

9

Behavior Trees

In a preceding chapter, we saw a basic but effective way to implement and manage character states and behaviors: **finite state machines** (FSMs). FSMs are simple to implement and intuitive, but they have a fatal flaw: it is tough to make them scale once there are many states and transitions. For example, imagine a character that behaves differently depending on its health and mana (high, medium, or low). We have a state in which both health and mana are high, one in which health is medium and mana is high, one in which they are both medium, and so on. In total, we have nine states just for those. If we add other conditions (such as player proximity, time of day, equipment, player's score, or whatever you may imagine), the number of states grows exponentially.

Luckily, we have a solution: **behavior trees** (BTs). In essence, BTs are just another way to visualize complex FSMs, but they are fast, provide reusability, and are easy to maintain. After their introduction in 2004 with *Halo 2*, they quickly became the preferred decision-making technique in games.

In this chapter, we will be doing the following:

- Exploring the basic principles of BTs, knowledge that you will be able to transfer to any BT plugin available for Unity (or other game engines)
- Implementing a small demo based on a popular free Unity plugin for BTs: **Behavior Bricks**

Technical requirements

For this chapter, you need Unity3D 2022 and the free plugin for Unity, *Behavior Bricks*. Don't worry, we will see how to install this plugin together. You can find the example project described in this chapter in the Chapter 9 folder in the book repository here: <https://github.com/PacktPublishing/Unity-Artificial-Intelligence-Programming-Fifth-Edition/tree/main/Chapter09>.

Introduction to BTs

A BT is a hierarchical tree of nodes that controls the AI character's behavior flow. It can also be used to coordinate groups of characters (for example, to model the attack pattern of a small platoon), or even disembodied agents such as an AI story director.

When we execute a BT's node, the node can return three states: **success**, **failure**, or **running** (if the node's execution is spread over multiple frames, for instance, if it plays an animation). When the BT executor runs a tree, it starts from the root and executes every node in order, according to rules written in the nodes themselves.

A node can be of three types:

- A **task** (a node without children), also called a **leaf**.
- A **decorator** (a node with a single child)
- A **composite** (a node with multiple children)

In general, leaves represent the *Action* that the characters can do or know (that is why they are commonly called an **Action** or **Task**); they may be actions such as **GoToTarget**, **OpenDoor**, **Jump**, or **TakeCover**, but also things like **IsObjectNear?** or **IsHealthLow?**. These actions depend on the character, the game, and the general game implementation.

A **decorator** is a node that modifies (decorates) the sub-tree under it (therefore, it can decorate both composite and task nodes). For example, a standard decorator is the **Negate** node. The node inverts the return value of the sub-tree; for instance, if the sub-tree returns *Success*, the decorator returns *Failure* and vice versa (of course, if the sub-tree returns *Running*, the decorator returns *Running* as well). Another everyday decorator is **Repeat**, a node that repeats its sub-tree a certain number of times.

Instead, a **composite** node represents a node with multiple children, and it is the most interesting case. There are two common composite nodes: **Sequence**, which runs all its children in order and returns *Success* if—and only if—all its children return *Success*, and **Selector**, which tries to execute all its children in order but returns *Success* as soon as one of its children returns *Success*. However, many BT implementations contain many more composite nodes (such as nodes that run their children in parallel or according to some dynamic priority value; we will see an example of such a node in the demo).

Of course, this tree structure is not enough. Nodes need to exchange information with each other or with the game world. For instance, a **GoToTarget** node needs to know the target and its location; an **IsObjectClose?** node needs to know which object we are referring to and what distance we consider close. Naturally, we could write a **GoToX** node for each object in the game (such as **GoToTree01** and **GoToDoor23**), but you can easily imagine that this becomes messy very quickly.

For this reason, all the BT implementations contain a data structure called **Blackboard**. As in a real-life physical blackboard, every node can write and read data into it; we just need to specify where to look for each node.

A simple example – a patrolling robot

Let's look at this example (which we will later implement in Unity). Imagine a patrolling robot that shoots anything that gets near it but works only during the daytime. We show the possible BT for this kind of agent in the following diagram:

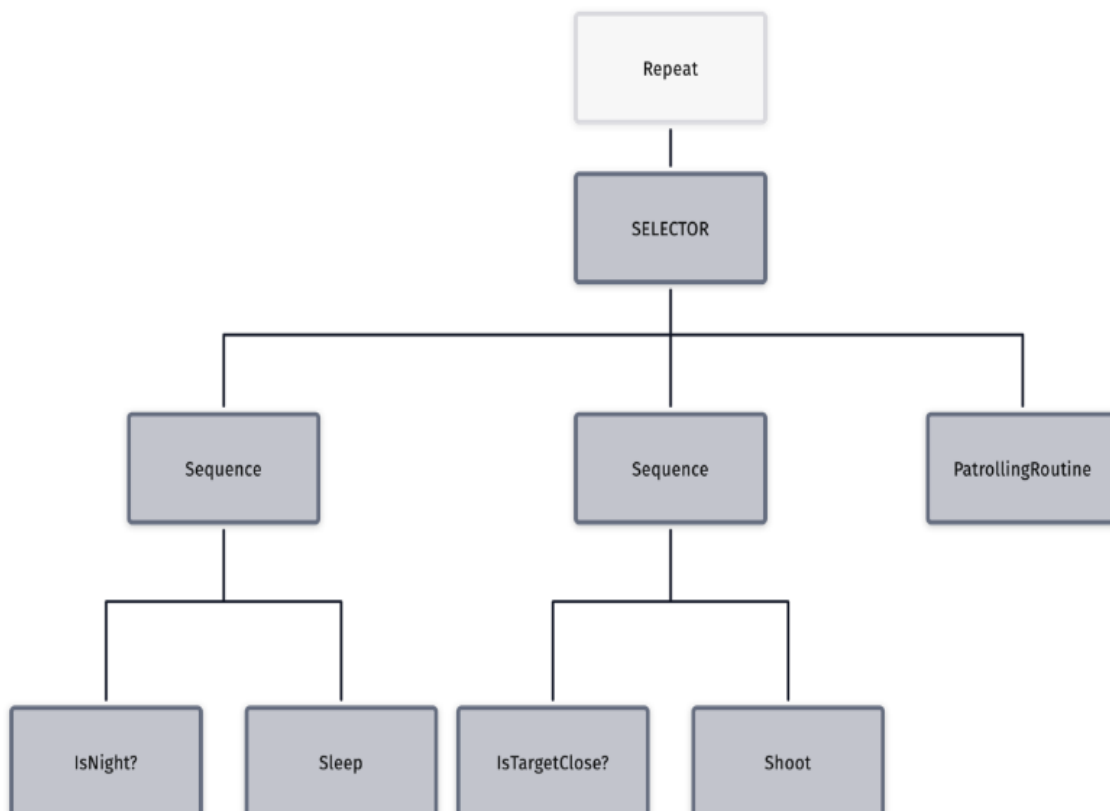


Figure 9.1 – Example BT for a simplified day-only patrolling robot

Let's run this BT, assuming that the target is close and it is not night:

1. The first node is a **Repeat** decorator; it does nothing but cycle the BTs, therefore, we can ignore it for now.
2. The **SELECTOR** node starts executing its first child; we go down to the left.
3. We are now at the first **Sequence** node; again, we execute the first node. **IsNight?** returns *Failure* (because it is not night!). Whenever one node returns *Failure*, the whole **Sequence** node returns *Failure*.
4. We traverse back up the tree to the **SELECTOR** node; now, we go to the second branch.
5. Again, we execute **Sequence**.
6. This time, however, **IsTargetClose?** returns *Success*, so we can proceed to the next node, **Shoot**, which runs a game function spawning an in-game projectile.

The pattern of **Sequence** | **Condition** | **Action** is equivalent to if *Condition* is *Success* then *Action*. This pattern is so common that many BT implementations allow you to stack the *Condition* and the *Action* together. Therefore, we can rewrite the tree as follows:

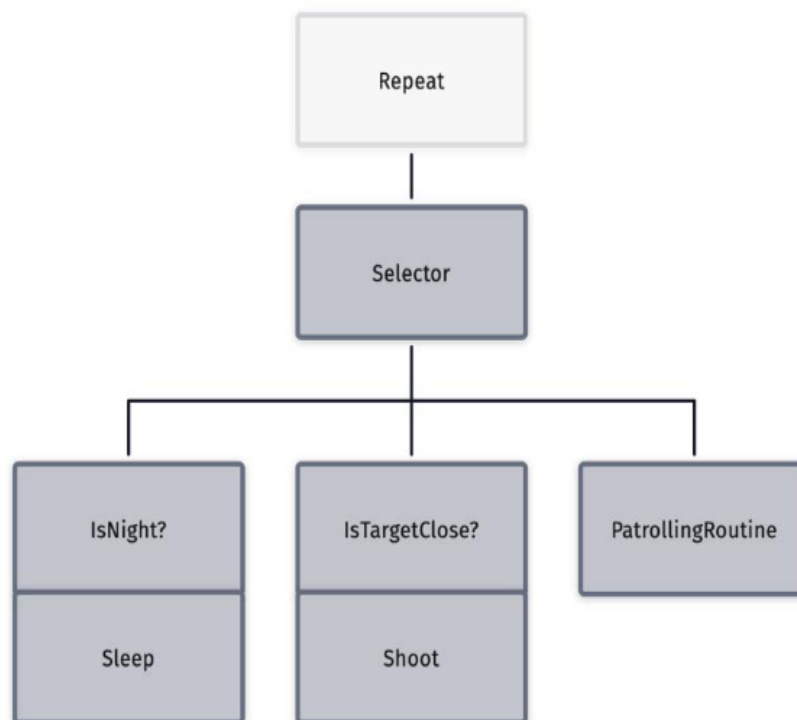


Figure 9.2 – A simplified BT

This tree is the same as the previous one but with a simplified Sequence pattern.

Implementing a BT in Unity with Behavior Bricks

Behavior Bricks is a robust but free BT implementation for Unity developed by the Complutense University of Madrid in Spain. Using Behavior Bricks, you can start using BTs in your projects without implementing BTs from scratch. It also has a visual editor where you can drop and connect nodes without any additional code.

Follow these steps to install Behavior Bricks:

1. We need to go to the *Unity Asset Store* by going on the website <https://assetstore.unity.com/>.
2. Search for Behavior Bricks.
3. Click on **Add to My Assets**. Once it's done, we can import it into our project.

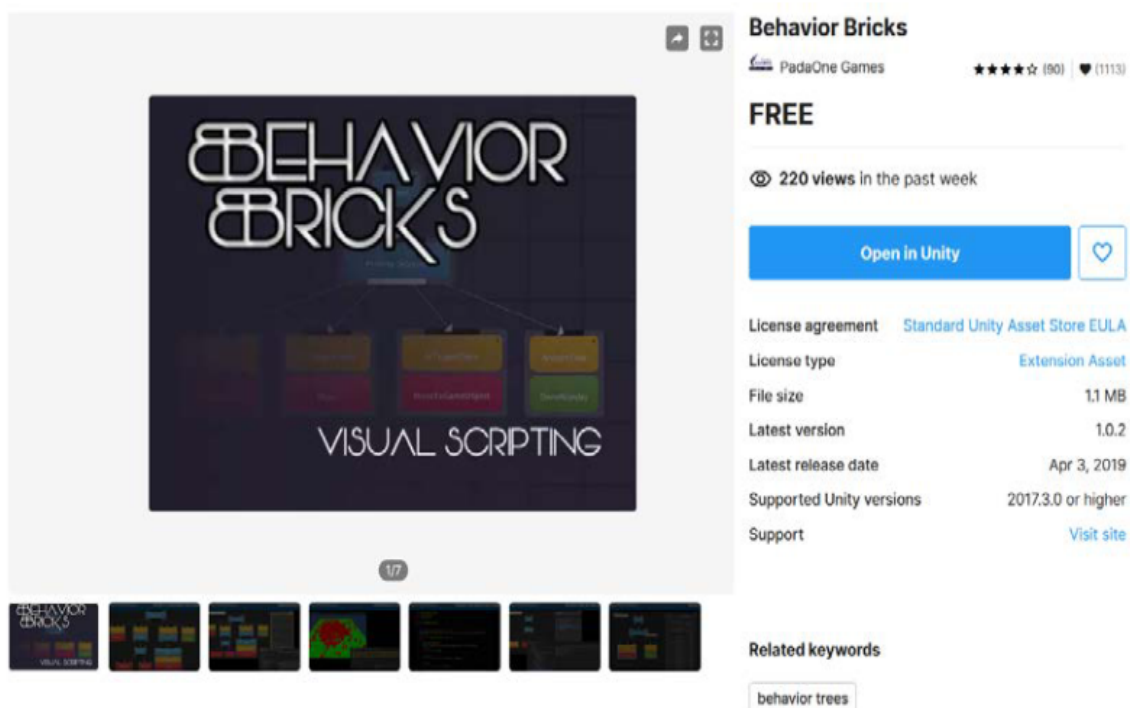


Figure 9.3 – Behavior Bricks Asset Store main page

4. Go to **Package Manager** (Window | Package Manager).
5. Go to **My Assets**.

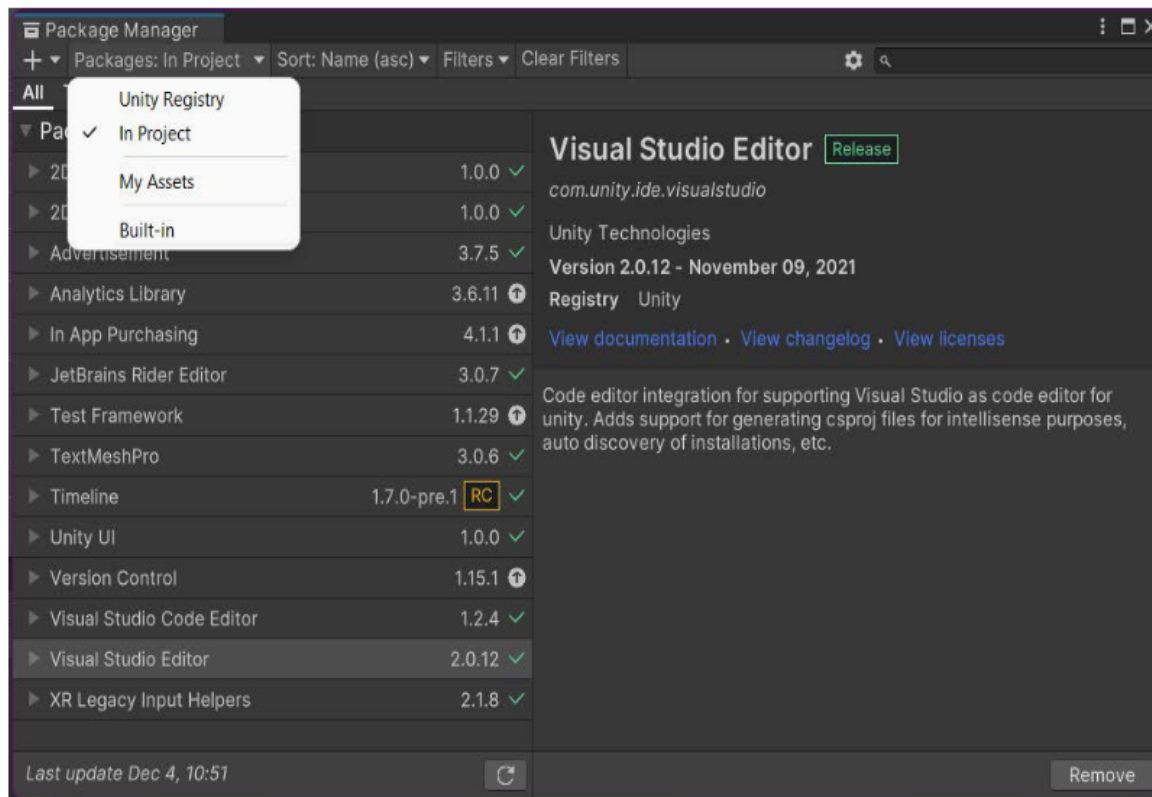


Figure 9.4 – The Package Manager window

6. Import the **Behavior Bricks** package by clicking on the **Import** button.

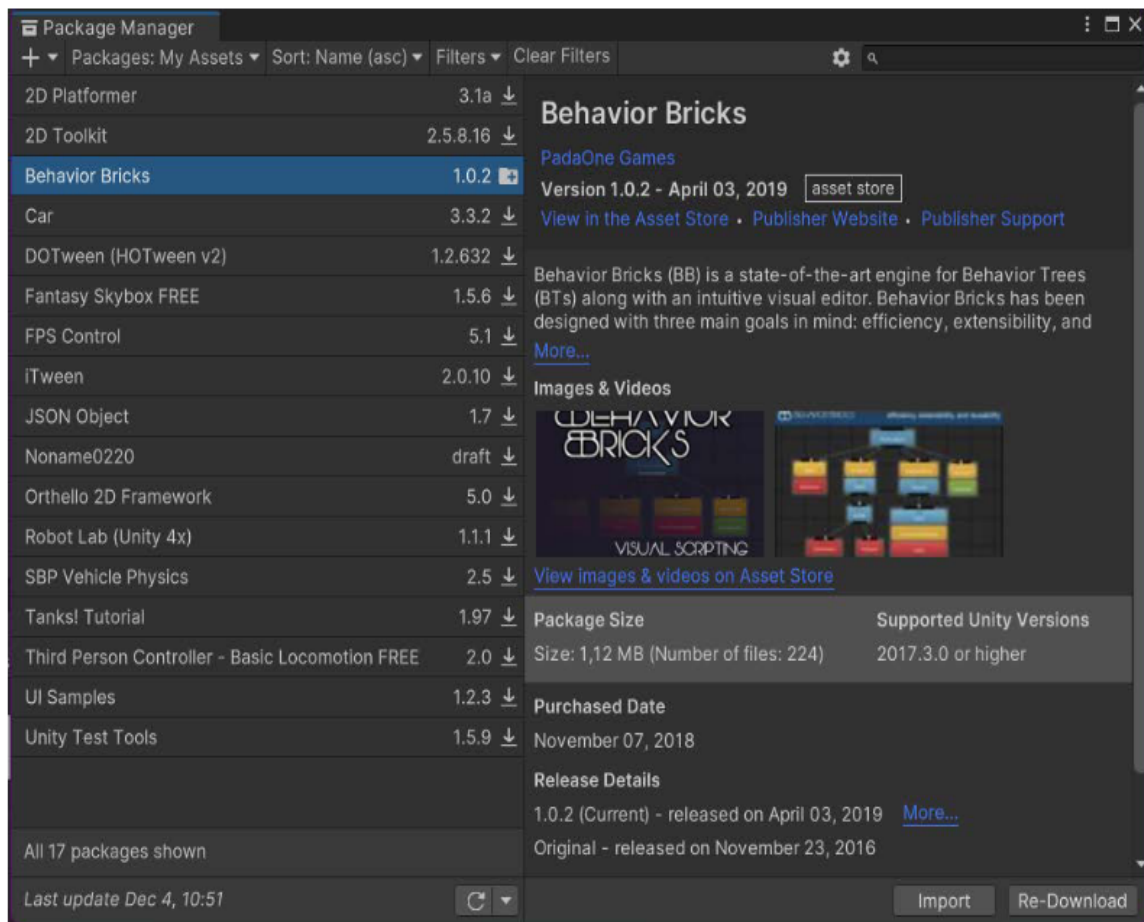


Figure 9.5 – Behavior Bricks in Package Manager

At this point, Behavior Bricks is ready to go, and we can proceed with our demo. The following steps give you a brief idea of the steps to follow:

1. Set up the scene.
2. Implement a day/night cycle.
3. Design the enemy behavior.
4. Implement the nodes.
5. Build the tree.
6. Attach the BT to the enemy.

Now, let's take a look at each of these steps individually.

Set up the scene

Let's follow a step-by-step process to do this:

1. We start by adding the game objects to the scene. We add a big plane to the scene, we add a `Box Collider` that encloses the entire plane, and we call it `Floor` (you may also add a texture if you like; be creative as it helps to have fun with these simple demos).

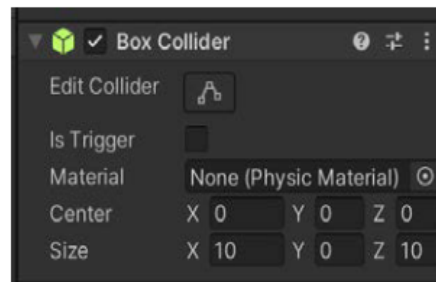


Figure 9.6 – Example of the Floor Box Collider

2. We add a sphere and a cube; we call the sphere *Player* and the cube *Enemy*. In the *Enemy*, we add another empty object and move it just outside the cube. We call it `shootPoint`, and it represents the placeholder for where the enemy shoots.
3. Then, place all these objects on the floor; you should have something similar to the following:

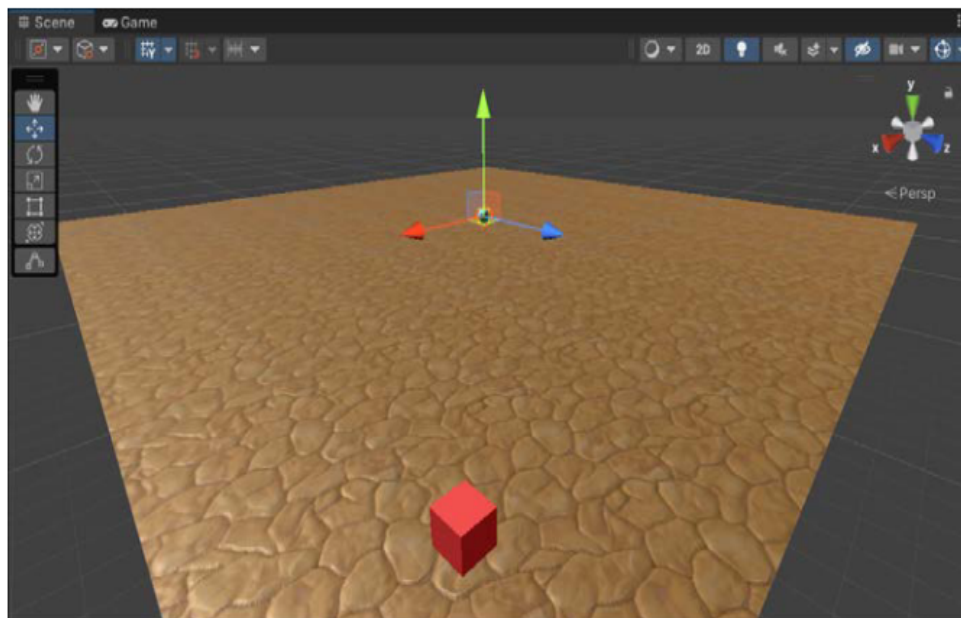


Figure 9.7 – The scene of our demo

4. Now, because we want the player and the enemy to move around, we need to create a `NavMesh` as described in *Chapter 8, Navigation Mesh*. Remember to add the `NavMesh Agent` component to both *Player* and *Enemy*!

5. Finally, if it is not present, add the **MainLight** tag to the *Direct Light* object.

Implement a day/night cycle

In this demo, we want to implement a basic day/night cycle. To do that, we attach the script `DayNightCycle.cs` to the *Direct Light* object. As with many scripts in this demo, we adapt the code from the *Quick Start Guide* provided by Behavior Bricks:

```
using UnityEngine;

public class DayNightCycle : MonoBehaviour {
    public event System.EventHandler OnChanged;
    public float dayDuration = 10.0f;
    public bool IsNight { get; private set; }
    public Color nightColor = Color.white * 0.1f;
    private Color dayColor;
    private Light lightComponent;

    void Start() {
        lightComponent = GetComponent<Light>();
        dayColor = lightComponent.color;
    }

    void Update() {
        float lightIntensity = 0.5f + Mathf.Sin(Time.time *
            2.0f * Mathf.PI / dayDuration) / 2.0f;

        bool shouldBeNight = lightIntensity < 0.3f;
        if (IsNight != shouldBeNight) {
            IsNight = shouldBeNight;
            // Invoke event handler (if set).
            OnChanged?.Invoke(this,
                System.EventArgs.Empty);
        }

        lightComponent.color = Color.Lerp(nightColor,
```

```

    dayColor, lightIntensity);    }
}

```

This script implements a typical day/night cycle. The way it works is quite intuitive. Let's have a look:

- At each `Update` step, we update the `lightIntensity` variable according to a sinusoidal wave.
- The variable cycles from 0 to 1 and, when the value is smaller than 0.3, we decide that it is nighttime.
- Finally, we update the light color according to the `lightIntensity` value, interpolating the day and night colors.
- Note the `onChanged` event. We call it every time we switch from daytime to nighttime, and from nighttime to daytime. Later, we use this event to create an **IsNight** node in the BT.

Design the enemy behavior

Now, it is time to design the enemy behavior. We need to do this before writing a single line of code. For this demo, we will adapt the code and assets provided by the example project in the *Behavior Bricks Quick Start Guide*. For more information, you can refer to it at this URL: <http://bb.padaonegames.com/doku.php?id=quick:program>.

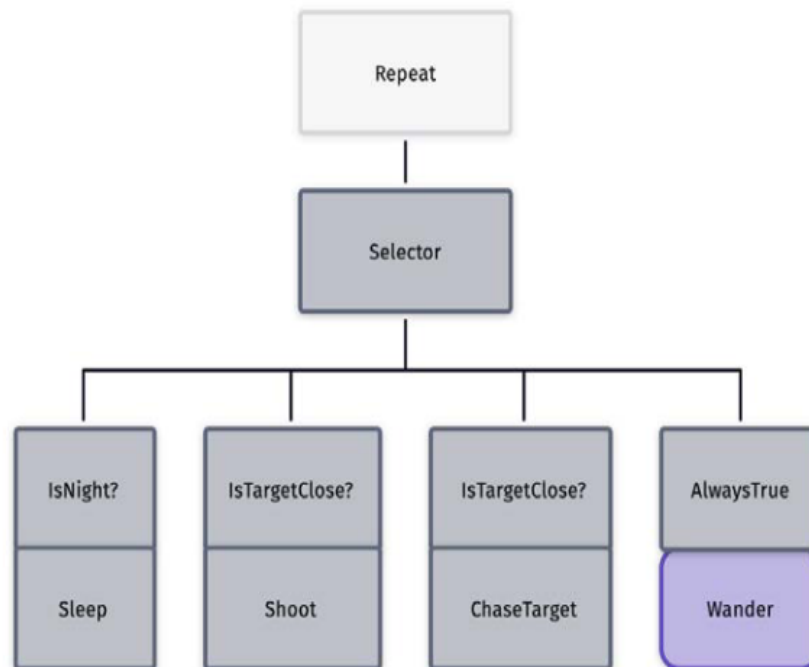


Figure 9.8 – The target BT we want to implement

The BT in *Figure 9.8* describes the following behavior:

- If it is night, the enemy is deactivated.
- If the target is very close, the enemy shoots at the target.
- If the target is further away, the enemy chases the target.
- Otherwise, the enemy just wanders around.

There are two important things to note:

- First, the two **IsTargetClose?** nodes differ in the value we consider close. In particular, we want to shoot the target only if we are close to it; otherwise, we just start chasing it.
- Second, and most importantly, the order of the nodes matters. Because the **Selector** works from left to right and stops at the first *Success*, we cannot put **ChaseTarget** before **Shoot**. Otherwise, the enemy will never shoot!

As a rule of thumb, we need to order conditions from the highest to the lowest priority. In fact, in the example, we put at the very end the action to execute when everything else fails (**AlwaysTrue** is a condition that always succeeds and works like the *else* branch of an *if* condition).

Note that **Wander** is in a different color because it is not a node but another BT. The lovely property of BTs is that you can reuse common BTs as nodes inside more complex BTs. The Wander BT simply makes the enemy move randomly on the map; fortunately, Behavior Bricks already includes it, so we don't need to implement it!

Implementing the nodes

After we have made a plan for our BT, the next step is to check whether our BT implementation of choice (in our case, Behavior Bricks) already includes some of the nodes we need. Of course, we want to reuse as many pre-made nodes as possible. Reading the Behavior Bricks documentation, we can see that it already includes nodes such as **IsTargetClose**, **MoveToGameObject**, **Wander**, and **AlwaysTrue**, plus, of course, **Repeat** and **Selector**.

Therefore, we need to write all the other tasks. Note that Behavior Bricks tasks are not `MonoBehaviors`; therefore, we do not need to attach them to some object in the scene. We only need to put the scripts in any folder in our project's assets, and we are good. Let's look at a step-by-step process to do this:

1. Let's start with the **ShootOnce** action by creating a `ShootOnce.cs` file in the project assets. First, we create a simple `Action` attribute called `ShootOnce` that, as the name says, shoots a single bullet:

```
using UnityEngine;

using Pada1.BBCore;
using Pada1.BBCore.Tasks;
using BBUnity.Actions;

[Action("Chapter09/ShootOnce")]
[Help("Clone a 'bullet' and shoots it through the Forward axis with the specified velocity.")]
public class ShootOnce : GOAction {
    // ...
}
```

In the beginning, we import Behavior Bricks modules. Then, we create the `ShootOnce` class by extending the generic `GOAction` class.

Note the class attributes; Behavior Bricks uses them to populate the BT visual editor. In the `Action` attribute, we specify that `Action` is an action, and we put it in the `Chapter09` collection with the name `ShootOnce`. The `Help` attribute is just a documentation string describing the action's purpose.

2. We describe the class attributes as usual. The only difference is that we decorate each attribute with the `InParam` attribute, which specifies that the BT executor needs to retrieve the following value from the blackboard:

```
[InParam("shootPoint")]
public Transform shootPoint;

[InParam("bullet")]
public GameObject bullet;
```

```
[InParam("velocity", DefaultValue = 30f)]
public float velocity;
```

For this action, we need a Bullet prefab, a place to instantiate the bullet (shootPoint) and the bullet velocity. Later, we will see how to set them up from the visual interface.

3. Now, it is time to write the real meat:

```
public override void OnStart() {
    if (shootPoint == null) {
        shootPoint =
            gameObject.transform.Find("shootPoint");
        if (shootPoint == null) {
            Debug.LogWarning("Shoot point not
                specified. ShootOnce will not work for "
                + gameObject.name);
        }
    }
    base.OnStart();
}

public override TaskStatus OnUpdate() {
    if (shootPoint == null || bullet == null) {
        return TaskStatus.FAILED;
    }
    GameObject newBullet = Object.Instantiate(
        bullet, shootPoint.position,
        shootPoint.rotation *
        bullet.transform.rotation );
    if (newBullet.GetComponent<Rigidbody>() == null) {
        newBullet.AddComponent<Rigidbody>();
    }
    newBullet.GetComponent<Rigidbody>().velocity =
        velocity * shootPoint.forward;
    return TaskStatus.COMPLETED;
}
```

Every Behavior Bricks node contains some default method called during the BT execution. We can overwrite them in our custom implementations. In this example, we see two of them: `OnStart` and `OnUpdate`. They are used very similarly to how we use `Start` and `Update` in `MonoBehavior`:

- The BT executor calls `OnStart` when the game creates the BT. In it, we initialize all the references we need. In this case, we get a reference to the `shootPoint` object. Note also that we must call `base.Onstart()` to initialize the base class.
- In `OnUpdate`, we write the intended action for the node, that is, what we want this node to do when the BT executor invokes it. In this case, the code is self-explanatory: we create a bullet and shoot it at the velocity stored in the settings.

If there is no problem, we mark the node as complete (so that the BT knows that it is a *Success*); otherwise (for example, if there is no `shootPoint` value), we mark the node as *Failed*.

4. Now that we have a base class for shooting once, we can create a new `Action` attribute for shooting continuously. Let's create a `Shoot.cs` file with the following content:

```

Using UnityEngine;

using Pada1.BBCore
using Pada1.BBCore.Tasks;

[Action("Chapter09/Shoot")]
[Help("Periodically clones a 'bullet' and shoots it
through the Forward axis with the specified velocity.
This action never ends.")]
public class Shoot : ShootOnce {
    [InParam("delay", DefaultValue = 1.0f)]
    public float delay;

    // Time since the last shoot.
    private float elapsedTime = 0;

    public override TaskStatus OnUpdate() {
        if (delay > 0) {
            elapsedTime += Time.deltaTime;

```

```

        if (elapsedTime >= delay) {
            elapsedTime = 0;
            return TaskStatus.RUNNING;
        }

    }

    base.OnUpdate();
    return TaskStatus.RUNNING; }
}

```

This class simply extends the `ShootOnce` class, adds a `delay` attribute (the time between consecutive shots), and then continuously reruns its parent class (`ShootOnce`). Note that this `Action` always returns `RUNNING`, meaning that it never completes as long as the BT selects it.

5. In the same way, we can create the remaining `Action` attribute. For instance, the `SleepForever` action is very straightforward: it just does nothing and suspends the execution of the BTs. Note that the class extends `BasePrimitiveAction`, which is the most basic form of `Action` in Behavior Bricks:

```

using Padal.BBCore;
using Padal.BBCore.Framework;
using Padal.BBCore.Tasks;

[Action("Chapter09/SleepForever")]
[Help("Low-cost infinite action that never ends. It does not consume CPU at all.")]

public class SleepForever : BasePrimitiveAction {
    public override TaskStatus OnUpdate() {
        return TaskStatus.SUSPENDED;
    }
}

```

6. Finally, we need to implement `IsNightCondition`. We show the `IsNightCondition` code in the following listing:

```

using Padal.BBCore;
using Padal.BBCore.Framework;

```



```
using Pda1.BBCore.Tasks;
using UnityEngine;

[Condition("Chapter09/IsNight")]
[Help("Checks whether it is night time.")]
public class IsNightCondition : ConditionBase {
    private DayNightCycle light;

    public override bool Check() {
        return SearchLight() && light.IsNight;
    }

    public override TaskStatus
        MonitorCompleteWhenTrue() {
        if (Check()) {
            return TaskStatus.COMPLETED;
        }
        if (light != null) {
            light.OnChanged += OnSunset;
        }
        return TaskStatus.SUSPENDED;
    }

    public override TaskStatus MonitorFailWhenFalse()
    {
        if (!Check()) {
            return TaskStatus.FAILED;
        }
        light.OnChanged += OnSunrise;
        return TaskStatus.SUSPENDED;
    }

    /// ...

    private bool searchLight() {
        if (light != null) {
```

```

        return true;
    }
    GameObject lightGO =
        GameObject.FindGameObjectWithTag(
            "MainLight");
    if (lightGO == null) {
        return false;
    }
    light = lightGO.GetComponent<DayNightCycle>();
    return light != null;
}
}

```

This class is more complex than the others, so let's go slow. First of all, `IsNightCondition` extends `ConditionBase`, which is a basic condition template in Behavior Bricks. This class does a simple job: on start, it searches for a light with the `MainLight` tag. If that exists, it takes its `DayNightCycle` reference, stores it in the `light` variable, and registers with the `OnChanged` event. Then, every time we ask for this condition, we check whether the `isNight` variable in `light` is true or false (see the `Check` method).

However, checking this every time would be very inefficient, in general. So, the `BaseCondition` class contains two helpful functions:

- `MonitorCompleteWhenTrue` is a function that is called by the BT executor when the last returned value is false and, in practice, sets up a system that suspends BT execution until the variable becomes true again.
- `MonitorFailWhenFalse` is a dual function: it is called when the monitored value is true and suspends BT execution until the variable switches to false.

For instance, let's look at `MonitorCompleteWhenTrue`. If `Check` is true (so it is night), we simply return `Complete`; otherwise, we register the `OnSunset` function with the `OnChanged` event. When the day/night cycle switches from day to night, `OnSunset` is called and, in turn, `EndMonitorWithSuccess` is called. `MonitorFailWhenFalse` works in the same way but in the opposite direction (monitoring when we pass from night to day):

```

public void OnSunset(object sender,
                    System.EventArgs night) {
    light.OnChanged -= OnSunset;
}

```

```

        EndMonitorWithSuccess();
    }

    public void OnSunrise(object sender,
                          System.EventArgs e) {
        light.OnChanged -= OnSunrise;
        EndMonitorWithFailure();
    }

```

In the preceding code block, there are the two `OnSunset` and `OnSunrise` event handlers included in the class. As usual, you can find the complete commented code in the book's repository.

Building the tree

Now that we have our nodes, we need to assemble the tree. To do that, follow these steps:

1. Right-click in the **Inspector** and go to the **Create** sub-menu.
2. Then, select **Behavior Tree**.
3. Choose a location and save.
4. An empty editor window should show onscreen; this is the tree editor.
5. You can right-click anywhere and start adding and connecting nodes.
6. To implement our tree, you need to recreate the tree shown in the following screenshot:

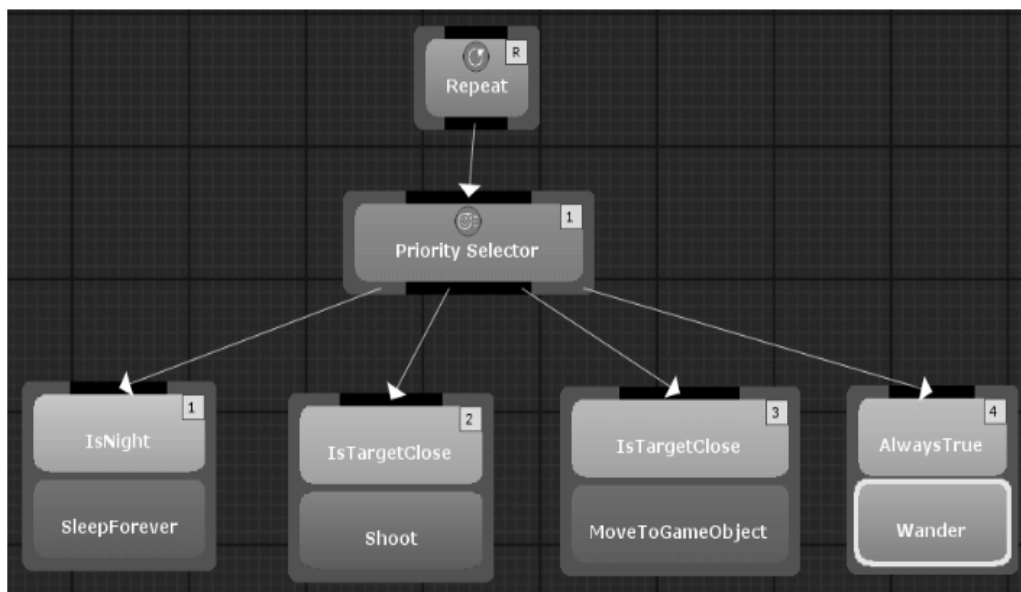


Figure 9.9 – The enemy BT in the Behavior Bricks editor

7. Select all the nodes, one at a time, and look for the input parameters; these are the parameters we specified in our classes. These parameters may be **CONSTANT**, meaning that we directly write a value for them, or a **BLACKBOARD** reference.
8. We need to set up the parameters with the following values:
 - In the first `IsTargetClose`, we specify the blackboard player as `target` and the constant 7 as `closeDistance` (if the player is not listed, click on **New Parameter**).
 - In the second `IsTargetClose`, we specify the blackboard player as `target` and the constant 20 as `closeDistance`.
 - In `Shoot`, we need to set 30 as the delay, the blackboard `shootPoint` as `shootPoint` (you probably need to create it with **New Parameter**), the blackboard bullet as the `bullet` prefab, and the constant 30 as `velocity`.
 - In `MoveToGameObject`, the target is the player value in the blackboard.
9. In `Wander`, we set a new blackboard parameter (`floor`) as `wanderArea`.

Attach the BT to the enemy

Now, it is time to attach this BT to the enemy's BT executor. For that, follow these steps:

1. Select the **Enemy** game object and add the **Behavior Executor** component to it.
2. In the **Behavior** field, drag and drop the BT we created before.
3. In **Behavior Parameters**, a list of all the blackboard parameters we defined in the previous step (`player`, `floor`, the enemy `shootPoint` firing location, and `bullet`) should appear.

4. Fill them with the appropriate objects, as shown in *Figure 9.10*:

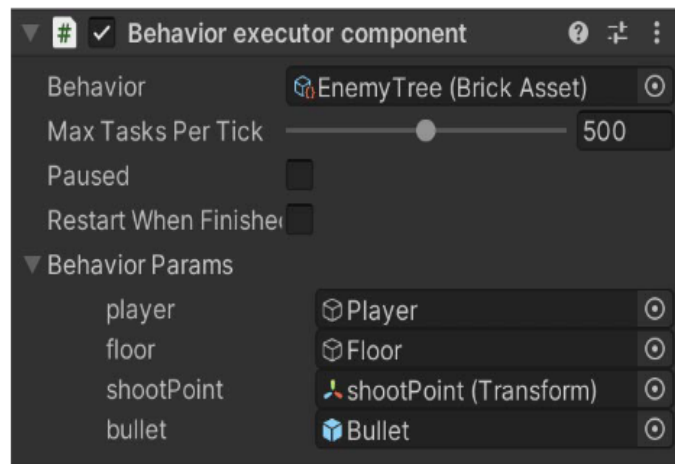


Figure 9.10 – The behavior executor component

At this point, the enemy should be ready to go. Click **Play** and you should see the enemy wandering around and, when close enough to the player, start chasing and shooting at it. Note that we did not implement a controller for the player, therefore, to change its position you need to edit the player in the Scene view (or attach one of the control scripts we developed in the previous chapters). For more details, look at the code included in this book.

Now that we have completed our first BT, what if we want to replicate with Behavior Bricks the same AI that we developed in *Chapter 2, Finite State Machines*, using an FSM? Try that as an exercise.

Summary

In this chapter, we explored the general background behind any BT implementation. We saw what a BT is, what its basic components are, and how can we use a BT to describe game character behavior. Then, we implemented a demo using a free plugin called Behavior Bricks. In the demo, we created the behavior for a simple scenario: the player and a patrolling robot. We also implemented a day/night cycle to spice up the scenario.

BTs are the cornerstones of modern AI for game characters. Implementation details and deeper examples would require a full book to explain them fully. Luckily, the web is full of resources for the curious reader.

Now, we will take a break from AI character design by looking at a different application of AI in games. In the next chapter, we will look at the fascinating field of procedural content generation.

Further reading

- The official Behavior Bricks project page from the Complutense University of Madrid in Spain: <http://gaia.fdi.ucm.es/research/bb/>.
- Behavior Bricks official documentation: <http://bb.padaonegames.com/doku.php>.
- Chris Simpson (the developer of *Project Zomboid*) wrote a nice explanation of BTs on Gamasutra: https://www.gamasutra.com/blogs/ChrisSimpson/20140717/221339/Behavior_trees_for_AI_How_they_work.php.
- *Chapter 6 of GameAI Pro*, which explores many implementation details of BTs (in C++), is free and available at the following link: https://www.gameai.pro.com/GameAIPro/GameAIPro_Chapter06_The_Behavior_Tree_Starter_Kit.pdf.

