instance of Server begins executing by entering the Init state.

A state declaration can optionally contain a number of state-specific declarations. A code block indicated by entry { ... } denotes an action that is executed when the state is entered, while a code block indicated by exit { ... } (not used in the above example) denotes an action that is executed when the state exits. A P# action (e.g. entry exit and SendPong), is a block of arbitrary P# and C# statements. As an example, the entry action in the state Init of Server contains two statements. The first statement, this.client = create(Client, this), creates a new instance of the Client machine and stores a reference to this instance in the field client. Note that P# allows the use of all the primitive types that C# provides (e.g. int and bool) and also introduces the machine type, which is a reference to a dynamically-created P# machine. The second statement in the entry action *raises* an event Unit, which causes control to exit the Init state and enter the Playing state. When a machine raises an event, it literally sends an event to itself. In P#, when a machine raises an event, or sends an event to another machine, the event is enqueued in the target machine's input queue. However, a raised event does not go through the queue; rather it terminates execution of the enclosing code block and is handled immediately.

Other than the entry and exit declarations, all other declarations inside a state are related to event handling. The declaration on Unit goto Playing in the state Init of the Server machine is an example of such a declaration: it indicates that the Unit event must be handled by exiting the state Init and transitioning to the state Playing. The declaration on Ping do SendPong in the state Init of the Server machine is another example: it indicates that the Ping event must be handled by invoking the action SendPong. P# also supports *anonymous* actions: the declaration on Pong do { ... } in the state Playing of the Client machine is such an anonymous action, which states that the code block between the braces must be executed when Pong is dequeued. When an action executes control remains in the state subsequent to this execution. This control primitive is useful for executing an event-driven loop in a state, such as the one in Playing for collecting Pong responses. Different states of a machine can choose to handle a particular event in a different way: the programmer is free to decide how an event should be handled.

A P# action can be any C# method that has no parameters. An example of an action is SendPong, which contains the send statement that is responsible for sending an event (in this case Pong) to the machine whose address is stored in the field client. The keyword this refers to the current instance of the machine (in this case an instance of the Server machine).

A machine can optionally send data to another machine, either when creating a machine (via the create statement) or when sending an event to a machine (via the send statement). Note that both create and send statements are non-blocking. In the above example, the Server machine sends a reference to itself (i.e. this) when creating the Client machine in the entry action of the Init state. The Client machine can retrieve this data by using the keyword payload, as in the entry action of the state Init. When a machine receives a payload it has to cast the data to its expected type; in this case the machine type (as it is a reference to the Server machine).

To start execution of a P# program, the programmer has to create an initial machine using the CreateMachine method provided by the PSharpRuntime API. This method accepts as a parameter the type of the machine to be created (in our case a Server machine) and an optional payload (not used in the above example). Because the CreateMachine method is non-blocking, we use the Console.ReadLine() statement so that the program does not exit prematurely. The PSharpRuntime API also provides a method for enqueueing events to a P# machine from C# code (not used in the above example). To do this, the programmer has to use the SendEvent method that accepts as a parameter a MachineId object, returned when creating a machine via the CreateMachine method, and an event object.

In the above example, the P# program begins with a single instance of Server being created and then entering state Init. Let us call this instance of the Server machine *server*. Machine *server* then creates an instance of the Client machine and raises the event Unit to enter the state Playing. Let us call this instance of the Client machine *client*. The machine *client* begins execution when *server* is in the state Playing, then *client* also transitions to the state Playing by raising a event Unit. From this point on, *client* and *server* exchange Ping and Pong events.

The most important safety specification of a P# program is that every event dequeued by a machine is handled; otherwise, the P# runtime reports an unhandled event error. The PingPong program satisfies this specification since the Server machine handles the Ping event and the Client machine handles the Pong event in every state where an event dequeue is possible.

In order to terminate a P# machine cleanly, it must dequeue a special halt event. In this example, after *client* sends 5 Ping events to *server*, it sends halt to *server* and then raises halt. Termination of a machine due to an unhandled halt event is valid behavior (the P# runtime does not report an error). From the point of view of formal operational semantics, a halted machine is fully receptive and consumes any event that is sent to it. The P# runtime implements this semantics efficiently by cleaning up resources allocated to a halted machine and recording that the machine has halted. An event sent to a halted machine is simply dropped. A halted machine cannot be restarted; it remains halted forever.

3. Advanced P# features

The following example illustrates the more advanced features of the P# language. This program implements a failure detection protocol. A FailureDetector machine is given a list of machines, each of which represents a daemon running at a node of a distributed system. The FailureDetector sends each machine in the list a Ping event and determines whether a machine has failed. A machine has failed if it does not respond with a Pong event within a certain time period. The FailureDetector uses an operating system timer to implement the bounded wait for the Pong event.

3.1. Modeling a machine

The code snippet below shows the implementation of the Timer machine. This machine is declared using the keyword model (instead of machine) to indicate that it represents an abstraction of the operating system (OS) timer. This abstraction *substitutes* the OS timer and is used to *systematically test* the interaction of the failure detector protocol with the underlying OS (see Section 4). During execution of a P# program, model machines are *replaced* by their actual implementations; a model machine is used only for systematic testing.

```
// Timer.psharp
namespace FailureDetector {
  // events from client to timer
  event Start;
  event Cancel;
  // events from timer to client
  event Timeout;
  event CancelSuccess;
  event CancelFailure;
  // local event for control transfer within timer
  event Unit;

  model Timer {
    machine client;

    start state Init {
      entry {
        this.client = (machine)payload;
        raise(Unit); // goto handler of Unit
      }

      on Unit goto WaitForReq;
    }

    state WaitForReq {
      on Cancel goto WaitForReq with {
        send(this.client, CancelFailure, this);
      };

      on Start goto WaitForCancel;
    }

    state WaitForCancel {
      ignore Start;

      on Cancel goto WaitForReq with {
        if (*) {
          send(this.client, CancelSuccess, this);
        } else {
          send(this.client, CancelFailure, this);
          send(this.client, Timeout, this);
        }
      };

      on default goto WaitForReq with {
        send(this.client, Timeout, this);
      };
    }
  }
}
```

Each instance of a `Timer` machine has a reference to a `Client` machine instance, stored in the `client` field. This client sends `Start` and `Cancel` events to the timer, which subsequently responds with `Timeout`, `CancelSuccess`, or `CancelFailure` events.

The timer has three states: `Init`, `WaitForReq` and `WaitForCancel`. It starts executing in the state `Init`, where it initializes the `client` field with the machine reference obtained by accessing `payload` and casting it to the type `machine`. It then waits in the state `WaitForReq` for a request from the client, responding with `CancelFailure` to a `Cancel` event and moving to the `WaitForCancel` state on a `Start` event.

The `ignore Start` declaration inside the `WaitForCancel` state of the timer denotes that whenever the event `Start` is dequeued it must be dropped without taking any further action.

The response to a `Cancel` event involves the use of nondeterminism to model the race condition between the arrival of a `Cancel` event from the client and the elapse of the timer. This nondeterminism is indicated by an `if` statement guarded by the keyword `*`, which returns a nondeterminitic boolean choice. The then-branch models the case when the `Cancel` event arrives before the timer elapses; in this case, `CancelSuccess` is sent back to the client. The else-branch models the case when the timer fires before the `Cancel` event arrives; in this case, `CancelFailure` and `Timeout` are sent back to the client one after another. The last event handler `on default goto WaitForReq with { ... }` transfers the control to the `WaitForReq` state, modeling that the timer has elapsed, if neither of the other event handlers in `WaitForCancel` can execute. The `with` statement block executes after the `exit` action of the exiting state. The event `default` is a special event that is internally generated by the P# runtime.

3.2. Substitution

A machine can be used to model another machine for systematic testing, using the *substitution* feature of the P# language. To achieve this, the programmer has to use the following special create statement:

```
create(Foo) models Bar;
```

In this case, the `Foo` machine is used to model the Bar machine. During systematic testing, the `Foo` machine will be created, whereas during real execution, the `Bar` machine will be created.

Likewise, a method can model another method for systematic testing. To achieve this, create a method that has the same name and parameters as the method to be modeled, and use the modifier `model` as follows:

```
void Foo() { }       // real method
model void Foo() { } // model method
```

In this case, the Foo method will be called instead of the Bar method during systematic testing, wheras the Bar method will be called during real execution.

3.3. Failure detection protocol

The failure detection protocol is based on the interaction of two types of machines, FailureDetector and Node, which are shown below. The code of the FailureDetector machine presents advanced features of P#, including push transitions and pop statements, deferred events, and monitors.

```
// FailureDetector.psharp
namespace FailureDetector {
  // request from failure detector to node
  event Ping;
  // response from node to failure detector
  event Pong;
  // register a client for failure notification
  event RegisterClient;
  // unregister a client from failure notification
  event UnregisterClient;
  // local events for control transfer within failure detector
  event RoundDone;
  event TimerCancelled;

  machine FailureDetector {
    List<machine> nodes;                 // nodes to be monitored
    Dictionary<machine, bool> clients;   // registered clients
    int attempts;                        // number of Ping attempts made
    Dictionary<machine, bool> alive;     // set of alive nodes
    Dictionary<machine, bool> responses; // collected responses in one round
    machine timer;

    start state Init {
      entry {
        this.nodes = new List<machine>();
        this.clients = new Dictionary<machine, bool>();
        this.alive = new Dictionary<machine, bool>();
        this.responses = new Dictionary<machine, bool>();
        this.nodes = payload as List<machine>;
        this.InitializealiveSet();
        this.timer = create(Timer, this);
        raise(Unit);
      }

      on RegisterClient do {
        this.clients[(machine)payload] = true;
      };

      on UnregisterClient do {
        if (this.clients.ContainsKey((machine)payload)) {
          this.clients.Remove((machine)payload);
        }
      };

      on Unit push SendPing;
    }

    state SendPing
    {
      entry {
        this.SendPings(); // send Ping events to machines that have not responded
        send(this.timer, Start, 100); // start timer for intra-round duration
      }

      on Pong do {
        // collect Pong responses from alive machines
        if (this.alive.ContainsKey((machine)payload))
        {
          this.responses[(machine)payload] = true;
          if (this.responses.Count == this.alive.Count) {
            // status of alive nodes has not changed
            send(this.timer, Cancel);
            raise(TimerCancelled);
          }
        }
      };

      on TimerCancelled push WaitForCancelResponse;

      on Timeout do {
        // one attempt is done
        this.attempts++;
        // maximum number of attempts per round == 2
        if (this.responses.Count < this.alive.Count && this.attempts < 2) {
          raise(Unit); // try again by re-entering SendPing
        } else {
          this.CheckaliveSet();
          raise(RoundDone);
        }
      };

      on Unit goto SendPing;
      on RoundDone goto Reset;
    }

    state WaitForCancelResponse {
      defer Timeout, Pong;

      on CancelSuccess do {
        raise(RoundDone);
```

```
      };

      on CancelFailure do {
        pop;
      };
    }

    state Reset {
      entry {
        // prepare for the next round
        this.attempts = 0;
        this.responses.Clear();
        send(this.timer, Start, 1000); // start timer for inter-round duration
      }

      on Timeout goto SendPing;
      ignore Pong;
    }

    void InitializealiveSet() {
      foreach (var node in this.nodes) {
        this.alive.Add(node, true);
      }
    }

    void SendPings() {
      foreach (var node in this.nodes) {
        if (this.alive.ContainsKey(node) && !this.responses.ContainsKey(node)) {
          monitor<Safety>(MPing, node);
          send(node, Ping, this);
        }
      }
    }

    void CheckaliveSet() {
      foreach (var node in this.nodes) {
        if (this.alive.ContainsKey(node) && !this.responses.ContainsKey(node)) {
          this.alive.Remove(node);
        }
      }
    }
  }
}
```

The state `Init` of the `FailureDetector` machine illustrates the use of `push` transitions. After appropriately initializing fields in the entry action, the raised event `Unit` is handled by *pushing* state `SendPing` on top of the current state `Init`. Thus, the use of `push` transitions creates a stack of states encoding the control of a state-machine. As long as state `Init` is on the stack, event handlers declared inside it are available to be executed regardless of changes in any states above it. The event handlers for `RegisterClient` and `UnregisterClient` are such available handlers. A `push` transition from Init to SendPing (rather than a goto transition) enables the declaration of these handlers in one place (the Init state) and their reuse everywhere else in FailureDetector. In addition to offering reuse of event handlers, push transitions also enable reuse of protocol logic for handling specific interactions with other machines. We later explain this use of a push transition in handling the interaction between FailureDetector and Timer.

When the state SendPing of the FailureDetector machine is entered, its entry action sends Ping events to all alive nodes that have not yet responded with a Pong event and starts a timer with a timeout value of 100ms. The machine stays in this state collecting Pong responses until either all alive nodes have responded or a Timeout event is dequeued. If each alive node has responded with a Pong before Timeout is dequeued, the timer is canceled and the event TimerCancelled is raised. Otherwise, the handler of Timeout is executed to determine whether another attempt to reach the potentially alive nodes should be made. If the number of attempts has reached the maximum number of attempts (2 in this example), then the nodes have failed.

The state SendPing of FailureDetector illustrates the use of a push transition to factor out the logic for handling timer cancelation. When TimerCancelled is raised after canceling the timer because all alive nodes have responded with Pong, the handler on TimerCancelled push WaitForCancelResponse pushes the state WaitForCancelResponse on top of the state SendPing. The state WaitForCancelResponse handles the interaction with the timer subsequent to its cancelation, returning control back to SendPing afterwards. The timer may respond with either CancelSuccess or CancelFailure. In the former case, the event RoundDone is raised which is not handled in state TimerCancelled causing the state to be popped and letting the state SendPing handle the RoundDone event. In the latter case, the pop statement executes causing TimerCancelled to be popped and a fresh event being dequeued in the state SendPing.

The state WaitForCancelResponse uses the code defer Timeout, Pong to indicate that it is not willing to handle Timeout and Pong states in this state. Therefore, while the machine is blocked in this state, the P# runtime does not dequeue these two events, instead *skips* them to retrieve any other event in the input queue.

When the FailureDetector machine is blocked in the state WaitForCancelResponse, its stack has three states on it. Starting from the bottom of the stack, these states are Init, SendPing, and WaitForCancelResponse. The Init state specifies do handlers for RegisterClient and UnregisterClient, the SendPing state specifies do handlers for Pong and Timeout, and the WaitForCancelResponse state defers Pong and Timeout. The dequeue logic for P# allows the execution of do handlers specified anywhere in the stack *unless* deferred in a state above. Therefore, in the state WaitForCancelResponse, the events RegisterClient and UnregisterClient may be dequeued, but the events Timeout and Pong may not.

```
// Node.psharp
namespace FailureDetector {
  machine Node {
    start state WaitPing {
      on Ping do {
        monitor<Safety>(MPong, this);
        send((machine)payload, Pong, this);
      };
    }
  }
}

// Safety.psharp
namespace FailureDetector {
  event MPing;
  event MPong;

  monitor Safety {
    Dictionary<machine, int> Pending;

    start state Init {
      entry {
        this.Pending = new Dictionary<machine, int>();
      }

      on MPing do {
        if (!this.Pending.ContainsKey((machine)payload)) {
          this.Pending[(machine)payload] = 0;
        }

        this.Pending[(machine)payload] = this.Pending[(machine)payload] + 1;
        assert(this.Pending[(machine)payload] <= 3);
      };

      on MPong do {
        assert(this.Pending.ContainsKey((machine)payload));
        assert(this.Pending[(machine)payload] > 0);
        this.Pending[(machine)payload] = this.Pending[(machine)payload] - 1;
      };
    }
  }
}
```

P# also allows programmers to write *assertions* that express invariants on the local state of a machine. This can be achieved using the `assert` statement. However, it is often useful to be able to write assertions about state across machines in a program. P# provides *monitors* that enable writing such specifications. Consider the problem of specifying that the difference in the number of `Ping` events sent to any machine can never be three more than the number of `Pong` events sent by it. This specification can be encoded using the monitor machine `Safety`. This monitor maintains the difference between the number of `Ping` and `Pong` events per machine in a C# dictionary and asserts that this number can be at most three. The failure detection protocol communicates with this monitor by sending it `MPing` and `MPong` events using a statement such as `monitor<Safety>(MPong, this)`.

3.4. Test driver machine

The machine `Driver` shows how to write a test driver to test the failure detection protocol. This machine models a client of the protocol. This client creates a few nodes to be monitored, creates an instance of the `Safety` monitor, an instance of `FailureDetector`, registers itself with the created instance of `FailureDetector`, and then enqueues the special `halt` event to each node created by it to terminate that node. Thus, the `Driver` machine creates a finite test program for the failure detection protocol.

```
// Driver.psharp
namespace FailureDetector {
  model Driver {
    machine FailureDetector;
    List<machine> NodeSeq;
    Dictionary<machine, bool> NodeMap;

    start state Init {
      entry {
        this.NodeSeq = new List<machine>();
        this.NodeMap = new Dictionary<machine, bool>();
        this.Initialize();
        create(Safety);
        this.FailureDetector = create(FailureDetector, this.NodeSeq);
        send(this.FailureDetector, RegisterClient, this);
        this.Fail();
      }
    }

    void Initialize() {
      for (int i = 0; i < 2; i++) {
        var node = create(Node);
        this.NodeSeq.Add(node);
        this.NodeMap.Add(node, true);
      }
    }

    void Fail() {
      for (int i = 0; i < 2; i++) {
        send(this.NodeSeq[i], halt);
      }
    }
  }

  public class Test {
    static void Main(string[] args) {
      PSharpRuntime.CreateMachine(typeof(Driver));
      Console.ReadLine();
    }
  }
}
```

Even though the test program encoded by machine Driver is finite, it can generate an enormous number of behaviors resulting primarily from the concurrent execution of a number of state machines: one Driver machine, two Node machines, one FailureDetector machine, and one Timer machine. At each step in an execution when a non-local action (creation of a machine or sending an event from one machine to another) is about to execute, there is a choice of picking *any* one of these machines to execute. The testing infrastructure embedded in the P# compiler *systematically enumerates* these behaviors; if an exception is raised or an assertion is violated, a path to the error is reported to the programmer.

The style of specifying test programs in the manner described above results in a compact description of a large set of test executions, considerably reducing the programmer's effort in specifying and generating them. For example, even though the Driver machine sends a halt event to each Node machine immediately after creating them, these send actions may be arbitrarily *delayed* if a nondeterministic scheduler chooses to execute the other machines in the program instead. The P# systematic tester has the capability to enumerate such behaviors to explore *tricky* interleavings between event handlers.

3.5. Using the P# framework APIs

The P# framework enables the developers to directly develop P# programs in native C# without the need of writing in the high-level P# language presented earlier in the examples. The positive of this approach is that it allows full integration with VS, but comes at the cost of more verbosity. The above PingPong program can be developed using the P# framework APIs as follows:

```
using Microsoft.PSharp;

namespace PingPong {
  class Unit : Event { }
  class Ping : Event { }
  class Pong : Event { }

  class Server : Machine {
    MachineId Client;

    [Initial]
    [OnEntry(nameof(InitOnEntry))]
    [OnEventGotoState(typeof(Unit), typeof(Playing))]
    class Init : MachineState { }

    void InitOnEntry() {
      this.Client = this.CreateMachine(typeof(Client), this);
      this.Raise(new Unit());
    }

    [OnEventDoAction(typeof(Unit), nameof(SendPong))]
    [OnEventDoAction(typeof(Ping), nameof(SendPong))]
    class Playing : MachineState {
      protected override void OnEntry() {
        this.Send((this.Machine as Server).Client, new Pong());
      }
    }

    void SendPong() {
      this.Send(this.Client, new Pong());
    }
  }

  class Client : Machine {
    MachineId Server;
    int Counter;
    [Initial]
    [OnEventGotoState(typeof(Unit), typeof(Playing))]
    class Init : MachineState {
      protected override void OnEntry() {
        (this.Machine as Client).Server = (MachineId)this.Payload;
        (this.Machine as Client).Counter = 0;
        this.Raise(new Unit());
      }
    }

    [OnEventGotoState(typeof(Unit), typeof(Playing))]
    [OnEventDoAction(typeof(Pong), nameof(SendPing))]
    class Playing : MachineState {
      protected override void OnEntry() {
        if ((this.Machine as Client).Counter == 5) {
          this.Raise(new Halt());
        }
      }
    }

    void SendPing() {
      this.Counter++;
      Console.WriteLine("\nTurns: {0} / 5\n", this.Counter);
      this.Send(this.Server, new Ping());
      this.Raise(new Unit());
    }
  }

  public class Program {
    static void Main(string[] args) {
      PSharpRuntime.CreateMachine(typeof(Server));
      Console.ReadLine();
    }
  }
}
```

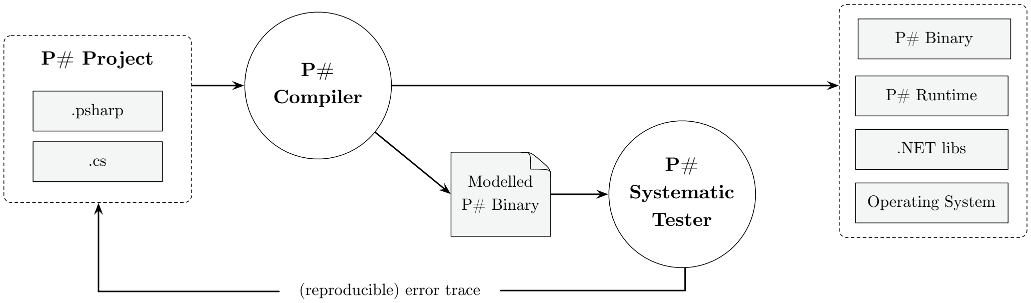
First import the `Microsoft.PSharp` library. To declare a new P# machine, create a new C# `class` that inherits from the type `Machine` (provided by the P# library). To create a new state, create a new `class` that inherits from the type `MachineState`. This state class must be nested inside a machine class. The start state can be declared using the `[Initial]` attribute.

To declare a state transition, use the `[OnEventGotoState(...)]` attribute, where the first argument to the attribute is the type of the received event and the second argument is the type of the target state. You can pass an optional third argument, `nameof(...)` (or simply a `string`), which denotes the name of the method that you want to be executed after exiting the state. To declare an action handler, use the `[OnEventDoAction(...)]` attribute, where the first argument to the attribute is the type of the received event and the second argument is the name of the action to be executed. For a push transition, use the `[OnEventPushState(...)]` attribute.

To declare an ignored event, use the `[IgnoreEvents(...)]` attribute, which takes a variable number of parameters, all of which are `typeof(...)`, denoting the type of the event to be ignored. Similar for deferring events, use the `[DeferEvents(...)]` attribute.

All P# statements are exposed as method calls of the Machine and MachineState classes.

4. Tools



The above figure shows a typical P# workflow. The programmer initially creates a P# application and then uses the compiler to parse, compile and systematically test this application. This process repeats until all bugs are discovered and fixed.

4.1. Compilation

The compiler executable is called `PSharpCompiler.exe`. It accepts a P# solution, which can contain a number of `.psharp` and `.cs` files, and various optional arguments as input. The options can be discovered by running `PSharpCompiler.exe /?` from the command line.

The compiler is based on a three-phase compilation approach: it initially parses the P# surface syntax and reports any P#-related syntax errors; it then rewrites the original P# program into an intermediate C# representation; it finally uses the Roslyn compiler to parse and compile the intermediate C# program to an executable file (`.exe`) or library (`.dll`), and link it with the P# libraries and C# system libraries. Any C#-specific compile errors will be reported in this final Roslyn-based compilation phase.

The P# compiler can be invoked on a P# solution with the following command:

```
.\PSharpCompiler.exe /s:${SOLUTION_PATH}\${SOLUTION_NAME}.sln
```

To build only a single specific project from a given solution use the `/p:${PROJECT_NAME}` command line option.

4.2. Execution

To execute the compiled program, run the executable that is produced by `PSharpCompiler.exe` (found in the directory specified by the P# project). If the compiled program is a library, then link the library as in any typical .NET project. A typical P# application consists of one or more P# machines communicating asynchronously with each other by sending and receiving events. The P# runtime is responsible for handling all the underlying asynchrony when a machine creates a new machine or sends an event to a target machine.

4.3. Systematic Testing

Once the programmer fixes all the statically discovered errors, the compiler can be used to systematically test the P# application. This is achieved by running the compiler in *bug-finding* mode. In this mode, the systematic tester takes control of the underlying schedule and systematically explores event handling interleavings to discover bugs in the P# program.

To switch to bug-finding mode the command-line option `/test` must be given when invoking the P# compiler.

By default, the systematic tester will explore a single iteration using an exploration depth bound of 1000. This depth bound is the maximum number of scheduling steps that the systematic tester will take while exploring a single schedule of the program. To increase the depth bound use the command line option `/db:x` where `x` is a positive integer. To increase the number of schedules to be explored (from program start to a terminal state) use the command line option `/i:x` where `x` is a positive integer.

If a dynamic error is discovered, the systematic testing will terminate, and a complete error trace starting from the initial state of the program is dumped on the disk in a text file (in the same directory as the compiled binaries of the P# application). The programmer can fix the found bug and run the compiler and systematic testing again on the modified program. Search statistics are also printed during and at the end of the systematic testing.

5. Glossary

Types

Syntax	**Description**
`machine`	A reference to a P# machine.
type	The set of all possible C# types (either primitive, such as `int` and `bool`, or custom).

Machines and Events

Syntax	**Description**
`default`	A pseudo-event that may be taken when no other event is triggered. Taking a `default` event sets `trigger` and `payload` to null.
`halt`	A predefined event that causes a machine to shutdown. The user implements a machine's response to `halt`. A machine is shutdown when its state stack becomes empty with `trigger` == `halt`.
`event` e [{`assert` | `assume`} k];	Declares an event.[a]
`machine` M [{`assert` | `assume`} k] `{ … }`	Declares a machine.[b]
`model` M [{`assert` | `assume`} k] `{ … }`	Declares a model machine.[b]
`monitor` M `{ … }`	Declares a property monitor.

[a] An event e may optionally be annotated with `assert k` or `assume k`. The former specifies that there must not be more than k instances of e in the input queue of any machine. The latter specifies that during systematic testing, an execution that increases the cardinality of e beyond k in some queue must not be generated. Both compile to an assertion in code generated for execution.

[b] A machine or model M may optionally be annotated with `assert k` or `assume k`. Their meaning is similar to that of the corresponding annotation for an event except that the bound k refers to the total number of events in the input queue of M.

States, State Variables, and Functions (declared inside machines)	
Syntax	**Description**
this	Refers to the current instance of a machine.
trigger	Refers to the event causing the current entry or exit of a state; it is initially null.
payload	Refers to the payload of the event causing entry or exit of a state; initially the value passed to the create operator.
[start] state S { … }	Declares a (starting) state S.
[model] method declaration	Declares a (model) C# method with zero or more formal parameters.

State Actions and Transitions (declared inside states)	
Syntax	**Description**
entry A;	An action A to be executed whenever this state is entered.
entry { … }	A code block to be executed whenever this state is entered.
exit A;	An action A to be executed whenever this state exits.
exit { … }	A code block to be executed whenever this state exits.
defer e_1, …, e_n;	A list of events to skip while examining the queue for an event to handle.
ignore e_1, …, e_n;	A list of events to immediately remove while examining the queue for an event to handle.
on e_1, …, e_n do A;	A list of events to immediately remove while examining the queue for an event to handle. Each removal causes execution of A.
on e_1, …, e_n do { … }	A list of events to immediately remove while examining the queue for an event to handle. Each removal causes execution of code block.
on e_1, …, e_n goto S [with A];	A handler triggered whenever some e_i is encountered in the queue. Causes removal of e_i from queue, execution of exit function, (execution of A), and entry into state S.
on e_1, …, e_n goto S with { … }	A handler triggered whenever some e_i is encountered in the queue. Causes removal of e_i from queue, execution of exit function, execution of code block, and entry into state S.
on e_1, …, e_n push S;	A handler triggered whenever some e_i is encountered in the queue. Causes removal of e_i from queue, pushing of current state onto state stack, and entry into state S.

P# Statements	
Syntax	**Description**
create (M , [v_1, …, v_n]);	Creates a new instance of a machine or monitor with type M, and with payload set to (v_1, …, v_n).
raise (ev , [v_1, …, v_n]);	Causes immediate handling of event expression ev (and sets payload to (v_1, …, v_n)).
send (dst, ev , [v_1, …, v_n]);	Sends to machine expression dst event expression ev (with payload to (v_1, …, v_n)).
pop;	Pops this state from the state stack and returns to the parent state. Fails if the state stack is empty and the trigger is not the halt event.
assert v;	Fails if the expression v does not evaluate to true.

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