Alternating bit protocol as an example of compositional system specification*

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Abstract

We show a complete modular specification of the alternating bit protocol. We use the syntax of Maude extended with our constructs for the synchronous composition. Also, we make intensive use of parameterized programming to encapsulate components and specify interfaces. This paper must be considered a companion to some of our previous ones.

Contents

1 Introduction

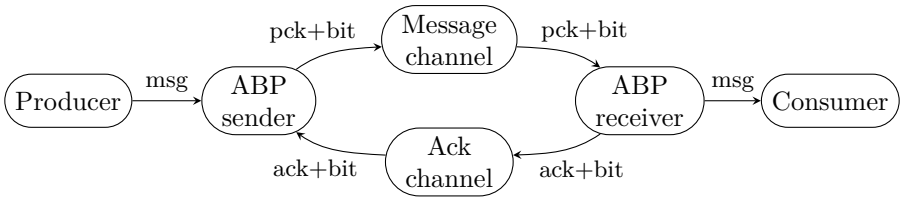
This is a companion paper to our previous [5, 4, 3]. In them, we describe an operation of synchronous composition for rewrite systems and the means to implement and use it in Maude. Some familiarity with those papers is probably needed to understand the present one. This contains an example implementing the alternating bit protocol. Parts of this example are already in [5], but here it is fully detailed and explained.

The example is coded using the syntax of Maude (described, for example, in [1]), extended with the constructs we propose for synchronous composition. Indeed, the code that follows is not executable in the existing implementation of Maude for two reasons. First, the extensions to the language that we propose to support synchronous composition have not been implemented as yet; we intend to do so soon. Second, we make intense use of parameterized programming. Though all of it is theoretically plausible and sticks to the proposals in [2], it is only partially implemented in Maude. (Full Maude, also described in [1], has got parameterized theories and views, but not to the limit that we use them here.)

2 The alternating bit protocol

The alternating bit protocol, or ABP, is used to transmit messages on a lossy channel, that is, a channel that can lose some of the messages it receives before delivering them at the other end. According to ABP, a bit is attached to each packet of information sent through the channel. The sender must keep on sending the same packet with the same bit until it receives an acknowledgement (let's abbreviate it to *ack*) from the receiver with that same bit. Then, the sender starts sending the next packet with the bit inverted. As also acks can be lost in the channel, the receiver must keep on acknowledging until it receives a new message, with a different bit, that suffices as proof that its ack was received and processed by the sender.

We consider an ABP system as consisting of six components:



At the ends there are a producer and a consumer, that do not care about communication protocols. The sender and the receiver implement the ABP. There are two channels: one for transmitting messages originating in the producer; the other for transmitting acks. We call *message* to whatever the producer wants to transmit to the consumer. The pieces of information that are sent through a channel are called *packets*. It is the sender's task to transform each message

into one or more packets; the receiver has the inverse task. What precisely is a packet depends on the protocol used. In our implementation of ABP, we make the rather unrealistic assumption that we can build channels capable of transmitting packets of whatever data type. Our implementation of channels is parametric on that data type.

The six modules in our diagram are not all of the same nature. The producer, the consumer, and the two channels can be seen as representing physical entities, while the sender and the receiver may well be pieces of software running on some of them. This difference, however, has no role in specifications.

3 Common

Some pieces of code are used often in the specification. They are best in a common module to be imported when and where needed. This section contains their specifications.

3.1 Stages

Atomic egalitarian modules are the ones that implement basic, non-composed systems, defining what states and transitions are in a particular component. The following module is useful to be imported in them:

```
fmod STAGES is
   sorts State Trans Stage .
   subsorts State Trans < Stage .
   op init : -> Stage .
endfm
```

A *stage* is either a state or a transition. We declare the name `init` for the initial stage; it can be a transition, as well as a state.

3.2 Properties

Properties are used to formulate syncing criteria. They can be thought of as ports or handles, different metaphors being appropriate in different cases. They work like functions that take values at states and at transitions. But we do not implement them as functions but like this (be aware that we slightly modify this definition in the next section):

```
fmod PPTY{X :: TRIV} is
   pr MAYBE{X} .
   sort Stage .
   sort Ppty{X} .
   op _@_ : Ppty{X} Stage -> Maybe{X} .
endfm
```

Just as a reminder, the theory `TRIV` is defined like this:

```
fth TRIV is
   sort Elt .
endfth
```

The idea, thus, is that an element of sort `Ppty{X}` evaluates, through the operator `@`, to a value of sort `X$Elt` at each stage. Indeed, this is not completely true for two reasons. First, a property may be undefined at some stages (the rationale for this is explained in [4, 3]). Second, the operator `@` is declared as returning a value of sort `Maybe{X}`, instead of plain `X$Elt`. The definition of the parametric module `MAYBE{X}` is this:

```
fmod MAYBE{X :: TRIV} is
   sort Maybe{X} .
   subsort X$Elt < Maybe{X} .
   op none : -> Maybe{X} .
endfm
```

That is, the sort `Maybe{X}` contains all values in the sort of the parameter, `X$Elt`, plus a dummy value called `none`. (In the standard implementation of `MAYBE` in Maude's prelude, this dummy element is called `maybe`, but the name `none` fits better for the use we make of it.) For instance, a property called `messageBeingSent` can be set to `none` when no value is being sent. Not every property needs to use this extra value, but we include it in the declaration for the cases when it is useful, that in the present paper are many. Finally, being undefined and being defined to `none` must not be confused: an undefined property does not pose any restriction for syncing. (All properties in our present implementation of ABP are completely defined.)

3.3 Matchable sorts

Our methodology mandates that each component system must be thoroughly meaningful by itself. Each has to be specified in such a way that it can be run either isolated or synced. In many cases, this means that a component shows a wildly non-deterministic behavior if run by itself. A receiver, for instance, must be glad to accept any value the sender can send. This could be represented in the receiver's side by a rewrite rule like this:

$$s(v, \ldots) \to s(v', \ldots)$$

Here, $s(\ldots)$ is some state term and v and v' are values of some sort that are received and stored by the receiver. However, Maude does not accept fresh variables on the right-hand side of a rule, because they are problematic for execution. A solution is to include the new value v' in a matching condition, where it can be instantiated:

$$s(v, \ldots) \to s(v', \ldots) \text{ if } \{v'\} \cup V := \text{set of possible values}$$

Maude knows how to solve the matching condition, in a non-deterministic way, and assign values to v' and V.

When the time comes for the composition to be performed, and syncing criteria are specified, the composed, global behavior can become deterministic, if the sender only sends a particular value at any given time, deterministically, as is usual. But if we are interested in executing or analyzing the receiver by

itself, the value of v' has to be chosen non-deterministically from the "set of possible values", which, of course, has to be finite for Maude to be able to solve the matching.

For our implementation of ABP here, we have insisted that it be parametric on the sort of messages being interchanged. According to the above, the parameter cannot be just a `TRIV`, but needs to provide the elements needed for writing and solving matching conditions, among them the set of all possible values for each sort that we want to use for syncing. For those reasons we define this theory:

```
fth MATCHABLE is
   sorts Elt Elts .
   subsort Elt < Elts .
   op noElts : -> Elts .
   op _&_ : Elts Elts -> Elts [comm assoc id: noElts] .
   op allElts : -> Elts .
endfth
```

With all the attributes `assoc`, `comm`, and `id:`, the operator `&` makes `Elts` equivalent to sets of `Elt`. This seems appropriate so that we can choose an `Elt` from an `Elts` non-deterministically with total freedom. (A technical side note: in Maude, it is not possible to declare a sort `Elt` and then state that we are going to use `SET{Elt}` as well. The argument for `SET` has to be a view, defined outside the current module.)

The constant `allElts` is interpreted as providing the whole set of possible values of sort `Elt`. The matching conditions we use will have the form `if E & EE := allElts`, for `E` and `EE` variables of sorts `Elt` and `Elts`, respectively.

As a consequence, the sorts returned by a property cannot, in general, be just a `TRIV`: they need to be a `MATCHABLE`. So we redefine the module `PPTY`:

```
fmod PPTY{X :: MATCHABLE} is
   pr MAYBE{Matchable}{X} .
   sort Stage .
   sort Ppty{X} .
   op _@_ : Ppty{X} Stage -> Maybe{X} .
endfm
```

To instantiate `MAYBE`, we are using the fact that a *matchable* sort can be used whenever a `TRIV` is expected:

```
view Matchable from TRIV to MATCHABLE is
   sort Elt to Elt .
endv
```

There are several instances of use of all this below.

The use of `MATCHABLE` can be seen as a dirty trick, and its need can be seen as an annoying consequence of our choices and Maude's design. For, suppose the sender and the receiver were specified together. And suppose the sender works in a deterministic way, so that if it has v stored, then it next sends and stores a new value $f(v)$, for some function f implemented as part of the sender's specification. Then, our rule would look like this:

$$s(v,\ldots)\ r(v,\ldots) \ \rightarrow\ s(f(v),\ldots)\ r(f(v),\ldots),$$

where s represents the sender's states and r the receiver's. There is no need for matching and matchable sorts here. But compositionality is lost in this way, both for specification and for verification. Also, there is some conceptually sound truth in the *matchable* solution. Real-world systems are not able to produce, send or receive data of unbounded size. Any system has its bounds, embedded into their construction. It is appropriate, then, to include such bounds as part of their specifications. The *matchable* trick provides an explicit solution for that.

4 Interfaces

We use theories (in the parameterized-programming sense) to specify the interfaces for component modules, understanding by this the list of properties they must define and their sorts. All the external world needs to know about an implementation module is that it conforms to the requirements of a given theory.

We are also interested in compositional verification. This is work still to be done, so we do not include here anything related to that. But let us point just that, to that aim, *assume* and *guarantee* temporal formulas can be included into a theory (with the needed extensions to Maude's syntax), with the same aim that `nonexec` equations are included into theories in standard Maude.

Properties can be used to emulate value passing, as described in [5, 4, 3]. In these cases, they can be understood as *directional*, that is, as being an *out* property at the sender side, and an *in* property at the receiver's. That is why we have shown directed arrows in the diagram above. However, properties *per se* are not directional, so that the producer and the consumer conform to the same interface, as do the sender and the receiver. This is exploited below.

One more note, before showing the code for the interfaces. We have decided to make all the ABP system parametric on the sort of the messages interchanged. As shown below, this means that we need to use parameterized theories and views. As noted above, this does not work in the current implementation of Maude (or Full Maude), but we still have preferred to take the chance to show the nice possibilities of the use of parameterized programming in rewriting logic.

4.1 Producer and consumer

Both producers and consumers must conform to an interface showing to the world a port through which messages are synced (sent in one case, received in the other). That is, they must conform to this parameterized theory:

```
th PROCESS-IF{Msg :: MATCHABLE} is
   pr PPTY{Msg} .
   op msgMoving : -> Ppty{Msg} .
endth
```

We always name interfaces with an ending `-IF`. We use the name `msgMoving` for the property, to be agnostic about whether it is being sent or received.

Syntactically, this is a functional theory, that is, it does not include any rules. Thus, it could be enclosed between `fth` and `endfth`. But the instantiations of

this theory have to be system modules, that is, modules including rules. So we feel it is more fitting to declare the theory as a system one. The same is true for other theories below.

(As a technical side note, Maude allows a functional theory to be instantiated by a system module. It happens, however, that a functional module parameterized by a functional theory becomes a system module when its parameter is instantiated by a system module.)

The parameter `Msg` represents the sort of the messages the process is able to send/receive. It must be instantiated (when needed) by a module (or, rather, a view) that conforms to the theory `MATCHABLE`. Indeed, when the whole system is put in place by syncing all the components, we must ensure that the producer and the consumer conform to `PROCESS-IF` instantiated with the same parameter, that is, that the producer produces the same sort of messages that the consumer is able to consume. See below. (To be strict, the sort of the messages produced must be a subsort of the ones that can be consumed.)

4.2 Sender and receiver

The sender and the receiver are the only components of the system that are aware of the protocol being used and that are expected to implement the ABP. Because the lack of directionality of properties, they conform to the same interface:

```
th PROTOCOL-IF{ProcMsg :: MATCHABLE,
               Pck2Chnl :: MATCHABLE,
               PckFChnl :: MATCHABLE} is
   pr PPTY{ProcMsg} + PPTY{Pck2Chnl} + PPTY{PckFChnl} .
   op procMsgMoving : -> Ppty{ProcMsg} .
   op pckLeaving2Chnl : -> Ppty{Pck2Chnl} .
   op pckComingFChnl : -> Ppty{PckFChnl} .
endth
```

There are three parameters and three properties, that happen to correspond one to one. This correspondence is not a general rule; indeed, interfaces do not even need to be parameterized at all. The first parameter, `ProcMsg`, represents the sort of the messages that the sender takes from the producer and that the receiver handles to the consumer. The second parameter, `Pck2Chnl`, represents the sort of the packets that the sender puts into the message channel, or the receiver puts into the ack channel, to be delivered at the other side. The third parameter, `PckFChnl`, is the sort of packets received from the channel. (We often use `2` as short for *to*, and `F` as short for *from*.) When putting the whole ABP system in place, the sending channel for the sender has to be the same as the receiving channel for the receiver, and vice versa.

It is the sender's job to split the message from the producer in as many pieces as needed and to transform it into one or more packets. The receiver has the job of decoding one or more packets to recover the message. This interface, as it stands, is valid for modules implementing any ack-based protocol, not just ABP. When putting the whole ABP system together, instantiations of some of

these parameters must coincide, to be coherent with the lines in the diagram above.

4.3 Channels

The complete ABP system uses two channels, one for message packets, the other for ack ones. Except for the sort of the packets sent through them, the interface for both channels is the same. Even the implementation of the inner workings of the channels can be the same, provided it is parametric on the sort of packets. This is the interface:

```
th CHANNEL-IF{Pck :: MATCHABLE} is
   pr PPTY{Pck} .
   ops pckComing pckLeaving : -> Ppty{Pck} .
endth
```

A channel can lose some of the packets that arrive to it, but it must be granted that a packet repeatedly put into the channel eventually reaches the other end. This kind of temporal properties can be added to a theory as semantic requirements, and would also help in compositional verification, assume-guarantee style. As already mentioned, this is pending work.

5 Blueprint

We call *blueprints* to the recipes that specify how to assemble component systems to build a composed one. Blueprints are coded as parameterized modules that receive as parameters the components, conforming to appropriate theories. The blueprint's job is to specify syncing criteria.

We have preferred not to assemble all the six components of the system in one whole unit. Instead, we assemble only the sender, the receiver, and the two channels, to produce a communication system to which a producer and consumer can be attached later. This is the blueprint for such a composition:

```
emod COMM-SYSTEM-BP
   { Sndr :: PROTOCOL-IF{Msg :: MATCHABLE,
                         MsgPck :: MATCHABLE,
                         AckPck :: MATCHABLE},
     MsgChnl :: CHANNEL-IF{MsgPck :: MATCHABLE},
     AckChnl :: CHANNEL-IF{AckPck :: MATCHABLE},
     Rcvr :: PROTOCOL-IF{Msg :: MATCHABLE,
                         AckPck :: MATCHABLE,
                         MsgPck :: MATCHABLE}
   } is
   sync Sndr || MsgChnl || AckChnl || Rcvr
      on Sndr$pckLeaving2Chnl = MsgChnl$pckComing
      /\ MsgChnl$pckLeaving = Rcvr$pckComingFChnl
      /\ Rcvr$pckLeaving2Chnl = AckChnl$pckComing
      /\ AckChnl$pckLeaving = Sndr$pckComingFChnl .
endem
```

There is much to be explained here. First, the module is enclosed between the keywords `emod` and `endem`. The `e` is for *egalitarian*. This is a new kind of

module that we propose, not present in standard Maude. Egalitarian modules are expected to include a `sync on` instruction. They must *protect* the result of the syncing, that is, they must not contain new rules, nor add new states or transition terms, nor make existing ones become equal. The only extra code that an `emod` is allowed to contain is whatever may be required for the definition of properties of the composed system, in case it is going to be used as a component in turn. We illustrate such an extreme in Section 8.

Each of the four parameters in `COMM-SYSTEM-BP` implements a theory that, in turn, is parameterized. All nested parameters have to be made explicit. Coincidence of names for parameters represents shared parameters. It is the case, for example, with `Msg`, that is a parameter of `Sndr` and `Rcvr`, and needs to be shared, as it represents the sort of the messages they interchange.

The `sync on` instruction shows which systems must be synced and with which criteria. We stick to a methodology according to which all modules in a `sync on` instruction must be among the parameters of the `emod` (this is not mandatory, however: they can be any modules already defined). Each criterion is a condition that must be satisfied when the properties are evaluated at the component stages visited at each given time.

The four criteria in our `on` clause nicely correspond to the four arrows in the diagram above. Each criterion tells that the value that is leaving a component is arriving to another.

For our implementation to work, each of these properties is expected to be defined at all states and transitions, with value `none` when no data interchange is taking place. In this way, each criterion ensures value-passing and simultaneity at the same time.

We use the syntax with the `$` symbol to make it clear to which component system each property belongs. This syntax is already used in Maude to qualify sort names from parameters. In standard Maude, operators need not be qualified, because the sorts of the operands are enough to disambiguate them. However, in our setting, we prefer to avoid mentioning stages explicitly in our criteria. So, we need a means to disambiguate.

I want to spend a few more lines on this. We have tried some other possible syntaxes for writing criteria. For instance:

```
emod M{M1 :: T1, M2 :: T2} is
   sort Stage .
   var G : Stage .
   sync M1 || M2
      on P1 @ M1(G) = P2 @ M2(G) .
endem
```

We use the name of the parameter modules as projection operators. The variable `G` is for the global, composed stage. Thus, it is explicit where each property is to be evaluated, and the `$`-syntax is not needed. This possibility, however, has a formal and a conceptual problem. The formal one is that the sort `Stage`, referred to the global, composed stages, can only be in existence after the `sync on` instruction, probably produced by it as a side effect. It is odd to declare `Stage` and `G` before that. The conceptual problem is that we prefer not to mention

the global stage, or even think about it. Because, what is the global stage of the system composed by Google's server and my browser? It does not matter, and it does not help to think of a global stage. We only need to make sure that the different components sync as appropriate. We concede that not all examples are as distributed as web browsing, but we still think it is better to avoid mentioning explicitly global stages.

6 Building packets

The setting above does not require any relation between messages (what the producer and the consumer need to interchange) and packets (what the channels are able to transmit). But they are certainly not independent. As a first approximation, we define next a module for building packets from some contents (a part of a message, for example) and a wrapper (a Boolean representing an alternating bit, in our case). It is important that both arguments are `MATCHABLE`, and that the result is as well.

```
fmod PACKET-BUILDER{Cnt :: MATCHABLE, Wrp :: MATCHABLE} is
   sorts Packet{Cnt, Wrp} Packets{Cnt, Wrp} .
   subsort Packet{Cnt, Wrp} < Packets{Cnt, Wrp} .
   op packet : Cnt$Elt Wrp$Elt -> Packet{Cnt, Wrp} .
   op noPackets : -> Packets{Cnt, Wrp} .
   op _&_ : Packets{Cnt, Wrp} Packets{Cnt, Wrp}
            -> Packets{Cnt, Wrp} [comm assoc id: noPackets] .
   op allPackets : -> Packets{Cnt, Wrp} .

   var C : Cnt$Elt .
   var W : Wrp$Elt .
   var CC : Cnt$Elts .
   var WW : Wrp$Elts .
   eq allPackets = cartesianProd(allElts.Cnt$Elts, allElts.Wrp$Elts) .

   op cartesianProd : Cnt$Elts Wrp$Elts -> Packets(Cnt, Wrp) .
   eq cartesianProd(noElts, WW) = noPackets .
   eq cartesianProd(C & CC, WW) = cartesianProdAux(C, WW)
                                  & cartesianProd(CC, WW) .
   eq cartesianProdAux(C, noElts) = noPackets .
   eq cartesianProdAux(C, W & WW) = packet(C, W)
                                    & cartesianProdAux(C, WW) .
endfm
view Packet{Cnt :: MATCHABLE, Wrp :: MATCHABLE}
   from MATCHABLE
   to PACKET-BUILDER{Cnt, Wrp} is
   sort Elt to Packet{Cnt, Wrp} .
   sort Elts to Packets{Cnt, Wrp}
   op noElts to noPackets .
   op _&_ to _&_ .
   op allElts to allPackets .
endv
```

In our case, wrappers are always Booleans, so we need to prove they are matchable:

```
view MatchableBool from MATCHABLE to BOOL + SET{Bool} is
   sort Elt to Bool .
   sort Elts to Set{Bool} .
   op noElts to empty .
   op _&_ to _,_ .
   op allElts to term (false, true) .
endv
```

The view `Bool` is the standard one from `TRIV` to `BOOL`, and is defined in Maude's prelude. We need to use Booleans and sets of Booleans together; that's why the destination of our view is `BOOL + SET{Bool}`. (A quite technical side note: the `MATCHABLE` theory requires `subsort Elt < Elts`. The standard implementation of `SET`, in Maude's prelude, includes `subsort X$Elt < NeSet{X} < Set{X}`, so everything works. But it is implementation dependent. That is, if `SET` were implemented using a constructor to transform an element into a singleton set, the view `MatchableBool`, as coded above, would not work.)

Packets sent from the receiver to the sender (that is, acks) consist, in our implementation, of the alternating bit plus a contents consisting on an *ack* mark. We need this:

```
fmod ACK is
   sort Ack .
   op ack : -> Ack .
endfm
view Ack from TRIV to ACK is
   sort Elt to Ack .
endv
view MatchableAck from MATCHABLE to ACK + SET{Ack} is
   sort Elt to Ack .
   sort Elts to Set{Ack} .
   op noElts to empty .
   op _&_ to _,_ .
   op allElts to ack .
endv
```

A concrete implementation of messages is missing, because we still insist that all our implementation is parametric on the sort of messages. So we assume that a module `MSG` and a view `MatchableMsg` have been defined, or are going to be defined when needed. With that, the two views that we are going to use are

```
Packet{Msg, MatchableBool}
Packet{MatchableAck, MatchableBool}
```

That means, in particular, that a message packet contains a whole message in one piece (in addition to the alternating bit).

7 Implementations

We show next possible implementations of the ABP sender, the ABP receiver, and the channels. As announced above, the two channels work the same, just with different arguments for the contents of packets, so only one implementation is needed for them.

7.1 ABP sender

It is often useful to identify the internal *modes* in which a system can be, and use them as part of the state terms and transition terms of the system. For the ABP sender, we use three state modes:

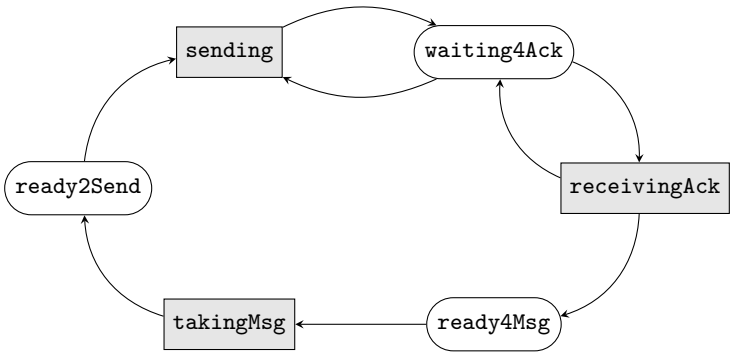
- `ready2Send`: ready to send a packet through the message channel,
- `waiting4Ack`: waiting for an ack to arrive through the ack channel, and
- `ready4Msg`: ready to receive a new message from the producer.

For transitions, we use three modes as well:

- `takingMsg`: taking a new message from the producer,
- `sending`: sending a packet through the message channel, and
- `receivingAck`: receiving a packet from the ack channel.

We tend to give transition modes names ending in, or containing, `ing` (in this particular case, also a state bears such a name).

With these modes, the workings of the sender can be pictured like this:



The flow from mode to mode is rather deterministic, except in two cases: after having received an ack, depending on the value of the alternating bit, we may need to keep waiting for an appropriate bit or to go on for the next message from the producer; and we can exit a `waiting4Ack` state either because we have indeed received an ack (be it valid or not) or because, tired of waiting, we decide to send our message one more time.

Apart from the mode, a state or transition term needs to include information about the internal configuration, or internal memory, of the system. In our case, the internal configuration of the sender may include the last message taken from the producer, the value of the alternating bit currently in use, the messages or packets ready to be interchanged, and so on. Many of these values would be `none` some time, even most of the time, but this is no problem. However, it seems appropriate to keep the number of variables to a small decent amount.

Our packets are built from messages and bits, and these two pieces of data are almost enough. These two values alone are enough to deduce the whole internal configuration of the sender, except in one case: when the sender is in the course of receiving an ack, the bit coming and the bit last sent have to be kept both, for comparison purposes. We decide, in this example, to use the same three data all the time, even though some of them are going to be `none` most of the time. See below how all this translates into code.

In the implementation of the sender that follows, each transition involves some interchange of data with other components. This seems to be a useful pattern, but it is not necessary: there may be *internal* transitions and also *interchanging* states. This is our implementation:

```
aemod ABP-SENDER{Msg :: MATCHABLE} is
   pr STAGES .
   pr MAYBE{Matchable}{Msg} .
   pr MAYBE{Bool} .
   sorts StateMode TransMode Config .
   ops ready2Send waiting4Ack ready4Msg : -> StateMode .
   ops takingMsg sending receivingAck : -> TransMode .
   op (_,_,_) : Maybe{Matchable}{Msg} Bool Maybe{Bool} -> Config .
   op (_,_) : StateMode Config -> State .
   op (_,_) : TransMode Config -> Trans .
   var M : Msg$Elt .
   var MM : Msg$Elts .
   var B : Bool .
   var C : Config .
   crl [(takingMsg, (M, B, none))] :
      (ready4Msg, (none, B, none)) => (ready2Send, (M, B, none))
      if M & MM := allElts .
   rl [(sending, C)] :
      (ready2Send, C) => (waiting4Ack, C) .
   rl [(sending, C)] :
      (waiting4Ack, C) => (waiting4Ack, C) .
   rl [(receivingAck, (M, B, not B))] :
      (waiting4Ack, (M, B, none)) => (waiting4Ack, (M, B, none)) .
   rl [(receivingAck, (M, B, B))] :
      (waiting4Ack, (M, B, none)) => (ready4Msg, (none, not B, none)) .
   eq init = (ready4Msg, (none, true, none)) .
endaem
```

This module is enclosed between `aemod` and `endaem`. The `e` in those keywords is for *egalitarian*, as above; the `a` is for *atomic*, that is, not composed. Atomic egalitarian modules are the ones used to implement basis systems. These are the only ones allowed to contain rules, and the definition of states and transitions. Syntactically, `aemod` is very similar to a standard system module, with the main difference that rule labels can be terms of any complexity.

The internal configuration of the sender is given by a triplet:

```
Maybe{Matchable}{Msg} Bool Maybe{Bool}
```

The only piece of data that is always available is the value of the alternating bit currently in use. It is set to `true` in the initial state `init`, and after that, it always has an actual Boolean value. The other two pieces of data, the message being processed and the bit being received, are sometimes `none`, and we need to

declare the parameters as `Maybe{...}`. The module `MAYBE` expects a `TRIV`, but we need to feed it a `MATCHABLE`; that is why we need the partially instantiating view `Matchable`.

The rules represent the mode transitions shown in the diagram, together with their associated changes in the internal configuration.

In the definition of the `init` stage, we set the initial message to `none`. It relies on this data being of a *maybe* sort, guaranteed to include the special value. Otherwise, the initial stage could not have been defined so easily, because it would depend on the particular instantiation of the parameter `Msg`.

This implementation needs some fairness conditions to work properly. Otherwise, the sender may have an ack available but ignore it and keep on sending the same message with the same bit, preventing the whole system from evolving. The same happens to the implementation of the receiver, and to that of the channels, both below. Fairness conditions like these ones are not possible to add as code within the implementation. Again, temporal properties like these ones, representing semantic requirements, can be added to our theories.

For this implementation to actually conform to `PROTOCOL-IF`, we need to define properties. In this case, it even seems the implementation is not complete without the properties, as their values tell us what they are ready to receive or send through their *ports*. Properties for syncing are usually defined in a module extending the one that specifies the inner workings of the system.

```
aemod ABP-SENDER-PPT{Msg :: MATCHABLE} is
   pr ABP-SENDER{Msg} .
   pr PACKET-BUILDER{Msg, MatchableBool} .
   pr PACKET-BUILDER{MatchableAck, MatchableBool} .
   pr PPTY{Msg} .
   pr PPTY{Packet{Msg, MatchableBool}} .
   pr PPTY{Packet{MatchableAck, MatchableBool}} .
   op procMsgMoving : -> Ppty{Msg} .
   op pckLeaving2Chnl : -> Ppty{Packet{Msg, MatchableBool}} .
   op pckComingFChnl : -> Ppty{Packet{MatchableAck, MatchableBool}} .
   var G : Stage .
   var M : Msg$Elt .
   vars B B' : Bool .
   eq procMsgMoving @ (takingMsg, (M, B, none)) = M .
   eq procMsgMoving @ G = none [owise] .
   eq pckLeaving2Chnl @ (sending, (M, B, none)) = packet(M, B) .
   eq pckLeaving2Chnl @ G = none [owise] .
   eq pckComingFChnl @ (receivingAck, (M, B, B')) = packet(ack, B') .
   eq pckComingFChnl @ G = none [owise] .
endaem
```

The view is now easy:

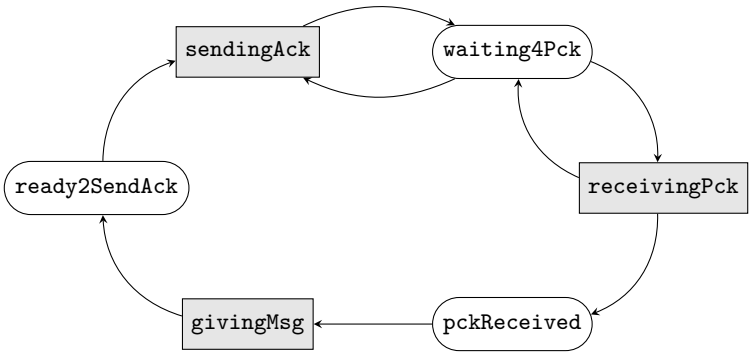
```
view AbpSender{Msg :: MATCHABLE}
   from PROTOCOL-IF{Msg,
                    Packet{Msg, MatchableBool},
                    Packet{MatchableAck, MatchableBool}}
   to ABP-SENDER-PPT{Msg} is
   op procMsgMoving to procMsgMoving .
   op pckLeaving2Chnl to pckLeaving2Chnl .
   op pckComingFChnl to pckComingFChnl .
```

```
endv
```

This view only needs a parameter to implement a theory with three, because the other two parameters are built from the first using the `PACKET-BUILDER` tool define earlier.

7.2 ABP receiver

The workings of the receiver are similar to the ones for the sender. We hope the diagram of modes and the code are now easy to understand with no further remarks.




```
aemod ABP-RECEIVER{Msg :: MATCHABLE} is
   pr STAGES .
   pr MAYBE{Matchable}{Msg} .
   pr MAYBE{Bool} .
   sorts StateMode TransMode Config .
   ops ready2SendAck waiting4Pck pckReceived : -> StateMode .
   ops givingMsg sendingAck receivingPck : -> TransMode .
   op (_,_,_) : Maybe{Matchable}{Msg} Bool Maybe{Bool} -> Config .
   op (_,_) : StateMode Config ->  State .
   op (_,_) : TransMode Config -> Trans .
   var M : Msg$Elt .
   var MM : Msg$Elts .
   var B : Bool .
   var C : Config .
   rl [(givingMsg, (M, B, none))] :
      (pckReceived, (M, B, none)) => (ready2SendAck, (none, B, none)) .
   rl [(sendingAck, C)] :
      (ready2SendAck, C) => (waiting4Pck, C) .
   rl [(sendingAck, C)] :
      (waiting4Pck, C) => (waiting4Pck, C) .
   crl [(receivingPck, (M, B, B))] :
      (waiting4Pck, (none, B, none) => (waiting4Pck, (none, B, none))
      if M & MM := allElts .
   crl [(receivingPck, M, B, not B)] :
      (waiting4Pck, (none, B, none)) => (pckReceived, (M, not B, none))
      if M & MM := allElts .
   eq init = (waiting4Pck, (none, false, none)) .
endaem
```

```
aemod ABP-RECEIVER-PPT{Msg :: MATCHABLE} is
   pr ABP-RECEIVER{Msg} .
   pr PACKET-BUILDER{Msg, MatchableBool} .
   pr PACKET-BUILDER{MatchableAck, MatchableBool} .
   pr PPTY{Msg} .
   pr PPTY{Packet{Msg, MatchableBool}} .
   pr PPTY{Packet{MatchableAck, MatchableBool}} .
   op procMsgMoving : -> Ppty{Msg} .
   op pckLeaving2Chnl : -> Ppty{Packet{MatchableAck, MatchableBool}} .
   op pckComingFChnl : -> Ppty{Packet{Msg, MatchableBool}} .
   var G : Stage .
   var M : Msg$Elt .
   vars B B' : Bool .
   eq procMsgMoving @ (givingMsg, (M, B, none)) = M .
   eq procMsgMoving @ G = none [owise] .
   eq pckLeaving2Chnl @ (sendingAck, (none, B, none)) = packet(ack, B) .
   eq pckLeaving2Chnl @ G = none [owise] .
   eq pckComingFChnl @ (receivingPck, (M, B, not B)) = packet(M, B) .
   eq pckComingFChnl @ G = none [owise] .
endaem
```

```
view AbpReceiver{Msg :: MATCHABLE}
   from PROTOCOL-IF{Msg,
                    Packet{Msg, MatchableBool},
                    Packet{MatchableAck, MatchableBool}}
   to ABP-RECEIVER-PPT{Msg} is
   op procMsgMoving to procMsgMoving .
   op pckLeaving2Chnl to pckLeaving2Chnl .
   op pckComingFChnl to pckComingFChnl .
endv
```

7.3 The channels

The implementation of a channel is quite straightforward. It can just accept a packet, deliver it, or lose it. We could use here the same *modes* thing as above, but it doesn't pay off for this simple system.

```
aemod CHANNEL{Pck :: MATCHABLE} is
   pr STAGES .
   pr MAYBE{Matchable}{Pck} .
   subsort Maybe{Matchable}{Pck} < State .
   ops acceptingPck deliveringPck : Pck$Elt -> Trans .
   op losingPck : -> Trans .
   var P : Pck$Elt .
   var PP : Pck$Elts .
   crl [acceptingPck(P)] : none => P if P & PP := allElts .
   rl [deliveringPck(P)] : P => none .
   rl [losingPck] : P => none .
   eq init = none .
endaem
```

```
aemod CHANNEL-PPT{Pck :: MATCHABLE} is
   pr CHANNEL{Pck} .
   pr STAGES .
   pr PPTY{Pck} .
```

```
   op pckComing pckLeaving : -> Ppty{Pck} .
   var P : Pck$Elt .
   var G : Stage .
   eq pckComing @ acceptingPck(P) = P .
   eq pckComing @ G = none [owise] .
   eq pckLeaving @ deliveringPck(P) = P .
   eq pckLeaving @ G = none [owise] .
endaem
```

```
view Channel{Pck :: MATCHABLE}
   from CHANNEL-IF{Pck}
   to CHANNEL-PPT{Pck} is
   op pckComing to pckComing .
   op pckLeaving to pckLeaving .
endv
```

8 Final system

With all the components implemented, it only remains to feed them to the blueprint to obtain the ABP system. We prefer to let the sort of messages as a parameter until the end:

```
emod ABP-SYSTEM{Msg :: MATCHABLE} is
   pr COMM-SYSTEM-BP{AbpSender{Msg},
                     Channel{Packet{Msg, MatchableBool}},
                     Channel{Packet{MatchableAck, MatchableBool}},
                     AbpReceiver{Msg}} .
endem
```

Before finishing, it is interesting to note that any implementation of `COMM-SYSTEM-BP` can be viewed as a channel—a kind of trustworthy channel. We only need to make explicit the properties:

```
emod COMM-SYSTEM-BP-PPT
   { Sndr :: PROTOCOL-IF{Msg :: MATCHABLE,
                         MsgPacket :: MATCHABLE,
                         AckPacket :: MATCHABLE},
     MsgChnl :: CHANNEL-IF{MsgPacket :: MATCHABLE},
     AckChnl :: CHANNEL-IF{AckPacket :: MATCHABLE},
     Rcvr :: PROTOCOL-IF{Msg :: MATCHABLE,
                         AckPacket :: MATCHABLE,
                         MsgPacket :: MATCHABLE}
   } is
   pr COMM-SYSTEM-BP{Sndr, MsgChnl, AckChnl, Rcvr} .
   pr PPTY{Msg} .
   ops msgComing msgLeaving : -> Ppty{Msg} .
   var G : Stage .
   eq msgComing @ G = procMsgMoving @ Sndr(G) .
   eq msgLeaving @ G = procMsgMoving @ Rcvr(G) .
endem
```

This also allows us to show how properties of a composed system are defined in terms of the properties of the components. The sort `Stage` for the composed system is assumed to be declared and defined (in a tuple-like way) as a side

effect of the `sync on` instruction. The same for the projection operators with the names of the component systems.

We are using here the global stage of the composed system, against which we argued in Section 5. It is difficult to avoid it, and it can be justified now: if the composed system is going to be used as a component in turn, it is an indication that it has a kind of unity, a complete existence as a system.

With these properties, the following shows how the system can be viewed as a channel:

```
view CommSystemAsChannel{Msg :: MATCHABLE}
   from CHANNEL-IF{Msg}
   pr COMM-SYSTEM-BP{AbpSender{Msg},
                     Channel{Packet{Msg, MatchableBool}},
                     Channel{Packet{MatchableAck, MatchableBool}},
                     AbpReceiver{Msg}
                    } is
   op pckComing to msgComing .
   op pckLeaving to msgLeaving .
endv
```

9 Final remarks

Unfortunately, as already mentioned, most of the code in this paper does not run on the current implementations of Maude and Full Maude. We can make do without nested parameters by using the *poor man's parameterization* trick: importing the implementation module `msg.maude` into any module that would instead take `Msg` as parameter. This is certainly not perfect. A complete implementation of parameterized programming in Maude would be great, but it remains to be seen if it will be available at some future time.

We take as our job to implement in the near future the other missing ingredient, that is, everything that is needed to perform the synchronous composition in Maude. Our aim is to make executable a specification equivalent to the one given up here.

References

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