A Behavior Language for Story-based Believable Agents

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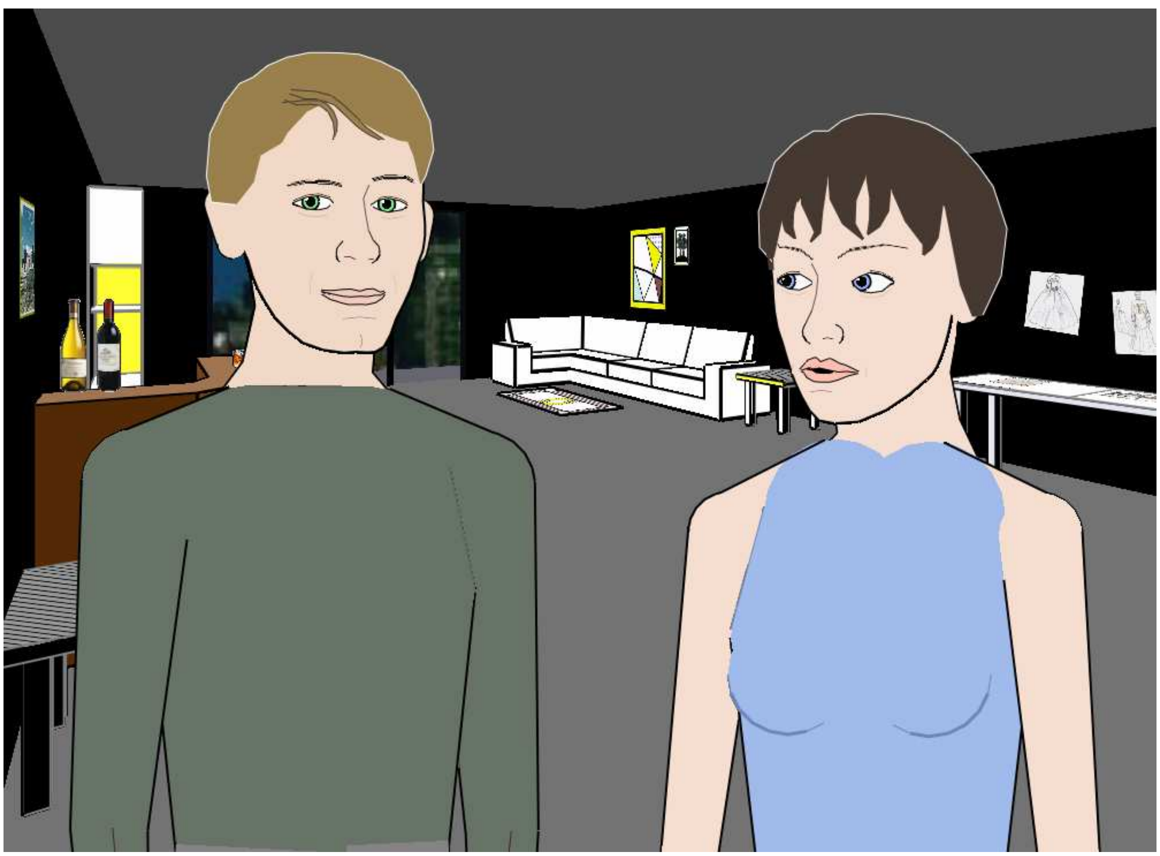
Abstract

ABL is a reactive planning language, based on the Oz Project language Hap, designed specifically for authoring believable agents - characters which express rich personality, and which, in our case, play roles in an interactive, dramatic story world called Façade. Here we give a brief overview of the language Hap and discuss the new features in ABL, focusing on ABL's support for multi-character coordination. We also describe the ABL idioms we are using to organize character behaviors in the context of an interactive drama.

Introduction

Façade is an attempt to move beyond traditional branching or hyper-linked narrative, to create a fully-realized interactive drama - a dramatically interesting virtual world inhabited by computer-controlled characters, within which the user (hereafter referred to as the player) experiences a story from a first person perspective (Mateas and Stern 2000). The complete, real-time, 3D, one-act interactive drama will be available in a free public release at the end of 2002.

You, the player, using your own name and gender, play the character of a longtime friend of Grace and Trip, an attractive and materially successful couple in their early thirties. During an evening get-together at their apartment that quickly turns ugly, you become entangled in the high-conflict dissolution of Grace and Trip's marriage. No one is safe as the accusations fly, sides are taken and irreversible decisions are forced to be made. By the end of this intense one-act play you will have changed the course of Grace and Trip's lives -- motivating you to re-play the drama to find out how your interaction could make things turn out differently the next time. The player interacts by navigating in the world, manipulating objects, and, most



Screen shot of *Façade* showing the characters Grace and Trip significantly, through natural language dialogue.

This project raises a number of interesting AI research issues, including drama management for coordinating plot-level interactivity, broad but shallow support for natural language understanding and discourse management, and autonomous believable agents in the context of interactive story worlds. This paper focuses on the last issue, describing the custom believable agent language developed for this project, and the idioms developed within this language for organizing character behaviors.

Project Goals

The field of interactive drama concerns itself with building dramatically interesting virtual worlds inhabited by computer-controlled characters, within which the user (hereafter referred to as the player) experiences a story from a first person perspective. Over the past decade there has been a fair amount of research on believable agents, that is, autonomous characters exhibiting rich personalities, emotions, and social interactions (Bates, Loyall and Reilly 1992; Blumberg 1996; Lester and Stone 1997; Mateas 1999; Stern 1999). There has been comparatively little work, however, exploring how the reactive behavior of believable agents can be integrated with the more deliberative nature of a story plot, so as to build interactive, dramatic worlds (Weyhrauch 1997). Likewise, the computer game industry has had little success in creating powerful interactive narrative experiences in their games. Although games often have characters in them, such as in adventure or role-playing games, with few exceptions they are not "believable", behaving one-dimensionally and predictably, with little potential for more than shallow interactivity.

Motivated by their belief that a "fully-realized" computer-based interactive drama has not yet been built, the authors are currently engaged in a three year collaboration to build Façade, an interactive story integrating an interdisciplinary set of artistic practices and artificial intelligence technologies.

Story Requirements

The story requirements describe the properties we wish our *particular* interactive drama to have. (These are not intended to be absolute requirements; that is, this is not a description of the properties that all interactive stories must have.)

Short one-act play. Any one run of the scenario should take the player 15 to 20 minutes to complete. We focus on a short story for a couple of reasons. Building an interactive story has all the difficulties of writing and producing a non-interactive story (film or play) plus all the difficulty of supporting true player agency in the story. In exploring this new interactive art form it makes sense to first work with a distilled form of the problem, exploring scenarios with the minimum structure required to support dramatically interesting interaction. In addition, a short one-act play is an extreme, contrarian response to the many hours of game play celebrated in the design of contemporary computer games. Instead of providing the player with 40 to 60 hours of episodic action and endless wandering in a huge world, we want to design an experience that provides the player with 15 to 20 minutes of emotionally intense, tightly unified, dramatic action. The story should have the intensity, economy and catharsis of traditional drama.

Relationships. Rather than being about manipulating magical objects, fighting monsters, and rescuing princesses, the story should be about the emotional entanglements of human relationships. We are interested in interactive experiences that appeal to the adult, non-computer geek, movie-and-theater-going public.

Three characters. The story should have three characters, two controlled by the computer and one controlled by the player. Three is the minimum number of characters needed to support complex social interaction without placing the responsibility on the player to continually move the story forward. If the player is shy or confused about interacting, the two computer controlled characters can conspire to set up dramatic situations, all the while trying to get the player involved.

The player should be the protagonist. Ideally the player should experience the change in the protagonist as a personal journey. The player should be more than an "interactive observer," not simply poking at the two computer controlled characters to see how they change.

Embodied interaction should matter. Though dialogue should be a significant (perhaps the primary) mechanism for character interaction, it should not be the sole mechanism. Embodied interaction, such as moving from one location to another, picking up an object, or touching a character, should play a role in the action. These physical actions should carry emotional and symbolic weight, and should have a real influence on the characters and their evolving interaction. The physical representation of the characters and their environment should support action significant to the plot.

Action takes place in a single location. This provides unity of space and forces a focus on plot and character interaction.

The player should not be over-constrained by a role. The amount of non-interactive exposition describing the player's role should be minimal. The player should not have the feeling of playing a role, of actively having to think about how the character they are playing would react. Rather, the player should be able to be herself as she explore the dramatic situation. Any role-related scripting of the interactor (Murray 1998) should occur as a natural by-product of their interaction in the world. The player should "ease into" their role; the role should be the "natural" way to act in the environment, given the dramatic situation.

ABL overview

ABL (**A B**ehavior **L**anguage, pronounced "able") is based on the Oz Project believable agent language Hap developed by A. B. Loyall (Loyall 1997, Bates, Loyall and Reilly 1992). The ABL compiler is written in Java and targets Java; the generated Java code is supported by the ABL runtime system.

ABL modifies Hap in a number of ways, changing the syntax (making it more Java-like), generalizing the mechanisms by which an ABL agent connects to a sensory-motor system, and, most significantly, adding new constructs to the language, including language support for multi-agent coordination in the carrying out of dramatic action. This section provides an overview of the ABL language and discusses some of the ways in which ABL modifies or extends Hap. The discussion of joint behaviors, the mechanism for multi-agent coordination, occurs in its own section below.

Hap Semantics

Since ABL builds on top of Hap, here we briefly describe the organization and semantics of a Hap program by walking through a series of examples. All examples use the ABL syntax.

Hap/ABL programs are organized as collections of behaviors. In sequential behaviors, the steps of the behavior are accomplished serially. As each step is executed, it either succeeds or fails; step success makes the next step available for execution. If any step fails, it causes the enclosing behavior to fail. An example sequential behavior is shown below.

```
sequential behavior AnswerTheDoor() {
  WME w;
  with success_test { w = (KnockWME) } wait;
  act sigh();
  subgoal OpenDoor();
  subgoal GreetGuest();
  mental_act { deleteWME(w); }
}
```

In this sequential behavior, an agent waits for someone to knock on a door, sighs, then opens the door and greets the guest. This behavior demonstrates the four basic step types, namely `wait`, `act`, `subgoal`, and `mental_act`. Wait steps are never chosen for execution; a naked wait step in a sequential behavior would block the behavior from executing past the wait. However, when combined with a success test, a wait step can be used to make a demon which waits for a condition to become true. Success tests are continuously monitored conditions which, when they become true, cause their associated step to immediately succeed. Though in this example the success test is associated with a wait step to make a demon, it can be associated with any step type.

Success tests, as well as other tests which will be described shortly, perform their test against the agent's working memory. A working memory contains a number of working memory elements (WMEs) which hold information. WMEs are like instances in an object-oriented language; every WME has a type plus some number of typed fields which can take on values. As described later on in the paper, WMEs are also the mechanism by which an agent becomes aware of sensed information. In this example the success test is looking for WMEs of type KnockWME, which presumably is placed in the agent's working memory when someone knocks on a door. Since there are no field constraints in the test, the test succeeds as soon as a KnockWME appears.

An act step tells the agent's body (sensory-motor system) to perform an action. For graphical environments such as Façade, physical acts will ultimately be translated into calls to the animation engine, though the details of this translation are hidden from the Hap/ABL program. In this example, the act makes the body sigh. Note that physical acts can fail - if the sensory-motor system determines that it is unable to carry out the action, the corresponding act step fails, causing the enclosing behavior to fail.

Subgoal steps establish goals that must be accomplished in order to accomplish the behavior. The pursuit of a subgoal within a behavior recursively results in the selection of a behavior to accomplish the subgoal.

Mental acts are used to perform bits of pure computation, such as mathematical computations or modifications to working memory. In the final step of the example, the mental_act deletes the KnockWME (making a call to a method defined on ABL agents), since the knocking has now been dealt with. In ABL, mental acts are written in Java.

The next example demonstrates how Hap/ABL selects a behavior to accomplish a subgoal through signature matching and precondition satisfaction.

```
sequential behavior OpenDoor() {
  precondition {
    (KnockWME doorID :: door)
    (PosWME spriteID == door pos :: doorPos)
    (PosWME spriteID == me  pos :: myPos)
    (Util.computeDistance(doorPos, myPos) > 100)
  }
  specificity 2;
  // Too far to walk, yell for knocker to come in
  subgoal YellAndWaitForGuestToEnter(doorID);
}

sequential behavior OpenDoor() {
  precondition { (KnockWME doorID :: door) }
  specificity 1;
  // Default behavior - walk to door and open
  . . .
}
```

In this example there are two sequential behaviors `OpenDoor()`, either of which could potentially be used to satisfy the goal `OpenDoor()`. The first behavior opens the door by yelling for the guest to come in and waiting for them to open the door. The second behavior (details elided) opens the door by walking to the door and opening it. When `AnswerTheDoor()` pursues the subgoal `OpenDoor()`, Hap/ABL determines, based on signature matching, that there are two behaviors which could possibly open the door. The precondition of both behaviors is executed. In the event that only one of the preconditions is satisfied, that behavior is chosen as the method to use to accomplish the subgoal. In the event that both preconditions are satisfied, the behavior with the highest specificity is chosen. If there are multiple satisfied behaviors with highest specificity, one is chosen at random. In this example, the first `OpenDoor()` behavior is chosen if the lazy agent is too far from the door to walk there ("too far" is arbitrarily represented as a distance > "100").

The precondition demonstrates the testing of the fields of a WME. The `::` operator assigns the value of the named WME field on the left of the operator to the variable on the right.[1] This can be used both to grab values from working memory which are then used in the body of the behavior, and to chain constraints through the WME test.

The last example demonstrates parallel behaviors and context conditions.

```
parallel behavior
YellAndWaitForGuestToEnter(int doorID) {
  precondition { (CurrentTimeWME t :: startT) }
  context_condition {
    (CurrentTimeWME t <= startT + 10000) }
  number_needed_for_success 1;

  with success_test {
    (DoorOpenWME door == doorID) } wait;
  with (persistent) subgoal YellForGuest(doorID);
}
```

In a parallel behavior, the steps are pursued simultaneously. `YellAndWaitForGuestToEnter(int)` simultaneously yells "come in" towards the door (the door specified by the integer parameter) and waits to actually see the door open. The persistent modifier on the `YellForGuest(int)` subgoal makes the subgoal be repeatedly pursued, regardless of whether the subgoal succeeds or fails (one would imagine that the behavior that does the yelling always succeeds). The `number_needed_for_success` annotation (only usable on parallel behaviors) specifies that only one step has to succeed in order for the behavior to succeed. In this case, that one step would be the demon step waiting for the door to actually open. The context condition is a continuously monitored condition that must remain true during the execution of a behavior. If the context condition fails during execution, then the behavior immediately fails. In this example, the context condition tests the current time, measured in milliseconds, against the time at which the behavior started. If after 10 seconds the door hasn't yet opened (the guest isn't coming in), then the context condition will cause the behavior to fail.

As failure propagates upwards through the subgoal chain, it will cause the first `OpenDoor()` behavior to fail, and eventually reach the `OpenDoor()` subgoal in `AnswerTheDoor()`. The subgoal will then note that there is another `OpenDoor()` behavior which has not been tried yet and whose precondition is satisfied; this behavior will be chosen in an attempt to satisfy the subgoal. So if the guest doesn't enter when the agent yells for awhile, the agent will then walk over to the door and open it.

Finally, note that parallel behaviors introduce multiple lines of expansion into a Hap/ABL program. Consequently, the current execution state of the program is represented by a tree, the active behavior tree (ABT), where the leaves of the tree constitute the current set of executable steps.

These examples give a sense for the Hap semantics which ABL reimplements and extends. There are many other features of Hap (also implemented in ABL) which it is not possible to re-describe here, including how multiple lines of expansion mix (based on priority, blocking on physical acts, and a preference for pursing the current line of expansion), declaration of behavior and step conflicts (and the resulting concept of suspended steps and behaviors), and numerous annotations which modify the default semantics of failure and success propagation. The definitive reference on Hap is of course Loyall's dissertation (Loyall 1997).

ABL Extensions

ABL extends Hap in a number of ways, including:

- Generalizing the mechanisms for connecting to the sensory-motor system. The ABL runtime provides abstract superclasses for sensors and actions. To connect an ABL program to a new sensory-motor system (e.g. animation engine, robot), the author merely defines specific sensors and actions as concrete subclasses of the abstract sensor and action classes. ABL also includes additional language constructs for binding sensors to WMEs. ABL then takes responsibility for calling the sensors appropriately when bound WMEs are referenced in working memory tests.
- Atomic behaviors. Atomic behaviors prevent other active behaviors from mixing in. Atomic behaviors are useful for atomically updating state (e.g. updating multiple WMEs atomically), though they should be used sparingly, as a time-consuming atomic behavior could impair reactivity.
- Reflection. ABL gives behaviors reflective access to the current state of the ABT, supporting the authoring of meta-behaviors which match on patterns in the ABT and dynamically modify other running behaviors. Supported ABT modifications include succeeding, failing or suspending a goal or behavior, and modifying the annotations of a subgoal step, such as changing the persistence or priority. Safe reflection is provided by wrapping all ABT nodes in special WMEs. Pattern matching on ABT state is then accomplished through normal WME tests. A behavior can only touch the ABT through the reflection API provided on these wrapper WMEs.
- Multiple named memories. Working memories can be given a public name, which then, through the name, are available to all ABL agents. Any WME test can

[1] In ABL, a locally-scoped appropriately typed variable is automatically declared if it is assigned to in a WME test and has not been previously explicitly declared.

simultaneously reference multiple memories (the default memory is the agent's private memory). Named memories are used by the joint behavior mechanisms (see below) for the construction of team memories. In Façade, named memories are also useful for giving agents access to a global story memory.

Dramatic Beats

The rest of this paper discusses ABL's support for joint action and the idioms we've developed for organizing character behaviors within Façade. But both the support for joint action and the programming idioms are motivated by an analysis which first appeared in (Mateas and Stern 2000) arguing that behaviors for story-based believable agents should be organized around the dramatic beat. This argument is briefly recapitulated here.

Autonomy and story-based believable agents

Most work in believable agents has been organized around the metaphor of strong autonomy. Such an agent chooses its next action based on local perception of its environment plus internal state corresponding to the goals and possibly the emotional state of the agent. Using autonomy as a metaphor driving the design of believable agents works well for believable agent applications in which a single agent is facilitating a task, such as instructing a student (Lester & Stone 1997), giving a presentation, or in entertainment applications in which a user develops a long-term relationship with the characters by "hanging-out" with them (Stern 1999). But for believable agents used as characters in a story world, strong autonomy becomes problematic. Knowing which action to take at any given time depends not just on the private internal state of the agent plus current world state, but also on the current story state, including the entire past history of interactions building on each other towards some end. The global nature of story state is inconsistent with the notion of an autonomous character that makes decisions based only on private goal and emotion state and local sensing of the environment.

Only a small amount of work has been done on the integration of story and character. This work has preserved the strong autonomy of the characters by architecturally dividing the responsibility for state maintenance between a drama manager that is responsible for maintaining story state, and the believable agents that are responsible for maintaining character state and making the moment-by-moment behavior decisions (e.g. Weyhrauch 1997). In this approach, the character is still responsible for most of the decision making. Occasionally the drama manager will modify one or more of the characters' behaviors (by giving them a new goal or directly instigating a behavior) so as to move the plot along. In the absence of the drama manager, the character would still perform its normal autonomous behavior. This architecture makes several assumptions regarding the nature of interactive drama and believable agents: drama manager decisions are infrequent, the internal structure of the believable agents can be reasonably decoupled from their interaction with the drama manager, and multiple-character coordination is handled within the agents. Let's explore each of these assumptions.

Infrequent guidance of strongly autonomous believable agents means that most of the time, behavior selection for the believable agents will occur locally, without reference to any (global) story state. The drama manager will intervene to move the story forward at specific points; the rest of the time the story will be "drifting," that is, action will be occurring without explicit attention to story movement. Weyhrauch (Weyhrauch 1997) does state that his drama manager was designed for managing the sequencing of plot points, that is, for guiding characters so as to initiate the appropriate next scene necessary to make the next plot point happen (whatever plot point has been decided by the drama manager). Within a scene, some other architectural component, a "scene manager," would be necessary to manage the playing out of the individual scene. And this is where the assumption of infrequent, low-bandwidth guidance becomes violated. As is described below, the smallest unit of story structure within a scene is the beat, a single action/reaction pair. The scene-level drama manager will thus need to continuously guide the autonomous decision making of the agent. This frequent guidance from the drama manager will be complicated by the fact that low-bandwidth guidance (such as giving a believable agent a new goal) will interact strongly with the moment-by-moment internal state of the agent, such as the set of currently active goals and behaviors, leading to surprising and potentially unwanted behavior. In order to reliably guide an agent, the scene-level drama manager will have to engage in higher-bandwidth guidance involving the active manipulation of internal agent state (e.g. editing the currently active goal tree). Authoring strongly autonomous characters for story-worlds is not only extra, unneeded work (given that scene-level guidance will need to intervene frequently), but actively makes guidance more difficult, in that the drama manager will have to compensate for the internal decision-making processes (and associated state) of the agent.

As the drama manager provides guidance, it will often be the case that the manager will need to carefully coordinate multiple characters so as to make the next story event happen. For example, it may be important for two characters to argue in such a way as to conspire towards the revelation of specific information at a certain moment in the story. To achieve this with autonomous agents, one could try to back away from the stance of strong autonomy and provide special goals and behaviors within the individual agents that the drama manager can activate to create coordinated behavior. But even if the character author provides these special coordination hooks, coordination is still being handled at the individual goal and behavior level, in an ad-hoc way. What one really wants is a way to *directly* express coordinated character action.

Integrating Plot and Character with the Dramatic Beat

Given that a strong architectural separation of character and story is problematic, one is left with the question of what architectural principle could be used to more tightly integrate character and story; the answer is found in the theory of dramatic writing in the concept of the dramatic beat.

In dramatic writing, stories are thought of as consisting of events that turn (change) values (McKee 1997). A value is a property of an individual or relationship, such as trust, love, hope (or hopelessness), etc. A story event is precisely any activity that turns a value. If there is activity – characters running around, witty dialogue, buildings and bridges exploding, and so on – but this activity is not turning a value, then there is no story event, no dramatic action. Thus one of the primary goals of an interactive drama system should be to make sure that all activity turns values. Of course these values should be changed in such a way as to make some plot arc happen that enacts the story premise (the Façade story premise is "To be happy you must be true to yourself"). Beats are the smallest unit of value change. Roughly, a beat consists of one or more action/reaction pairs between characters. Generally speaking, in the interest of maintaining economy and intensity, a beat should not last longer than a few actions or lines of dialogue.

In Façade beats become first class architectural entities, consisting of *both* the declarative knowledge needed to sequence beats in a dramatically interesting way (the details of Façade's drama manager are not discussed in this paper) and the procedural knowledge, expressed as ABL behaviors, necessary for the characters to jointly carry out the dramatic action within the beat. The rest of this paper discusses ABL's support for joint action and the idioms (ways of using ABL) that we have developed for organizing behaviors within a beat.

Support for Joint Action

In order to facilitate the coordination of multiple characters, we have extended the semantics of Hap to support *joint goals and behaviors.* The driving design goal of joint behaviors is to combine the rich semantics for individual expressive behavior offered by Hap with support for the automatic synchronization of behavior across multiple agents.

Joint Behaviors

In ABL, the basic unit of coordination is the joint behavior. When a behavior is marked as joint, ABL enforces synchronized entry and exit into the behavior. Part of the specification for an "offer the player a drink" behavior from Façade is shown below. This will be used as the guiding behavior specification in the joint behavior examples provided in this paper. To simplify the discussion, the example leaves out the specification of how player activity would modify the performance of this beat; the next section describes idioms for supporting interactivity. Also, it should be pointed out that though this example involves only two characters coordinating, the coordination framework and implemented infrastructure is general enough to handles teams of *n* coordinating characters.

> (At the beginning of the behavior, Trip starts walking to the bar. If he gets to the bar before the end of the behavior, he stands behind it while delivering lines.)
> **Trip**: A beer? Glass of wine? (Grace smiles at player. Short pause)
> **Trip**: You know I make a mean martini. (Grace frowns at Trip partway into line. At the end of line, she rolls her eyes at the ceiling.)
> **Grace**: (shaking her head, smiling) Trip just bought these fancy new cocktail shakers. He's always looking for a chance to show them off. (If Trip is still walking to the bar, he stops at "shakers". At "shakers" Trip looks at Grace and frowns slightly. At the end of the line he looks back at the player and smiles. If he was still on the way to the bar, he resumes walking to the bar).

In order to perform this coordinated activity, Grace and Trip must first synchronize on offering a drink, so that they both know they are working together to offer the drink. Grace and Trip both have the following behavior definition in their respective behavior libraries.

```
joint sequential behavior OfferDrink() {
  team Grace, Trip;
  // The steps of Grace's and Trip's OfferDrink()
  // behaviors differ.
}
```

The declaration of a behavior as `joint` tells ABL that entry into and exit from the behavior must be coordinated with team members, in this case Grace and Trip. *Entry* into a behavior occurs when the behavior is chosen to satisfy a subgoal. *Exit* from the behavior occurs when the behavior succeeds, fails, or is suspended. Synchronization is achieved by means of a two-phase commit protocol:

1. The initiating agent broadcasts an intention (to enter, succeed, fail or suspend) to the team.
2. All agents receiving an intention respond by, in the case of an entry intention, signaling their own intention to enter or a rejection of entry, or in the case of exit signaling their own intention to succeed, fail, or suspend.
3. When an agent receives intentions from all team members, the agent performs the appropriate entry into or exit from the behavior.[1]

[1] Appropriate timeouts handle the case of non-responding agents who fail to send appropriate intention or ready messages.

Imagine that Trip pursues a joint `OfferDrink()` subgoal and picks the joint `OfferDrink()` behavior to accomplish the subgoal. After the behavior has been chosen, but before it is added to the ABT, Trip negotiates entry with his teammate Grace. On receipt of the intention-to-enter `OfferDrink()`, Grace checks if she has a joint behavior `OfferDrink()` with a satisfied precondition. If she does, she signals her intention-to-enter. Trip and Grace then exchange ready-messages and enter the behavior. In Trip's case the behavior is rooted normally in the ABT at the subgoal which initiated behavior selection, while in Grace the spawned subgoal and corresponding joint behavior are rooted at the collection behavior at the root of the ABT.[1] If Grace didn't have a satisfied joint `OfferDrink()` behavior, she would send a reject message to Trip, which would cause Trip's `OfferDrink()` subgoal to fail, with all the normal effects of failure propagation (perhaps causing Trip to pursue an *individual* `OfferDrink()` goal). Note that during the negotiation protocol, the agents continue to pursue other lines of expansion in their ABT's; if the protocol takes awhile to negotiate, behavior continues along these other lines.

The negotiation protocol may seem overly complex. In the case that all the team members are on the same machine (the case for Façade), one can assume that negotiation will be very fast and no messages will be lost. Therefore it may seem that agents only need to exchange a pair of messages for behavior entry, while the initiator only needs to send a single message for behavior exit. However, even in the same-machine case, the team members are fully asynchronous, and thus a joint behavior in one agent may succeed while the matching joint behavior in another agent fails - negotiation is necessary to come to agreement as a team on the status of the behavior. And the simplified protocol would certainly break in the distributed case where team member's messages may be lost, or in cases where an agent might disappear unexpectedly (e.g. a game where agents can be killed) in the middle of the negotiation.[2]

But the most interesting feature the more complex negotiation protocol provides are authorial "hooks" for attaching transition behaviors to joint behavior entry and exit. Sengers, in her analysis of the Luxo Jr. short by Pixar, identified behavior transitions as a major means by which narrative flow is communicated (Sengers 1998). Animators actively communicate changes in the behavior state of their characters (e.g. the change from playing to resting) by having the characters engage in short transitional behaviors that communicate why the behavior change is happening. Sengers' architectural extensions to Hap provided support for authoring individual transition behaviors (Sengers 1998). However, she also noted that animators make use of coordinated multi-character transitions to communicate changes in multi-character behavioral state, but did not provide architectural support for this in her system. By exposing the negotiation protocol to the agent programmer, ABL can support the authoring of behaviors which *communicate transitions in multi-agent behavior state*.

[1] A collection behavior is a variety of parallel behavior in which every step need only be *attempted* for the behavior to succeed.

[2] The negotiation protocol can easily be extended to a three-phase protocol to support lost messages.

Posting Actions and Step Synchronization

In addition to synchronizing on behavior entry and exit, ABL provides other mechanisms for synchronizing agents, namely support for posting information to a team working memory, and the ability to synchronize the steps of sequential behaviors. Below are the two `OfferDrink()` behaviors for Trip and Grace.

Trip's behavior:

```
joint sequential behavior OfferDrink() {
  team Trip, Grace;

  with (post-to OfferDrinkMemory)
    // Individual behavior for initial offer
    subgoal InitialDrinkOffer();
  subgoal LookAtPlayerAndWait(0.5);
  with (synchronize) joint subgoal
    SuggestMartini();

  // react to Grace's line about fancy shakers
  with (synchronize) joint subgoal
    FancyCocktailShakers();
}
```

Grace's behavior:

```
joint sequential behavior OfferDrink() {
  team Trip, Grace;

  // wait for Trip to say first line
  with (success_test { OfferDrinkMemory
    (CompletedGoalWME name == iInitialDrinkOffer
                     status == SUCCEEDED)})
    wait;
  subgoal LookAtPlayerAndWait(0.5);

  // react to Martini suggestion
  with (synchronize) joint subgoal
    SuggestMartini();
  with (synchronize) joint subgoal
    FancyCocktailShakers();
}
```

Whenever a joint behavior is entered, the ABL runtime automatically creates a new named team working memory that persists for the duration of the joint behavior.[3] This team memory, which can be written to and read from by any member of the team, can be used as a communication mechanism for coordinating team activity. The first subgoal of Trip's behavior is annotated with a `post-to` annotation; for any subgoal marked with `post-to`, a CompletedGoalWME is added to the named memory when the subgoal completes (with either success or failure). A CompletedGoalWME, the definition of which is provided by the ABL runtime, contains the name of the goal, its

[3] By default the name of the team memory is the concatenation of the name of the behavior and the string "Memory".

completion state (success or failure), the name of the agent who performed the goal, any goal arguments, and a timestamp. The `post-to` annotation automatically fills in the appropriate arguments. This facility, inspired by the sign management system in Senger's extension of Hap (Sengers 1998), can be used to provide an agent with a selective episodic memory. This facility is useful even in a single agent situation, as the future behavior of an agent may conditionally depend on past episodic sequences. Since the ABT no longer has state for *already completed* subgoals and actions, an ABL agent's reflective access to its own ABT doesn't by itself provide access to past episodic sequences. However, in a team situation, access to episodic state can be used to coordinate team members. In the first line of Grace's behavior, a demon step monitors the team memory for the completion of `InitialDrinkOffer()`. In the behavior spec above, Grace doesn't begin directly reacting to Trip until after Trip's first line. Keep in mind that an ABL agent pursues multiple lines of expansion, so while Grace is waiting for Trip to complete his first line, she will continue to behave, in this case engaging in small idle movements as she smiles at the player. When Trip completes his first subgoal, an appropriate CompletedGoalWME is posted to the team memory; Trip then moves onto his second subgoal, to look at the player and wait for about half a second. The posting of the CompletedGoalWME causes Grace's first line to succeed, and she also, independently, waits for about half a second. One of them will be first to finish waiting, and will move onto the next line, which, being a joint behavior, reestablishes synchronization.

The last two subgoals of Grace's and Trip's behaviors are annotated with a `synchronize` annotation. To understand what this does, first imagine the case where the annotation is *absent*. Assume Grace is the first to finish the second subgoal (the goal to look at the player and wait). Grace will then attempt to satisfy the subgoal `SuggestMartini()`, causing Trip to spawn this goal at the root of his ABT and enter his local version of `SuggestMartini()`. As they jointly pursue the `SuggestMartini()` line of expansion, Trip will continue to pursue the `OfferDrink()` line of expansion, eventually initiating `SuggestMartini()` on his side, causing Grace to spawn the goal at her root and enter another copy of the behavior. At this point each is pursuing two copies of the joint behavior `SuggestMartini()`, one copy rooted at the subgoal within `OfferDrink()`, and the other rooted at the root of the ABT. This is not what the behavior author intended; rather it was intended that when the characters synchronize on the joint subgoal `SuggestMartini()`, they would each begin pursing their local version of `SuggestMartini()` rooted at the respective subgoals within their local versions of `OfferDrink()`. The `synchronize` annotation allows a behavior author to specify that a joint behavior should be rooted at a specific subgoal, rather than at the ABT root. `Synchronize` is only allowed within joint behaviors as an annotation on a goal that has at least one joint behavior with matching signature in the behavior library. In the case of sequential joint behaviors, synchronization on a `synchronize` subgoal forces the success of all steps between the current step counter position and the `synchronize` subgoal, and moves the step counter up to the `synchronize` subgoal.

Beat Idioms

Developing a believable agent language such as ABL involves simultaneously defining and implementing language constructs which support the authoring of expressive behavior, and the exploration of idioms for expressive behavior *using* the language. This section describes the ABL idioms used in authoring beat behaviors.

Above we described the ABL support for coordinating multiple believable agents. But of course in an interactive drama there is always an additional character, the human player, whose behavior can't be directly coordinated using joint goals and behaviors. The idioms described in this section are the behavior organization techniques we've developed for incorporating player interactivity into the accomplishment of dramatic action within a beat.

Beat behaviors are divided into three categories: *beat goals*, *handlers*, and *cross-beat behaviors*. A greeting beat, in which Trip greets the player at the door, will provide examples of these three behaviors categories and the relationships between the categories. To simplify the discussion, the example involves a single character (rather than a team) interacting with the player.

In the greeting beat, Trip wants to initially greet the player ("Hey! So glad you could make it. Thanks for coming over man."), yell for Grace ("Grace, come on out! Our guest is here."), and invite the player in ("Come on in, don't be shy"). These are the three *beat goals* of the greeting beat and should be accomplished sequentially.

Of course, during this greeting, the player will engage in various actions which should be handled in the context of the greeting. These interactions take the form of physical movement, object manipulation, and natural language text typed by the player. At the beat behavior level, player text is captured by WMEs representing the meaning of the text as a discourse act.[1] *Handlers* are demons responsible for handling player interaction. For the purposes of this example, assume that the greeting beat wants to handle the cases of the player greeting Trip, the player referring to Grace, and the player preemptively walking into the apartment before she has been invited in. The code below starts the handlers and begins the sequence of beat goals.

```
parallel behavior StartTheBeat() {
```

[1] For translating surface text into formally represented discourse acts, Façade employs a custom rule language for specifying templates and discourse chaining rules. The discourse rule compiler targets Jess, a CLIPS-like forward-chaining rule language (available at http://herzberg.ca.sandia.gov/jess/).

```
  with (priority 1)
    subgoal StartTheHandlers();
  subgoal BeatGoals();
}

parallel behavior StartTheHandlers() {
  with (persistent, priority 20)
    subgoal handlerDAGreet();
  with (persistent, priority 15)
    subgoal handlerDAReferTo_grace();
  with (priority 10, ignore_failure)
    subgoal handlerPreInviteAptMove();
}

sequential behavior BeatGoals() {
  with (persistent when_fails)
    bgOpenDoorAndGreetPlayer();
  with (persistent when_fails) bgYellForGrace();
  with (persistent when_fails) bgInviteIntoApt();
}
```

Handlers are started in various priority tiers corresponding to the relative importance of handling that interaction. Priorities are used to resolve cases where another player interaction happens in the middle of handling the previous player interaction, or when simultaneous player interactions occur. A higher priority handler can interrupt a lower priority handler, while same or lower priority handlers must wait for a higher priority handler to finish before handling the nested interaction. Generally handlers are persistent; when a handler finishes responding to an interaction, it should “reset” and be ready to deal with another interaction in the same category. In general handlers are higher priority than beat goals so that if an interaction occurs in the middle of the beat goal, the handler will “wake up” and interrupt it.

Handlers tend to be meta-behaviors; that is, they make use of reflection to directly modify the ABT state. When a handler triggers, it fails the current beat goal, potentially succeeds other beat goals, possibly pursues a beat goal within the handler (effectively reordering beat goals), and engages in its own bit of handler specific behavior. In some cases the handler specific behavior may entail mapping the recognized action to a different recognized action, which will then trigger a different corresponding handler. Below is a simplified version of `handlerDAReferTo_grace()`.

```
sequential behavior handlerDAReferTo_grace() {
  with (success_test { (DAReferToWME topicID ==
                        eTopic_grace) } ) wait;
  with (ignore_failure) subgoal
    handlerDAReferTo_grace_Body();
  subgoal DAReferTo_grace_Cleanup();
}

// by mentioning Grace, we will say "Grace? uh
// yeah" and then yell for Grace but only if we
// aren't currently doing bgYellForGrace!
sequential behavior handlerDAReferTo_grace_Body()
{
  precondition {
    (GoalStepWME signature == "bgYellForGrace()"
                 isExecuting == false) }
  subgoal handlerDA_InterruptWith(
    eTripScript_graceuhyeah,
    eFullExpression_blank);
  subgoal handlerDAReferTo_grace_Body2();
}

// we aren't currently doing yellForGrace, and if
// we haven't completed yellForGrace, then do it
sequential behavior
  handlerDAReferTo_grace_Body2() {
  // Goal still exists in the ABT so it hasn't
  // been completed
  precondition {
   (GoalStepWME signature == "bgYellForGrace()")
  }
  specificity 2;
  subgoal SetBeatGoalSatisfied(
    "bgYellForGrace()", true);
  with (persistent when_fails)
    subgoal bgYellForGrace();
}

// otherwise we must have already completed
// yellForGrace, so say "She's coming, I don't
// know where she's hiding"
sequential behavior
  handlerDAReferTo_grace_Body2() {
  specificity 1;
  subgoal handlerDA_InterruptWith(
    etripScript_shescomingidontknow,
    eFullExpression_smallSmile);
}
```

When the player refers to Grace (perhaps saying, “I’m looking forward to meeting Grace”, or “Where is Grace”, or “Hi Grace”) this handler is triggered. The handler body behavior uses reflection to test if the beat goal to yell for Grace is currently not executing. If it is executing (e.g. Trip was in the middle of yelling for Grace when the player said “Where’s Grace”), the body precondition fails, causing the handler to fail, which then restarts because of the persistence annotation, leaving Trip ready to handle another reference to Grace. Effectively Trip ignores references to Grace if he’s in the middle of yelling for Grace. Otherwise, Trip interrupts whatever he is saying with “Oh, yeah…”. `handlerDAInterruptWith` uses reflection to fail the currently executing beat goal, thus, as the name implies, interrupting the beat goal. When the handler is finished, the `persistent when_fails` annotation will causes any handler-failed beat goals to restart. After saying “Oh yeah…” Trip either performs the yell for Grace beat goal within the handler (and succeeds it out of the `BeatGoals` behavior) or, if yell for Grace has already happened, says “She’s coming. I don’t know where she’s hiding.” This handler demonstrates how player interaction can cause beat goals to be interrupted, effectively reordered, and responded to in a way dependent on what has happened in the beat so far.

The final category of beat behaviors are the *cross-beat behaviors*. These are behaviors that cross beat goal and handler boundaries. An example beat goal behavior is the staging behavior that an agent uses to move to certain dramatically significant positions (e.g. close or far conversation position with the player or another agent, into position to pickup or manipulate another object, etc.). A staging request to move to close conversation position with the player might be initiated by the first beat goal in a beat. The staging goal is spawned to another part of the ABT. After the first beat goal completes its behavior, other beat goals and handlers can happen as the agent continues to walk towards the requested staging point. Of course at any time during a cross-beat behavior, beat goals and handlers can use reflection to find out what cross-beat behaviors are currently happening and succeed or fail them if the cross-beat behaviors are inappropriate for the current beat goal's or handler's situation.

The example in this section involved only a single character interacting with the player. Multi-agent beats use the same idioms for coordinating beat goals, responding to player interaction, and pursing longer term goals; the various beat behaviors just become joint behaviors instead of individual behaviors.

Conclusion

ABL provides a rich programming framework for authoring story-based believable agents. Here we've described ABL's novel features and provided examples of how we're using these features to author characters for Façade, an interactive dramatic world.

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