Simulation-based Testing with BeamNG.tech

Tutorial @ SBST 2021

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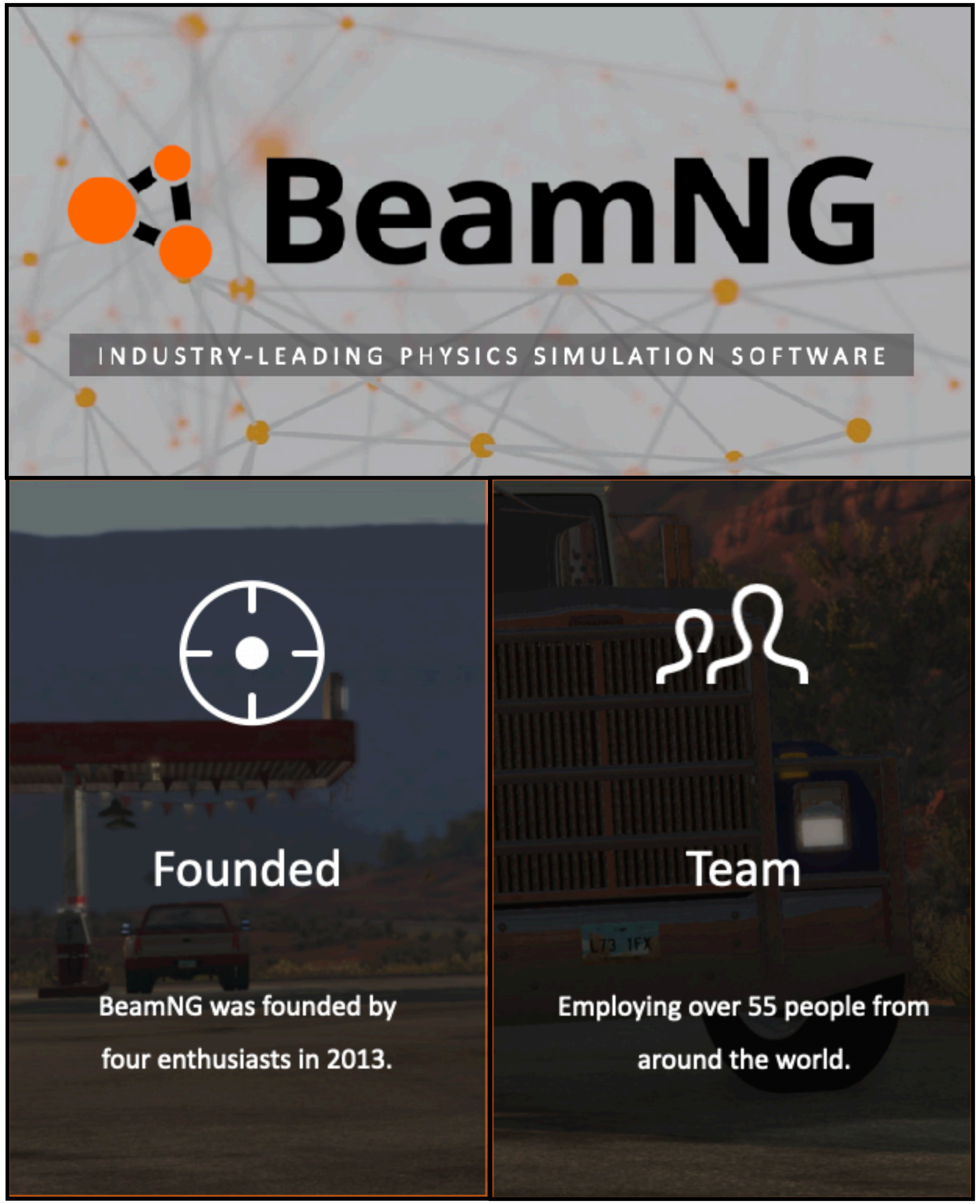
What's BeamNG.tech?

- **Photo-realistic**, **accurate**, **soft-body** physics *"engine capable of real-time simulation of vehicle dynamics and damage, all on consumer-grade hardware"*

- Developed by **BeamNG GmbH,** an international tech company (based in Germany) also working in the **gaming** industry

- Specialized on driving simulations, but "can simulate everything" (e.g., mods exists for drones, pedestrians, & more)



Who Does Use it?

- Researchers:
  - Papers in major SE/ST conferences
  - Several Tools for SBST
- Students:
  - More than 20+ Master and Bachelor theses (UniPassau, USI, ZHAW)
  - Advanced seminars

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AsFault

Automatically Testing Self-Driving Cars with Search-Based Procedural Content Generation

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DeepJanus

Model-based Exploration of the Frontier of Behaviours for Deep Learning System Testing

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Paolo Tonella, Software Institute - USI, Lugano, Switzerland, paolo.tonella@usi.ch

AC3R

Generating Effective Test Cases for Self-Driving Cars from Police Reports

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Driving Simulator Validation of Machine Learning Classification for a Surface Electromyography-Based Steering Assistance Interface

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Using Wearable Sensors to Detect Workload on Driving Simulated Scenarios

Víctor CORCOBA[a,1], Zoe FALOMIR[b], Nourelhoda MOHAMED[c]
[a] *Informatics Department, University of Oviedo, Spain*
[b] *Bremen Spatial Cognition Centre (BSCC), University of Bremen, Bremen, Germany*
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NEW

DeepHyperion: Exploring the Feature Space of Deep Learning-Based Systems through Illumination Search

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SBST Tool Competition 2021

Sebastiano Panichella[*], Alessio Gambi[†], Fiorella Zampetti[‡] and Vincenzo Riccio[§]
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Deeper **Frenetic** **GA Bezier** **SWAT**

After today, maybe also you will use it

Goals of this Tutorial

It’s a *Beginners* tutorial

- Part I: Get a grip on BeamNG.tech
- Part II: Basics of simulation-based tests
- Part III: Examples of automated test generation

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> ***Disclaimer**: We show only a fraction of the possibilities enabled by BeamNG.tech. The simulator is designed to be extensible and most of its code is **open source**.*

Part I: Getting Started

Resources

Fork me on GitHub

https://github.com/se2p/sbst-2021-tutorial

- Setup instructions
- Code examples
- Copy of the slides
- Links to additional resources

Obtaining the Simulator

Getting Started

- The simulator can be obtained **for free** after registering at https://register.beamng.tech/

- Use a valid **university** email address for the registration

- After registration you should get a confirmation email (check the spam folder!) with a `tech.key` file and the link to download the simulator.

- In this tutorial, we use the **BeamNG.tech version `v0.21.3.0`**

Installing the Simulator

Getting Started

- The simulator comes as *tar-ball* and does **not** require any specific installation, just extract it somewhere it can fit (~16.5 GB)
- <u>**Avoid**</u> **special characters** and **spaces** in paths
- We will refer to this folder as <BNG_HOME>
    - For this tutorial, we use "C:\\BeamNG.tech.v0.21.3.0"

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Officially, the simulator can run only under Windows, but you can try it also on Mac OS using Parallels (note, Parallels is **shareware**)

Running the Simulator

Getting Started

- The simulator can be **started manually** by double-clicking on

```
<BNG_HOME>\\Bin64\\BeamNG.tech.x64.exe
```

- Note that starting the simulator manually will **not automatically start the Python API** so you will not able to control remotely the simulator.

- However, you can still use the simulator to **browse existing maps** and **create new content** using the various editors

Running the Simulator

Getting Started

- The simulator can be **started** from Powershell using the following command:

```
<BNG_HOME>\\Bin64\\BeamNG.tech.x64.exe -console -rport 64256
  -nosteam -physicsfps 4000 -userpath <BNG_USER>
  -lua "registerCoreModule('util/researchAdapter')"
```

- `<BNG_USER>` is the *work dir* of the simulator, you can choose any folder on your system as long as that is writable and have no spaces or special characters in its name and path
- `<BNG_USER>` must contain the registration key (i.e., `tech.key`) otherwise the simulator will **not** work

Running the Simulator

Getting Started

- The simulator can be **started** (and **controlled**) using its Python API, `BeamNGpy`
- `BeamNGpy` is available on GitHub and on PyPI as `beamngpy`
- Running the simulator using the Python API requires to set an env variable called `BNG_HOME` pointing to <`BNG_HOME`> or provide this value as input parameter.
- We tested the examples using Python versions `3.7` and `3.9`
- <`BNG_USER`> instead is not mandatory. If not specified, `BeamNGpy` defaults to `~\\Documents\\BeamNG.tech_userpath`
    - Remember: **no special characters or empty space**

Installing the Dependencies

- \``Code\README.md`\` contains the verbose descriptions on how to install the Python dependencies, please refer to that if you face issues.
- **TL;DR**
    - create a new virtual environment: `py.exe -m venv .venv`
    - activate it: `.\.venv\Scripts\activate`
    - update pip: `py.exe -m pip install --upgrade pip`
    - update utilities: `pip install --upgrade setuptools wheel`
    - Install the library: `pip install beamngpy==1.19.1`

Running the Simulator

Assumption: BeamNGpy correctly installed

```python
from beamngpy import BeamNGpy, Scenario, Road

# Specify location of BeamNG home and BeamNG user folders
BNG_HOME = "C:\\BeamNG.tech.v0.21.3.0"
BNG_USER = "C:\\BeamNG.tech_userpath"

beamng = BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER)

# Start BeamNG by setting launch to True
bng = beamng.open(launch=True)

try:
    input('Press enter when done...')
finally:
    bng.close()
```

example1.py

Running the Simulator

Assumption: BeamNGpy correctly installed

```python
from beamngpy import BeamNGpy, Scenario, Road

# Specify where BeamNG home and user are
BNG_HOME = "C:\\BeamNG.tech.v0.21.3.0"
BNG_USER = "C:\\BeamNG.tech_userpath"

# Use Python Context Manager so it automatically closes
with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER):
    input('Press enter when done...')
```

Part II

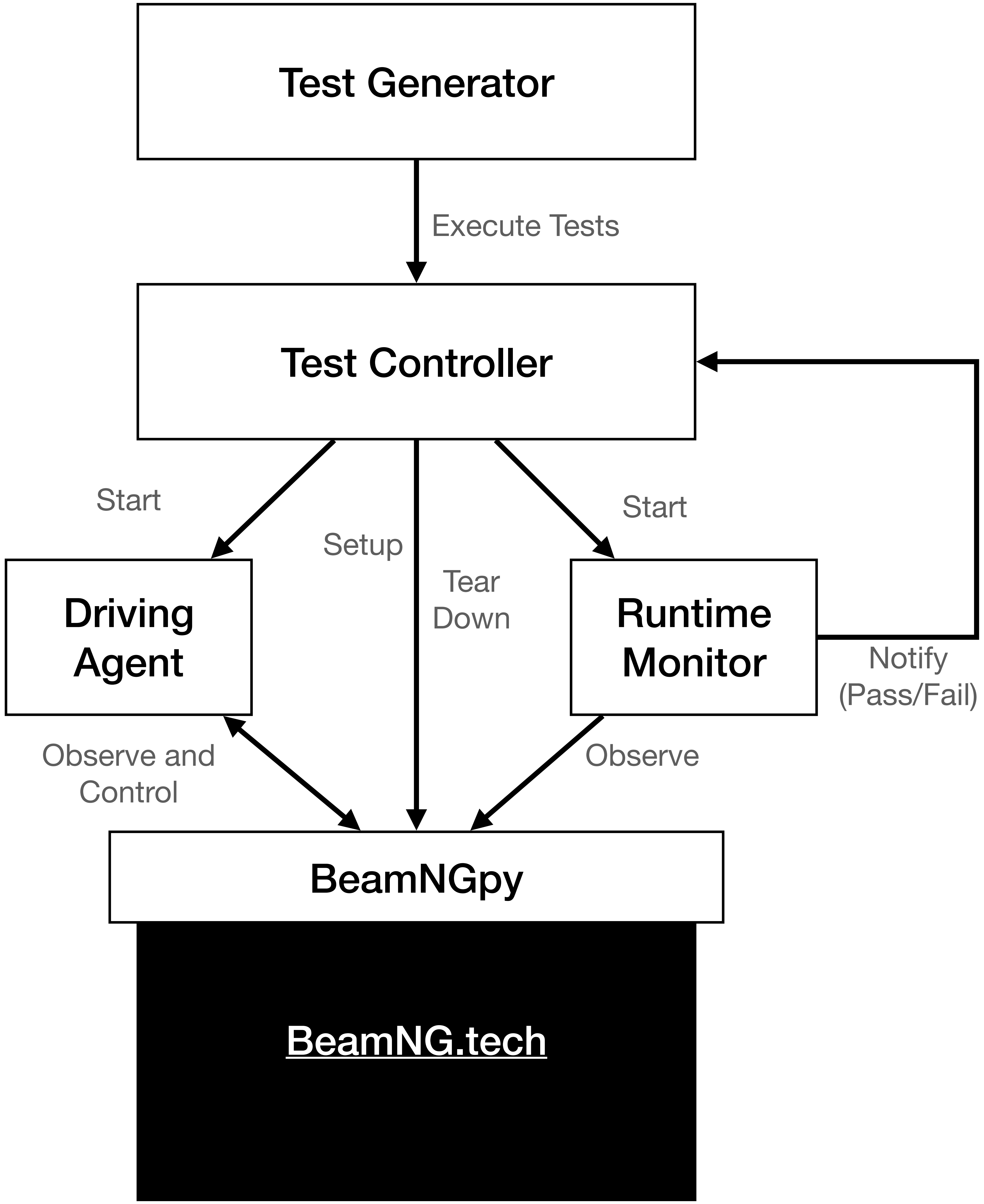
Simulation-Based Testing

Introduction

- Simulation-based testing can be used to implement **X**-in-the-loop testing
  - We focus on Software-in-the-loop (SIL)

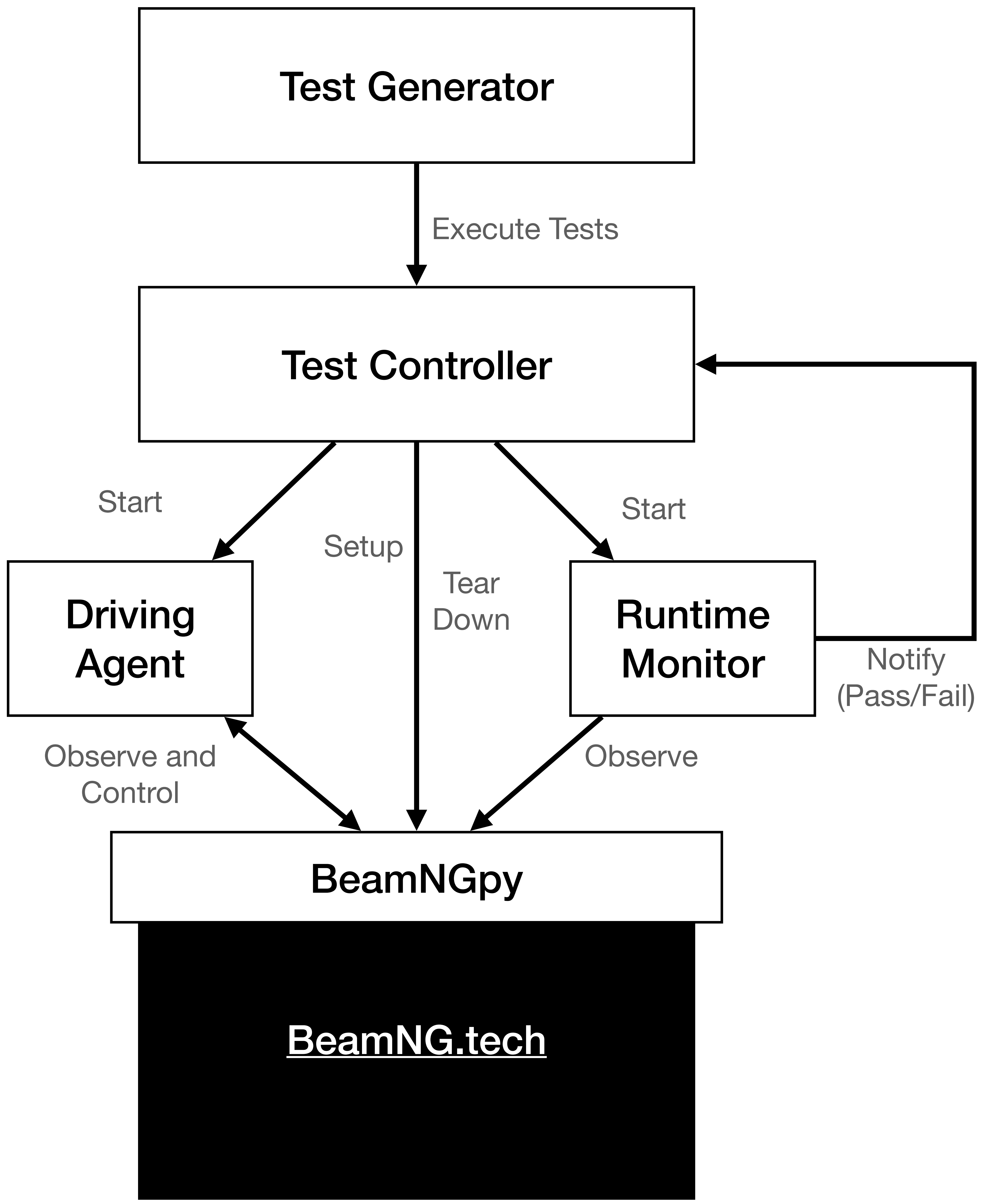
- Test subjects are **continuous controllers** and may be based on **ML/AI**
  - Notoriously difficult to test by traditional means

Reference Architecture



Reference Architecture

- **Test Generator** (either human or algorithm) to generate the tests.



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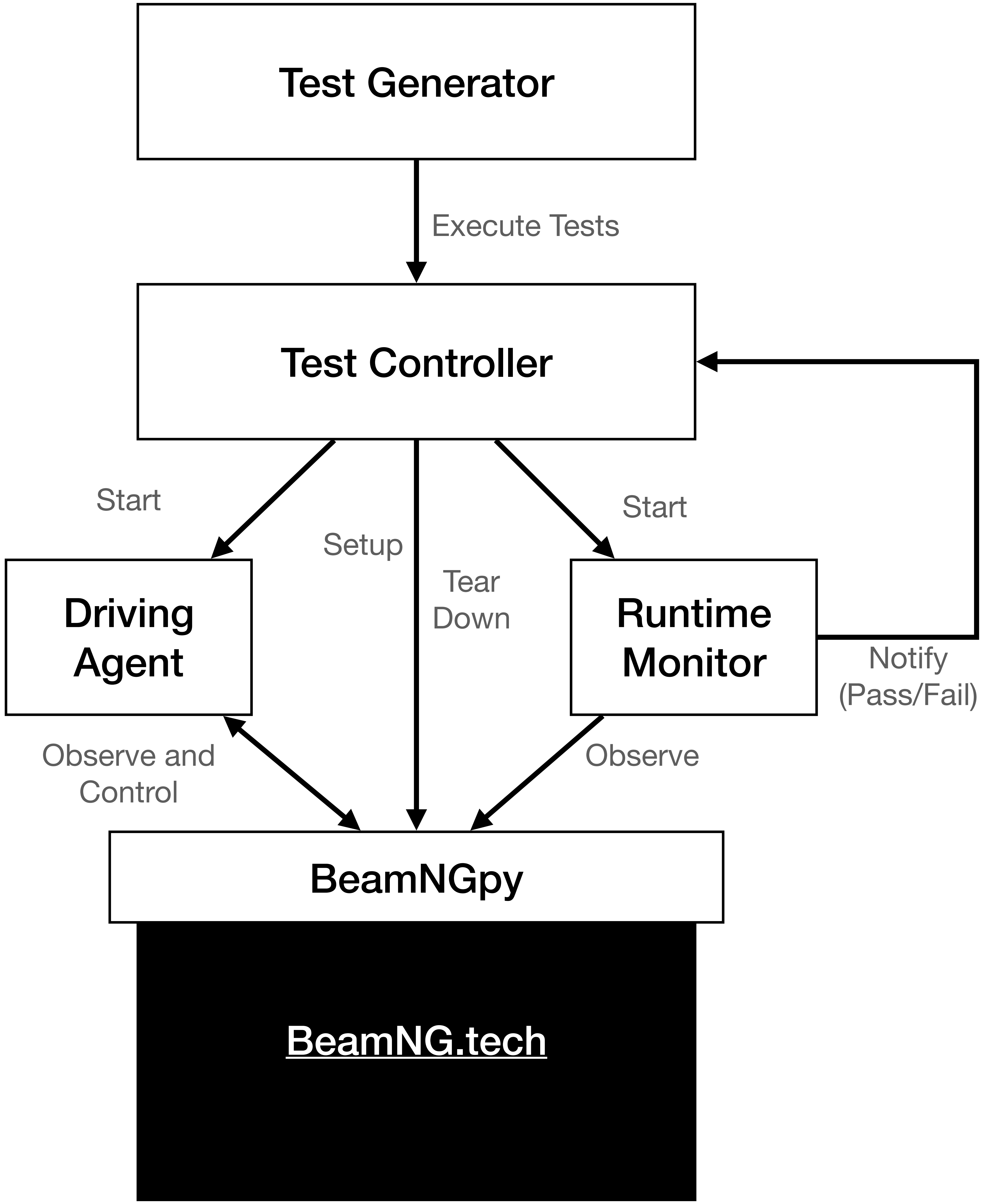

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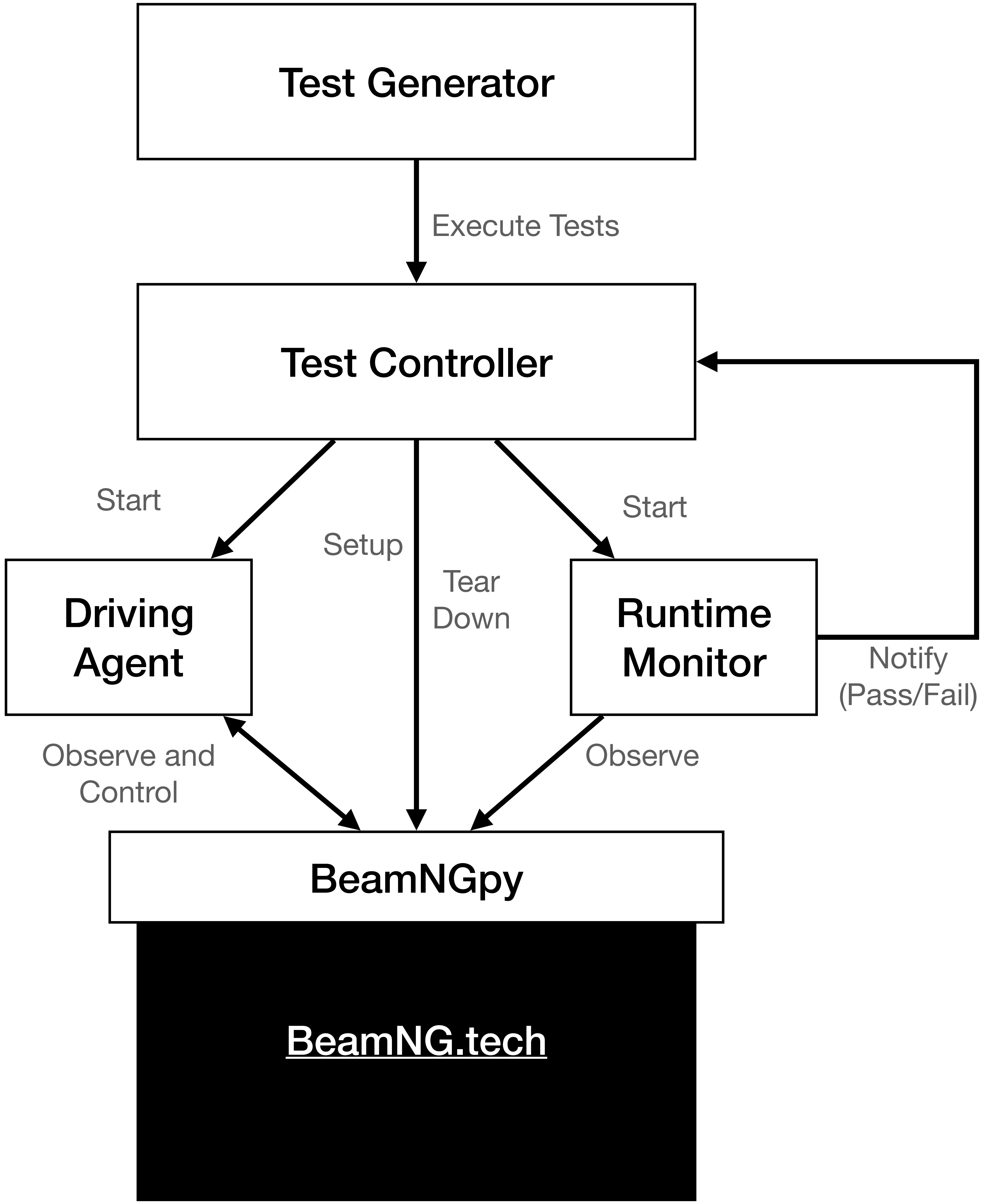

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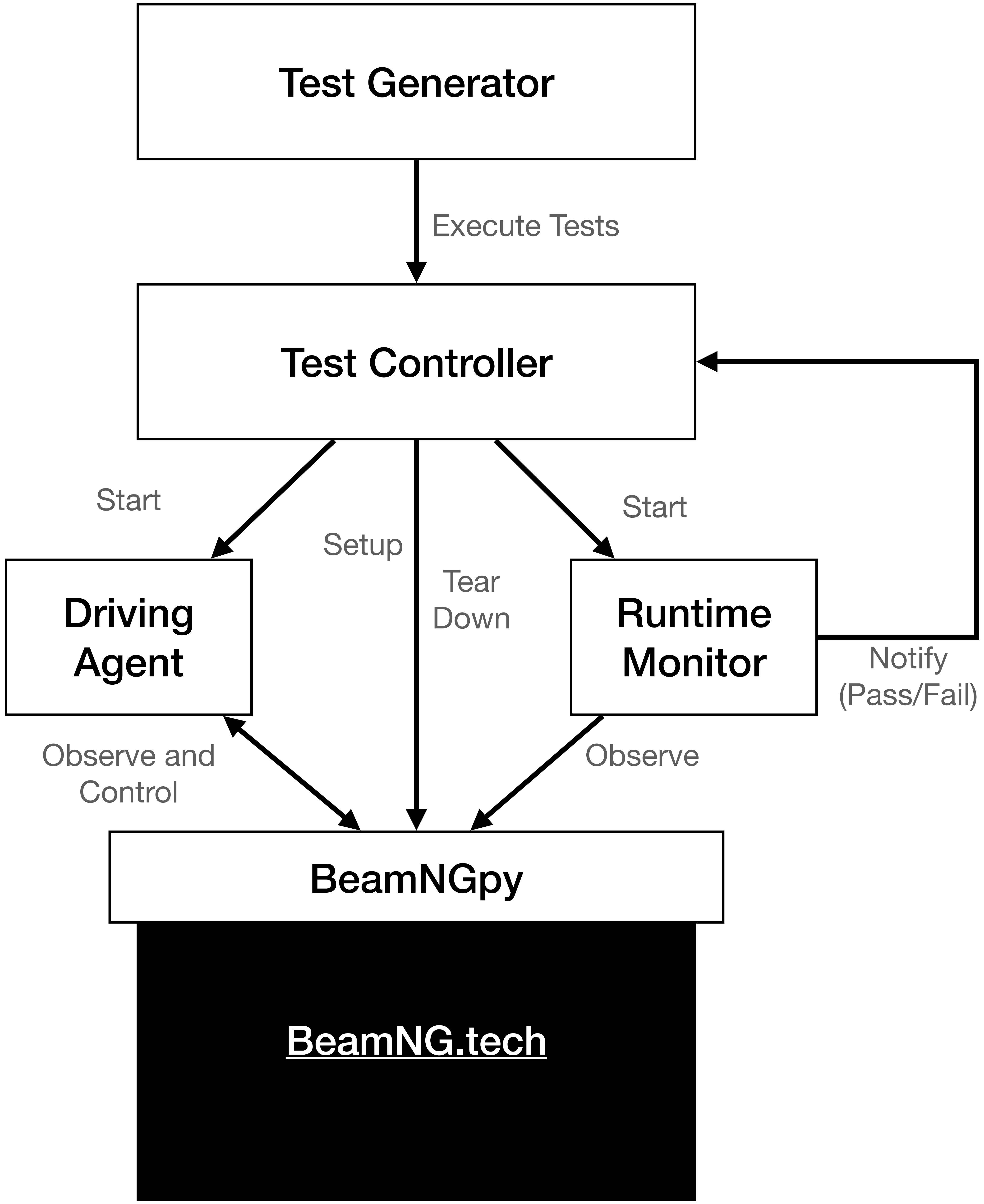
- **BeamNG.tech** is the simulator (considered as black-box)



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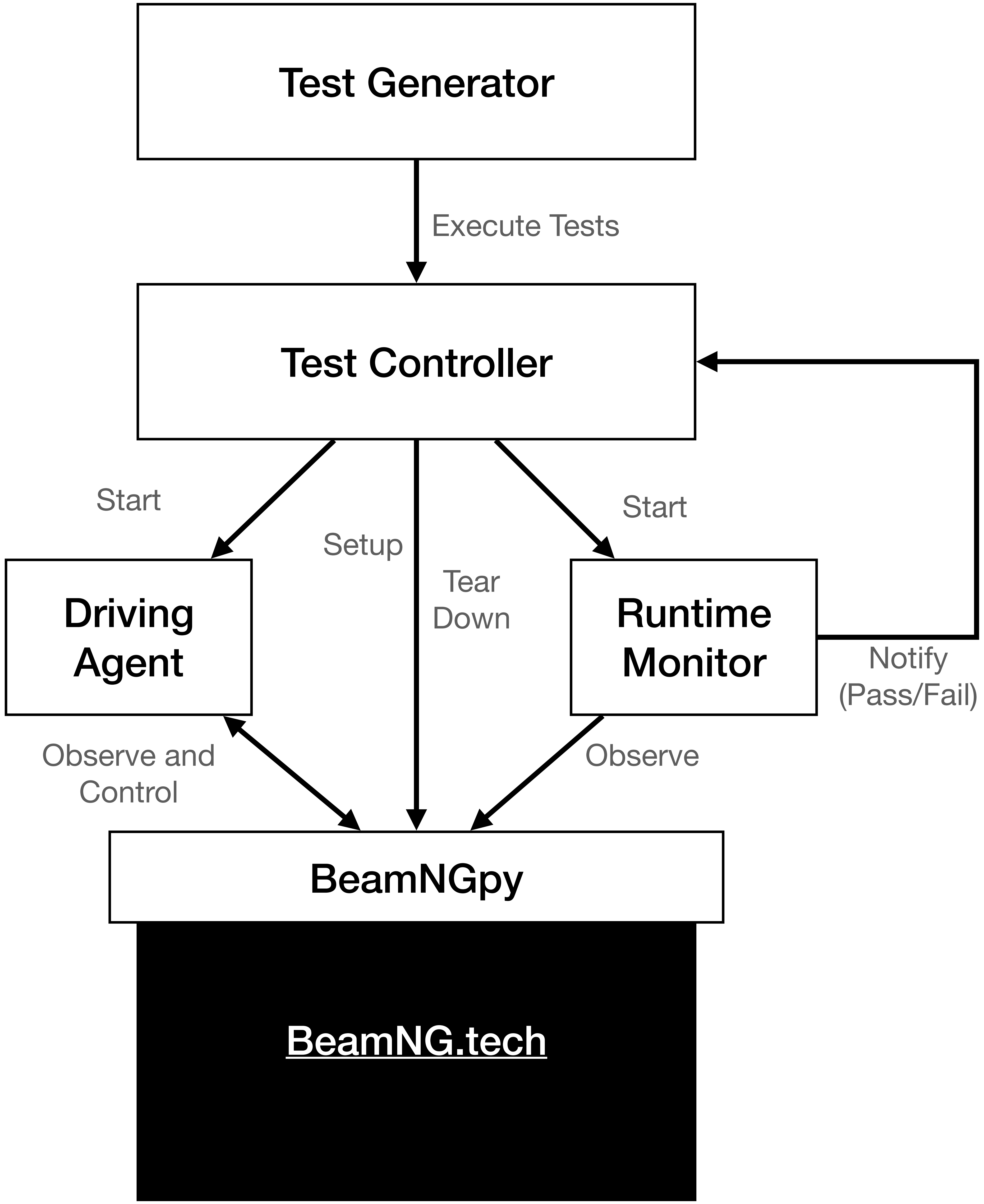
- **Runtime Monitor** to monitor execution and check oracles



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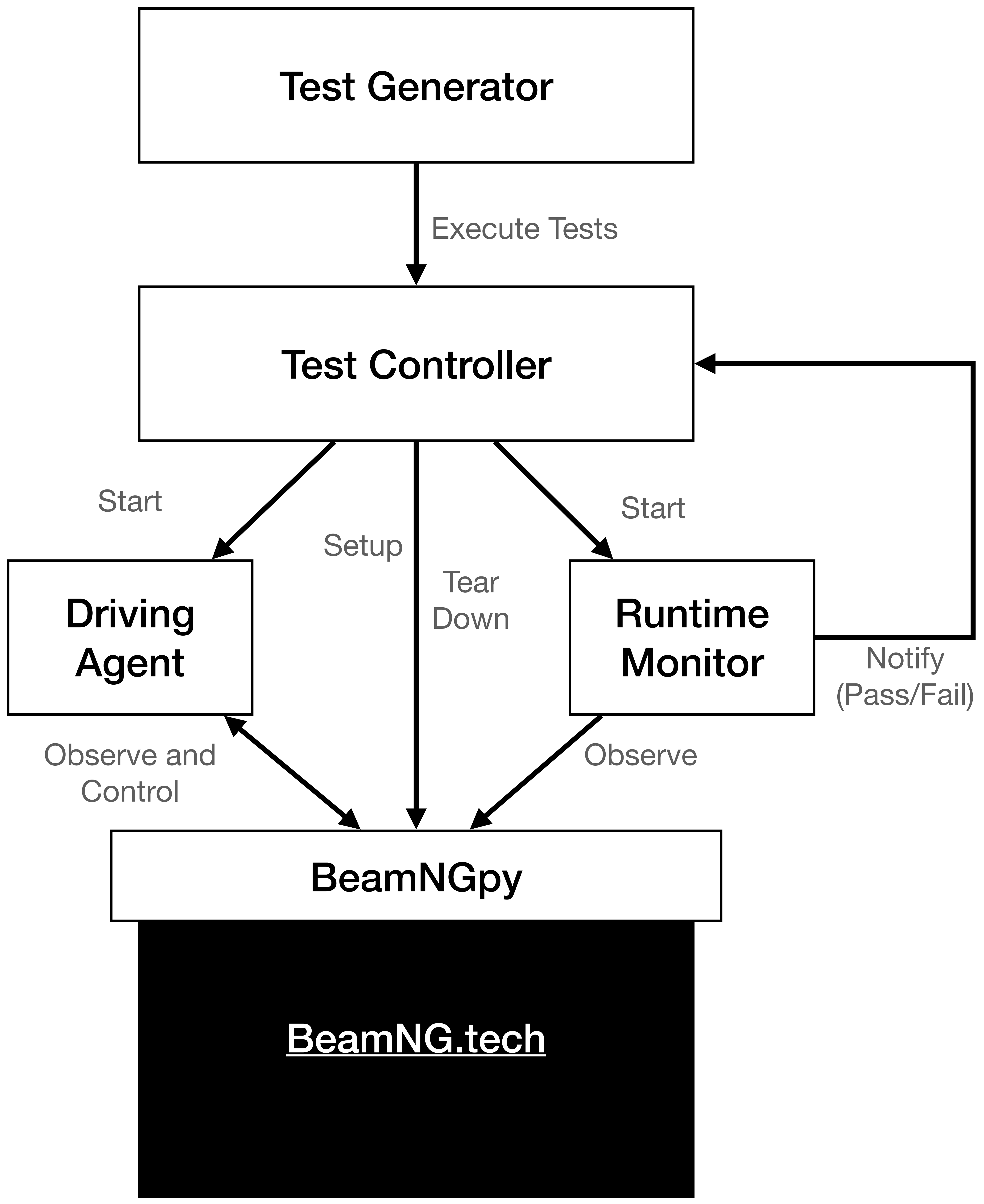
- **Driving Agent** is the test subject that gets sensor data and drives the ego-car



Anatomy of a Simulation-based Test

- **Precondition:** A running simulator
- Set the **environment** (terrain, map, roads)
- Set the test **initial conditions** (placement of vehicles, obstacles)
- Configure **runtime monitors** (positive/negative oracles)
- Configure the **test subject** (connect to ego-car, instruct about test goal/task)
- Add **some dynamism** (NPC, traffic)

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Fresh vs Shared Simulator Instances

- One can start a new instance of the simulator **for each test** or start only one instance of the simulator and **reuse it for all the tests**
- Starting a fresh instance may reduce flakyness/pollution, but it takes more time
- One can also run **multiple concurrent instances** of the simulation (not shown in this tutorial) provided enough computing resources are available for running the simulators **and** the test subjects (GPU-Intensive)

Fresh Instance

```python
class StartFreshInstanceOfTheSimulator(unittest.TestCase):

    def test_that_simulation_start(self):
        with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER):
            do_something()

    def test_that_simulation_restart(self):
        with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER):
            do_something_else()
```

simple-test.py

Fresh Instance (2)

```python
class StartFreshInstanceOfTheSimulatorUsingSetupAndTearDown(unittest.TestCase):

    def setUp(self):
        beamng = BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER)
        self.bng = beamng.open(launch=True)

    def tearDown(self):
        if self.bng:
            self.bng.close()

    def test_that_simulation_start(self):
        do_something()

    def test_that_simulation_restart(self):
        do_something_else()
```

simple-test.py

```python
class SharedInstance(unittest.TestCase):
    beamng = None

    @classmethod
    def setUpClass(cls):
        bng = BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER)
        cls.beamng = bng.open(launch=True)

    @classmethod
    def tearDownClass(cls):
        if cls.beamng:
            cls.beamng.close()
```

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simple-test.py

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    beamng = None

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        cls.beamng = bng.open(launch=True)

    @classmethod
    def tearDownClass(cls):
        if cls.beamng:
            cls.beamng.close()
```

```python
def test_that_can_connect_to_simulator(self):
    client_a = BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER)
    try:
        client_a.open(launch=False, deploy=False)
        do_something()
    finally:
        client_a.skt.close()

def test_that_can_reconnect_to_simulator(self):
    client_b = BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER)
    try:
        client_b.open(launch=False, deploy=False)
        do_something_else()
    finally:
        client_b.skt.close()
```

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Levels and Scenarios

- Simulation-based tests with BeamNG.tech take place inside **scenarios**
- Scenarios are defined in the context of **levels**
- Levels contain **terrains**, **maps**, **props/arts**, **materials**, and other meta-data required to execute the simulation
- **Levels** must be **manually** defined, **scenarios** can be defined **programmatically**
- Currently, BeamNG.tech contains 19 levels (more can be downloaded)
- Levels are locate inside the `levels` folders inside <BNG_HOME> and <BNG_USER>

This PC > Local Disk (C:) > BeamNG.tech.v0.21.3.0 > levels >

Name	Date modified
automation_test_track	5/19/2021 8:14 AM
autotest	5/19/2021 8:14 AM
Cliff	5/19/2021 8:14 AM
derby	5/19/2021 8:15 AM
driver_training	5/19/2021 8:15 AM
east_coast_usa	5/21/2021 11:43 AM
garage	5/19/2021 8:16 AM
glow_city	5/19/2021 8:16 AM
GridMap	5/19/2021 8:17 AM
hirochi_raceway	5/19/2021 8:17 AM
Industrial	5/19/2021 8:18 AM
italy	5/19/2021 8:20 AM
jungle_rock_island	5/19/2021 8:21 AM
showroom_v2_white	5/19/2021 8:21 AM
small_island	5/19/2021 8:22 AM
smallgrid	5/21/2021 12:35 PM
template	5/19/2021 8:22 AM
Utah	5/19/2021 8:23 AM
west_coast_usa	5/19/2021 8:24 AM

Driving on Existing Roads

- Almost all the **existing** levels come with **maps** that include **roads**
- Maps can be **queried** using BeamNGpy but are not yet full HD Maps
- All the levels can be loaded and used "as they are" or can be customized

```
with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER) as bng:
    level_name='Utah'
    scenario_name='ai_test'
    scenario = Scenario(level_name, scenario_name)
    scenario.make(bng)
    bng.load_scenario(scenario)
    bng.start_scenario()
    input('Press enter when done...')
```

load_scenario_and_roads.py

Procedural Road Generation

- Roads can be **procedurally generated** and added to existing scenarios
- Roads **geometry** is defined as sequences of road nodes, i.e., points `(x,y,z)` plus `width`
- Roads have **attributes**, including id, material, lane configuration, and direction

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```
road_nodes = [(0, 30, 0, 8), (20, 30, 0, 8), (40, 30, 0, 8), (60, 30, 0, 8)]
# TIG level courtesy of Precrime group, Lugano
scenario = Scenario('tig', 'test_scenario_1')
road = Road('road_rubber_sticky', rid='road_1')
road.nodes.extend(road_nodes)

scenario.add_road(road)
scenario.make(bng)
bng.load_scenario(scenario)
bng.start_scenario()
```

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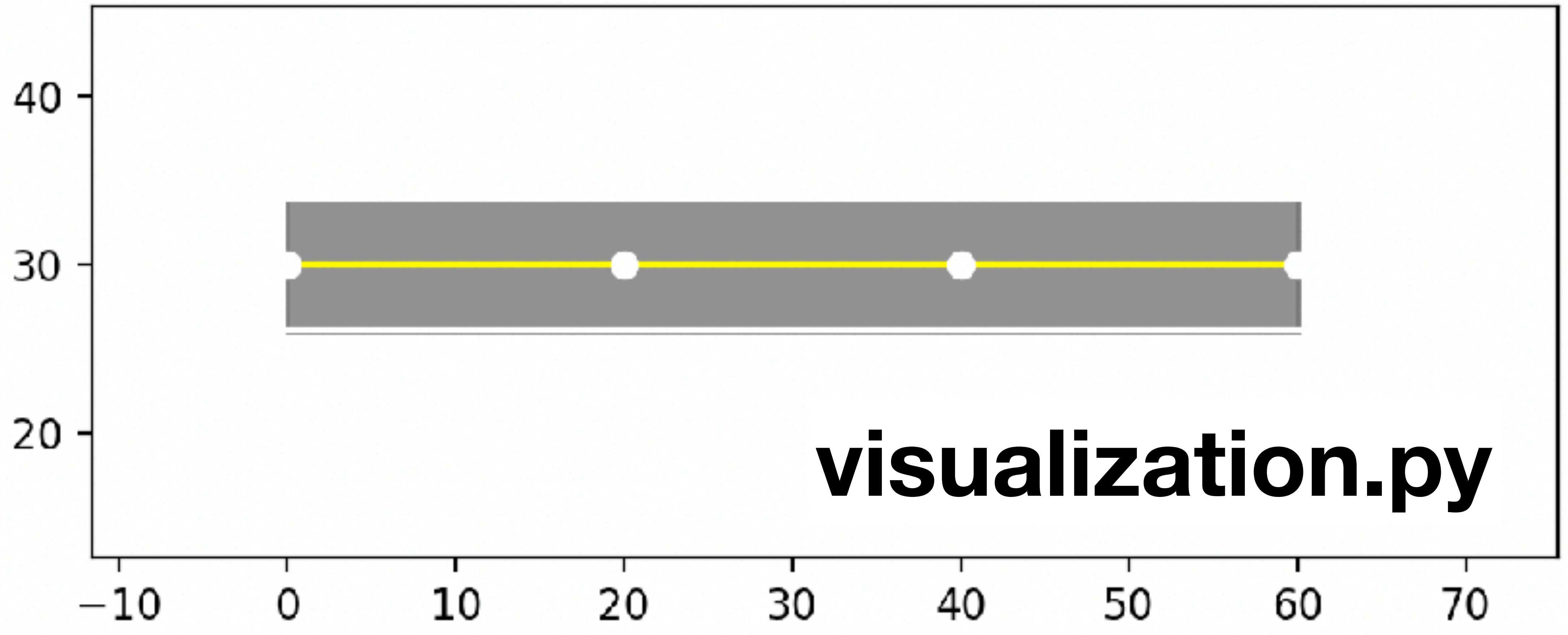


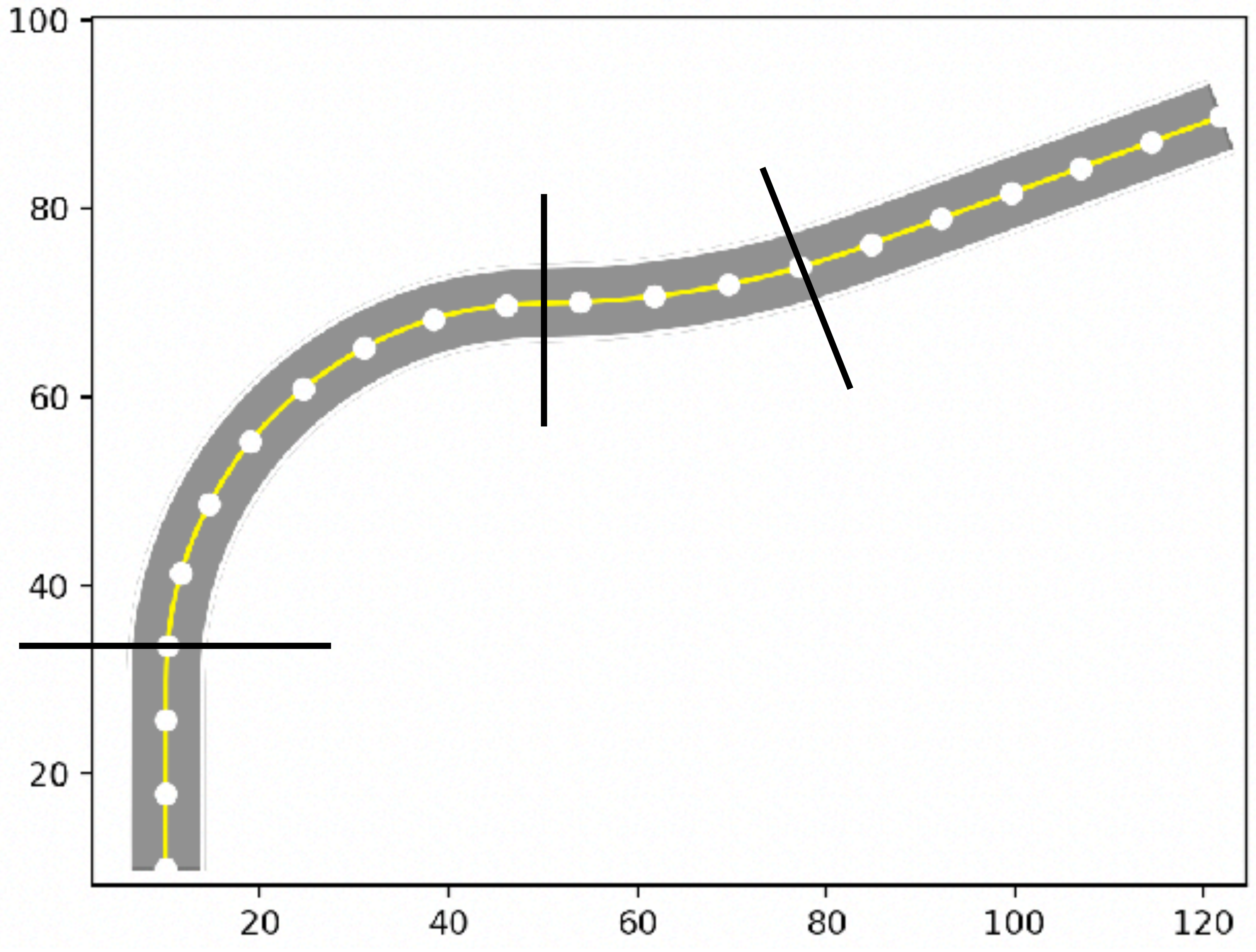
visualization.py

Procedural Road Generation (2)

- One technique to generate roads is to define **sequences of road segments** such as *straight* and *turns*, and generate the road nodes from them given an initial location and direction (**AsFault**)

```
road_segments.append([
 {'type': 'straight', 'length': 20.0},
 {'type': 'turn', 'angle': -90.0, 'radius': 40.0},
 {'type': 'turn', 'angle': +20.0, 'radius': 100.0},
 {'type': 'straight', 'length': 40.0}
])
```

trajectory_generator.py

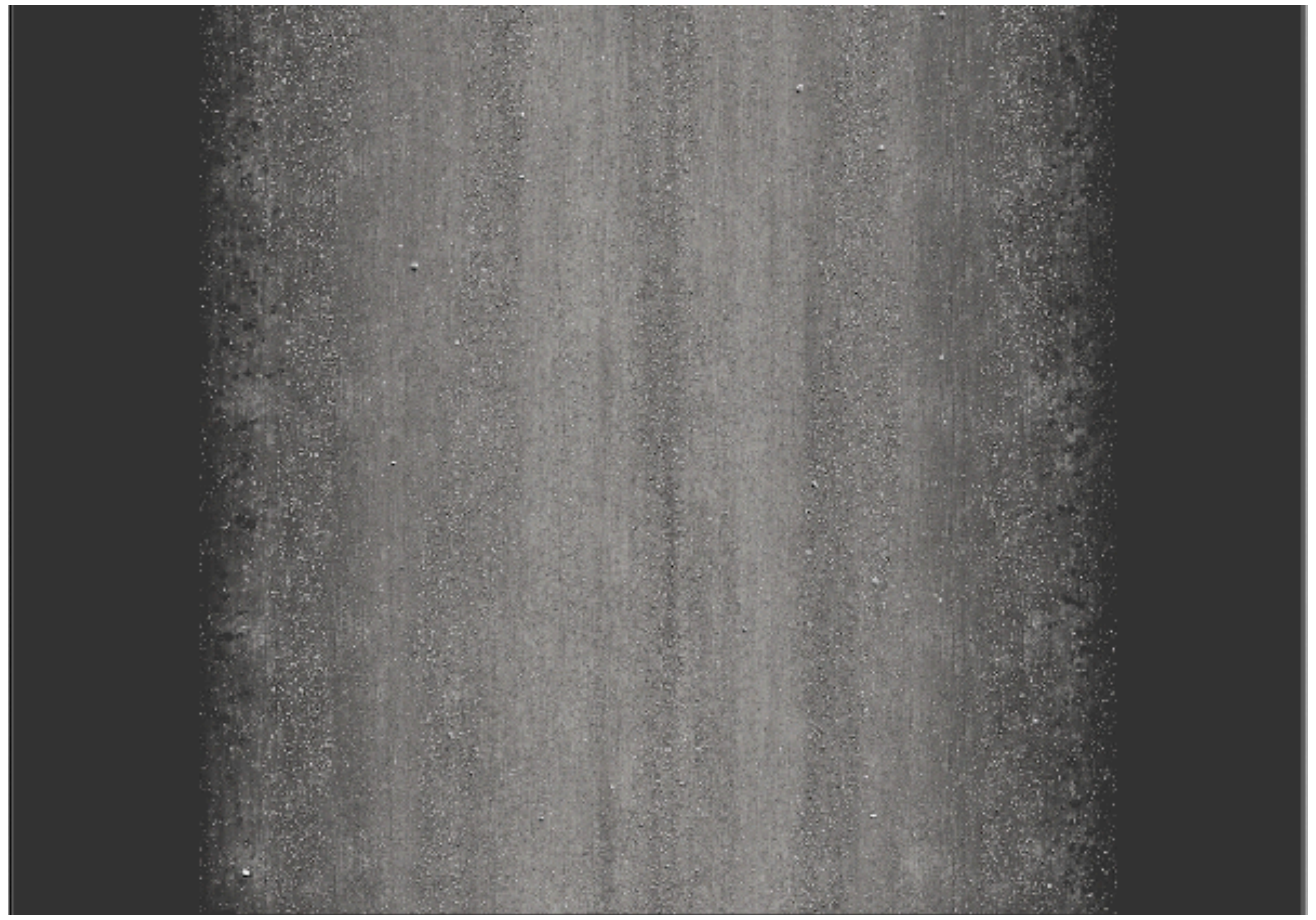


- Many other techniques are available, implemented by tools like **AC3R**, **DeepJanus**, **DeepHyperion**, and the participants of the **SBST Tool Competition**

Lane Markings

- Roads are rendered using **textures** associated to the **materials** they are made of (e.g, `road_rubber_sticky`)

- Textures do not come automatically with **lane markings**, in that case the generated roads will be plain vanilla



Lane Markings as Roads

```
right_marking = Road('line_white', rid='right')
right_marking.nodes.extend(rm_nodes)
scenario.add_road(right_marking)

left_marking = Road('line_white', rid='left')
left_marking.nodes.extend(lm_nodes)
scenario.add_road(left_marking)

central_marking = Road('line_yellow', rid='central')
central_marking.nodes.extend(cm_nodes)
scenario.add_road(central_marking)

road = Road('road_rubber_sticky', rid='road')
road.nodes.extend(road_nodes)
scenario.add_road(road)
```

- Lane markings can be generated by *stacking* "thin roads" on top of the base pavement, so their textures are rendered together (**AsFault**, **AC3R**)
- A similar technique can be used to add skid marks, dirt, and other effects on the road

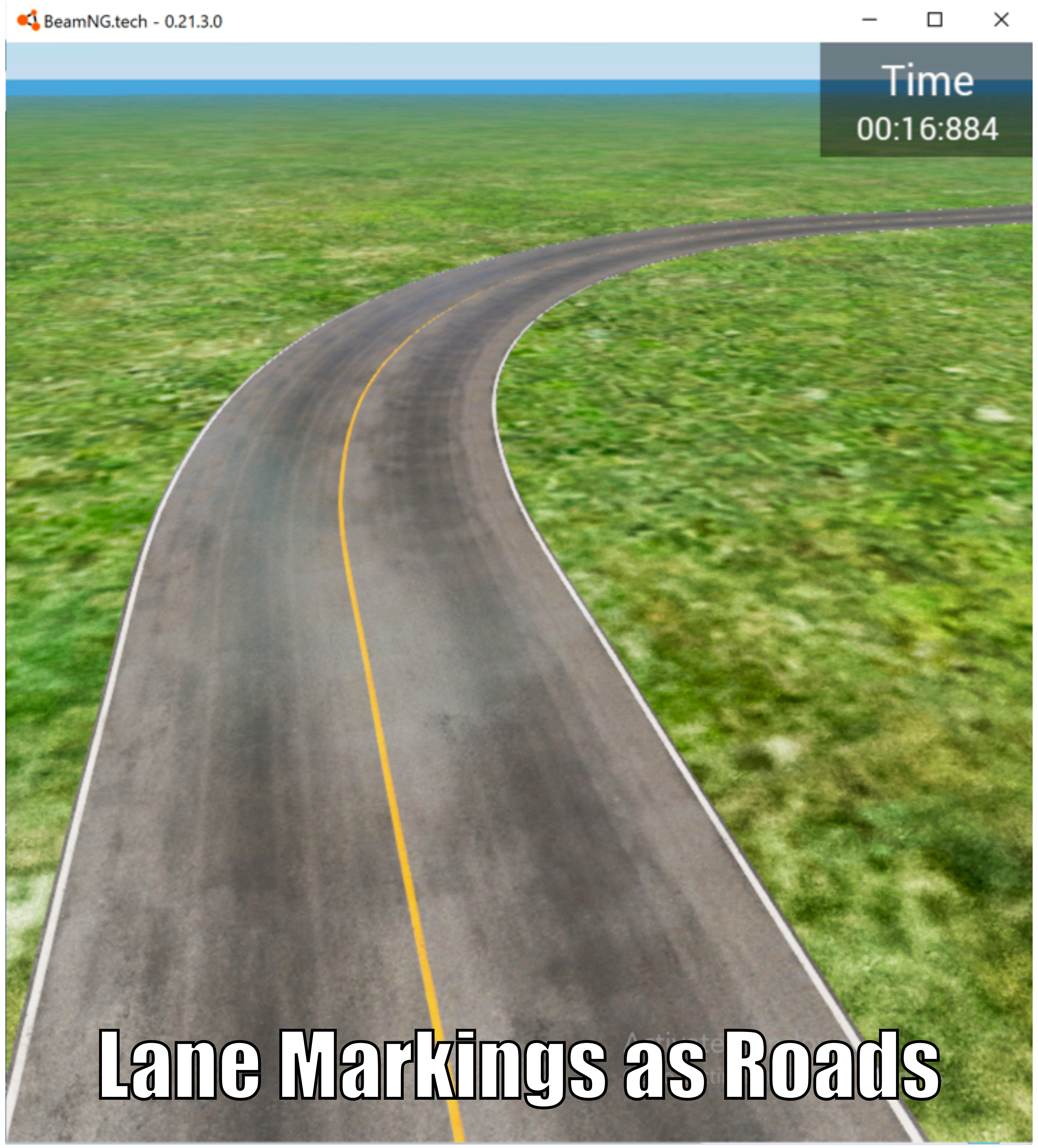
trajectory_generator.py

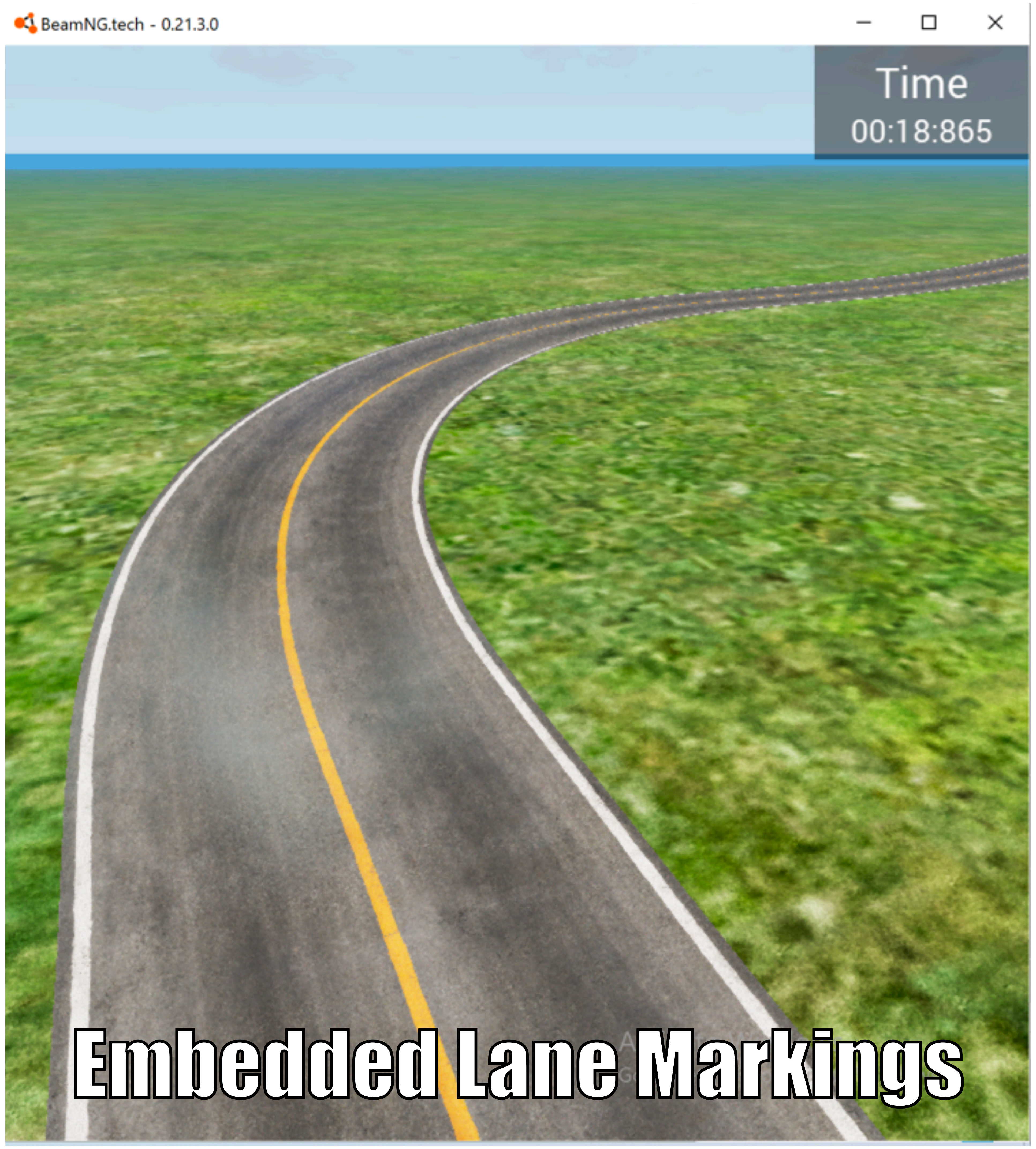
Embedded Lane Markings

- Lane markings can be also generated by *embedding* them in the textures associated to the road materials (**DeepJanus, DeepHyperion, Tool Competition Pipeline**)

```
scenario = Scenario('tig', 'test_scenario_2')
 # This material comes already with lane markings
road = Road('tig_road_rubber_sticky', rid='road_1')
road.nodes.extend(road_nodes)
scenario.add_road(road)
```

Example


BeamNG.tech - 0.21.3.0
Time
00:16:884
Lane Markings as Roads


BeamNG.tech - 0.21.3.0
Time
00:18:865
Embedded Lane Markings

Further Environment Customization

- BeamNGpy also supports changing some aspects of the environment, including **time of the day** (night/day-light)

Anatomy of a Simulation-based Test

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- Set the **environment** (terrain, map, roads)
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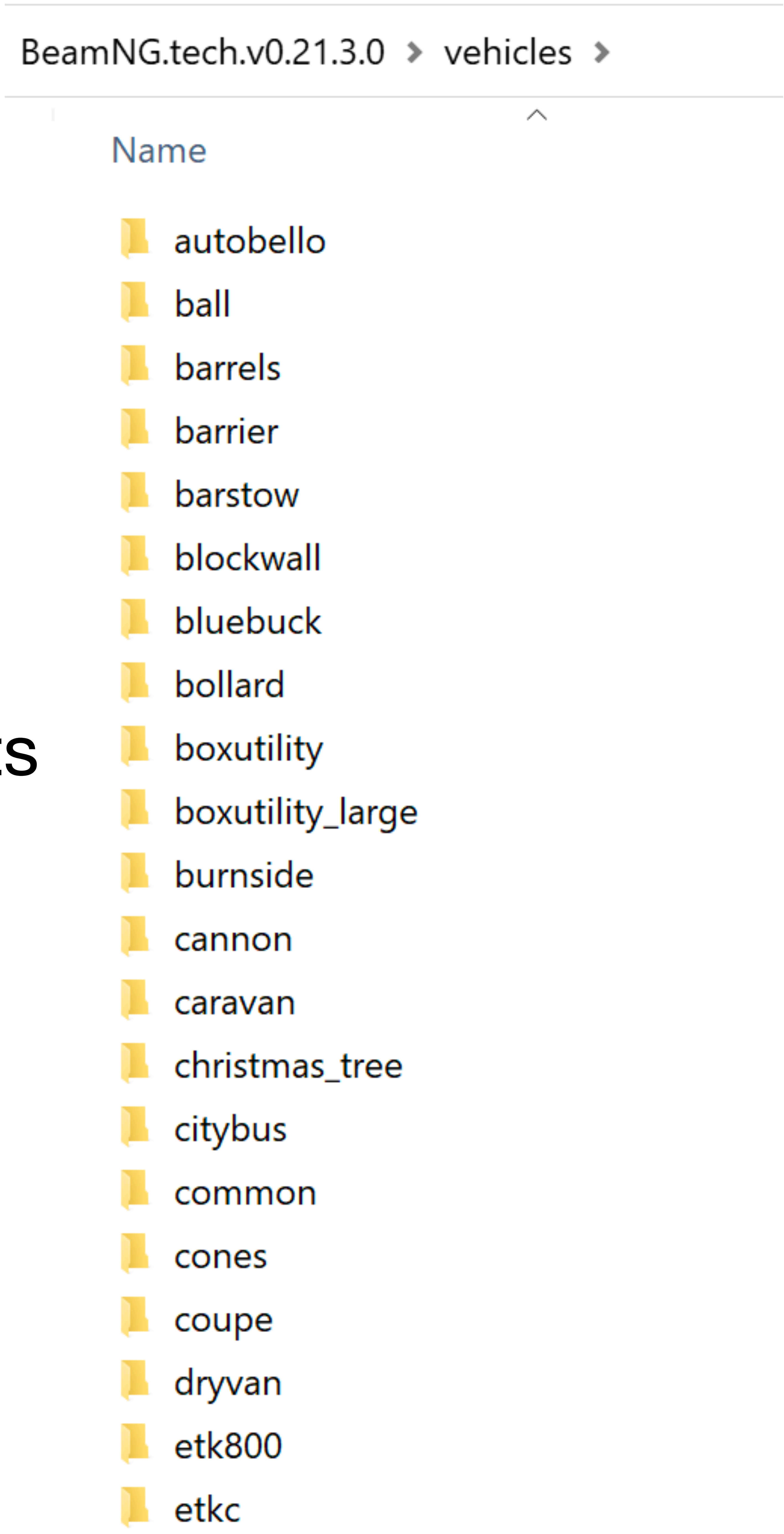
- Configure the **test subject** (connect to ego-car, instruct about test goal/task)
- Add **some dynamism** (NPC, traffic)

Placing Vehicles and Objects

- BeamNG allows multiple **vehicles** and **objects** to be **placed** at arbitrary locations and **rotated** in any direction

- **Vehicles** and complex objects composed of (moving) parts have a **model.** Models are listed in the <BNG_HOME>\vehicles folder.

- **Objects** are static (e.g., concrete barriers, buildings) and can be found inside the various <BNG_HOME>**\art** folders or procedurally generated



place_vehicles_and_obstacles.py

Placing Vehicles


```
# Ego-car: beginning of the road, in the middle of the right lane
ego_pos = translate(start_of_the_road, 0.0, -lane_width*0.5)
# Move the car a little inside the road
ego_pos = translate(ego_pos, length_car, 0.0)
ego_vehicle = Vehicle('ego', model='etk800', licence='ego', color="red")
self.scenario.add_vehicle(ego_vehicle, pos=(ego_pos.x, ego_pos.y, ego_pos.z),
rot_quat=direction_of_the_road)

# Create a yellow small car in front of the ego-car, in same lane, following the same direction
heading_vehicle_pos = translate(ego_pos, +20.0, 0.0)
heading_vehicle = Vehicle('heading', model='autobello', licence='heading', color="yellow")
self.scenario.add_vehicle(heading_vehicle, pos=(heading_vehicle_pos.x, heading_vehicle_pos.y, ground_level),
rot=None, rot_quat=direction_of_the_road)

# Create a bus in front of the ego, but on the opposite lane, following the opposite direction
opposite_vehicle_pos = translate(ego_pos, +10.0, +lane_width)
opposite_vehicle = Vehicle('opposite', model='citybus', licence='opposite', color="white")
self.scenario.add_vehicle(opposite_vehicle, pos=(opposite_vehicle_pos.x, opposite_vehicle_pos.y, ground_level),
rot=None, rot_quat=opposite_direction_of_the_road)
```

Placing Vehicles

- Vehicles can collide with other vehicles and objects, but **cannot** be placed "mid-air" nor in the ground. Otherwise, they **fall and crash** or **crash immediately**

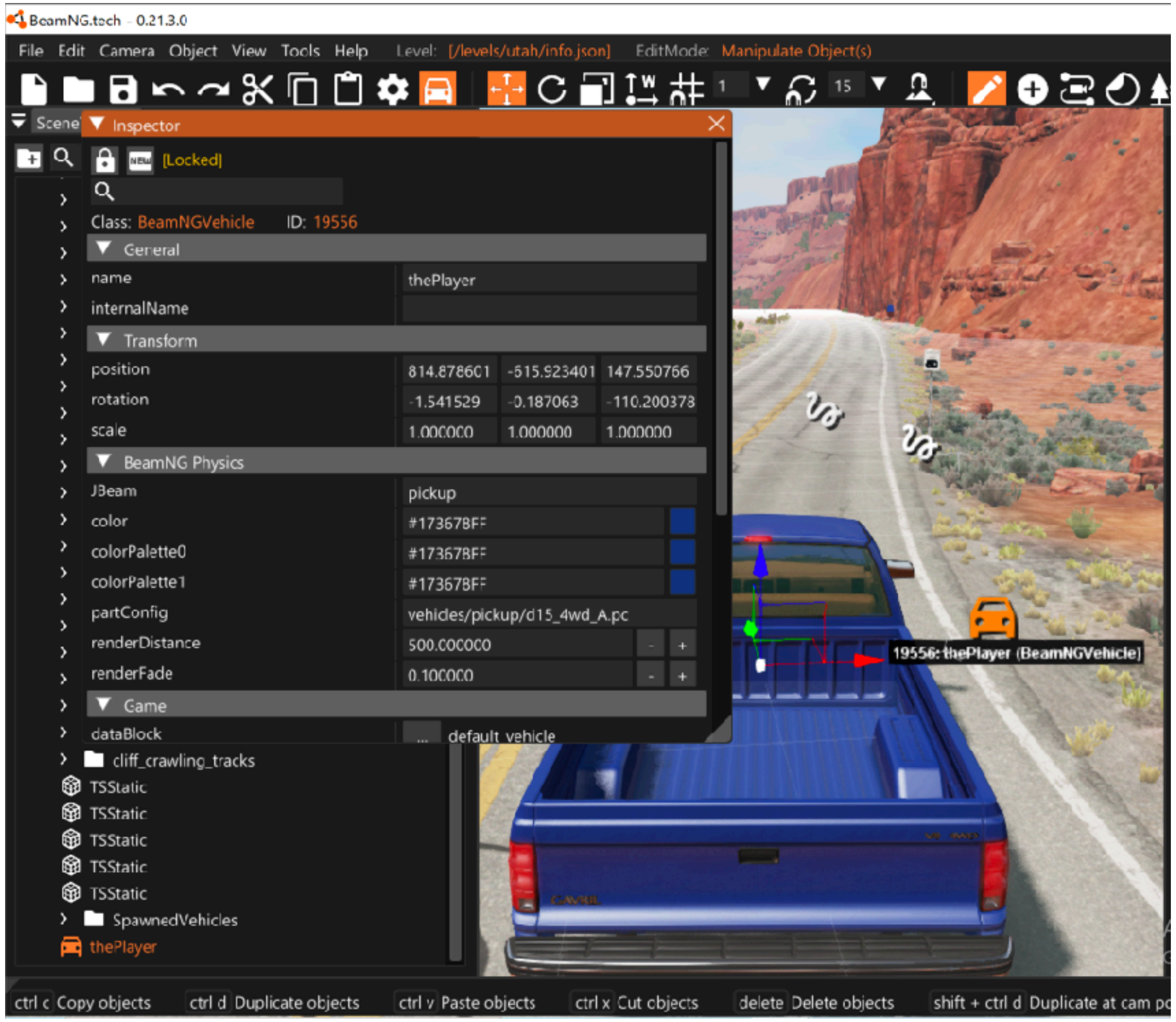
```
#Adding a vehicle in the wrong place, i.e., mid-air, will cause it to fall and break
def test_generate_ground_and_flying_vehicles(self):
    ground_level = -28.0
    # Create a vehicle and put it on the ground, ground is at -28.0 in tig level
    vehicle = Vehicle('vehicle', model='etk800', licence='ground', color="red")
    self.scenario.add_vehicle(vehicle, pos=(0, 0, ground_level), rot=None, rot_quat=(0, 0, 1, 0))

     # Create a vehicle at 0, so 28.0 meters above the ground of tig level
    flying_vehicle = Vehicle('flying_vehicle', model='etk800', licence='flying', color="yellow")
    self.scenario.add_vehicle(flying_vehicle, pos=(0, 10, 0), rot=None, rot_quat=(0, 0, 1, 0), cling=False)
```

Obtaining Object Locations

- One can **query** the simulator to obtain locations and geometry of the roads in the map and accessing info about the other elements loaded by the simulator

- One can **pause** the simulator (Press J)**,** open the **world editor** (Press F11), and use the **inspector tool** to find out the location of the simulated entities



Placing Objects

- Objects can (but do not have to) collide with vehicles and other objects, and can be placed "mid-air", on the ground, and in the ground.
  - **Simple** geometrical objects (e.g., sphere) can be **procedurally generated**
  - **Complex** objects (e.g., barrier) must exist (i.e., as `.dae`) and can be **imported**

```
# A procedurally generated speed bump
# spanning the entire road width
bump = ProceduralBump(name='bump',
 pos=(pos.x, pos.y, pos.z), rot=None,
 rot_quat=(0, 0, 0, 1),
 width=1.0, upper_length= 2*(lane_width-0.1),
 length=2*(lane_width+0.1), upper_width=0.4,
 height=0.1, material="bumber")
self.scenario.add_procedural_mesh(bump)
```

```
# An imported concrete barrier
barrier = StaticObject(name='barrier',
 pos=(pos.x, pos.y, pos.z),
 rot=None,
 rot_quat=facing_of_the_road,
 scale=(1, 1, 1),
 shape='/levels/west_coast_usa/art/shapes/race\
/concrete_road_barrier_a.dae')
self.scenario.add_object(barrier)
```

Anatomy of a Simulation-based Test

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- Add **some dynamism** (NPC, traffic)

Positive vs Negative Oracles

- Testing **continuous controllers** requires the definition of **positive oracles** to establish when a test passes and **negative oracles** to decide when it **fails**
    - Examples of positive oracles are **target areas** that the ego-car must reach or traverse.
    - Examples of negative oracles are **timeouts**, **damages** (safety), **lack of movement** (liveliness), and **"forbidden" areas** (safety).
- Oracles can be checked **on-line** or **off-line**. On-line checking requires **runtime monitors,** off-line checking requires to **persist the data**.

Sensors

- Oracles can be defined on **objects' state** (e.g., pos, rotation), **absolute values** (simulation time), **physical quantities** (e.g., speed, acceleration, forces), and other **sensor values** (e.g., pixel-perfect annotations, steering wheel position)
- The data required to evaluate the oracles can be collected by **polling** the simulator via the **sensors** abstraction
- Sensors must be **attached** to vehicles
- BeamNGpy implements many sensors, including `State`, `Timer`, `Camera`, `Electrics`, `Lidar`, and more

A Simple Sensor: State

```
from beamngpy.sensors import State

# Attach a State sensor to the vehicle
state_sensor = State()
self.ego_vehicle.attach_sensor('state', state_sensor)

with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER) as bng:
    self.scenario.make(bng)
    bng.load_scenario(self.scenario)
    bng.start_scenario()
    for i in range(1,TIMEOUT):
        sleep(10) # Wait
        self.ego_vehicle.poll_sensors() # Poll Data
```

Position-based Oracle

```python
# This class implements an oracle to check if the vehicle reached a target location (circular area)
# It uses the State sensor to get the position of the vehicle
from shapely.geometry import Point

class TargetAreaOracle():

    def __init__(self, target_position, radius, state_sensor):
        self.target_position = Point(target_position)
        self.radius = radius
        self.state_sensor = state_sensor

    def check(self):
        # Get current position from the state_sensor and measure distance to target
        distance_to_goal = self.target_position.distance(Point(self.state_sensor.data['pos']))
        return distance_to_goal < self.radius
```

Putting All Together

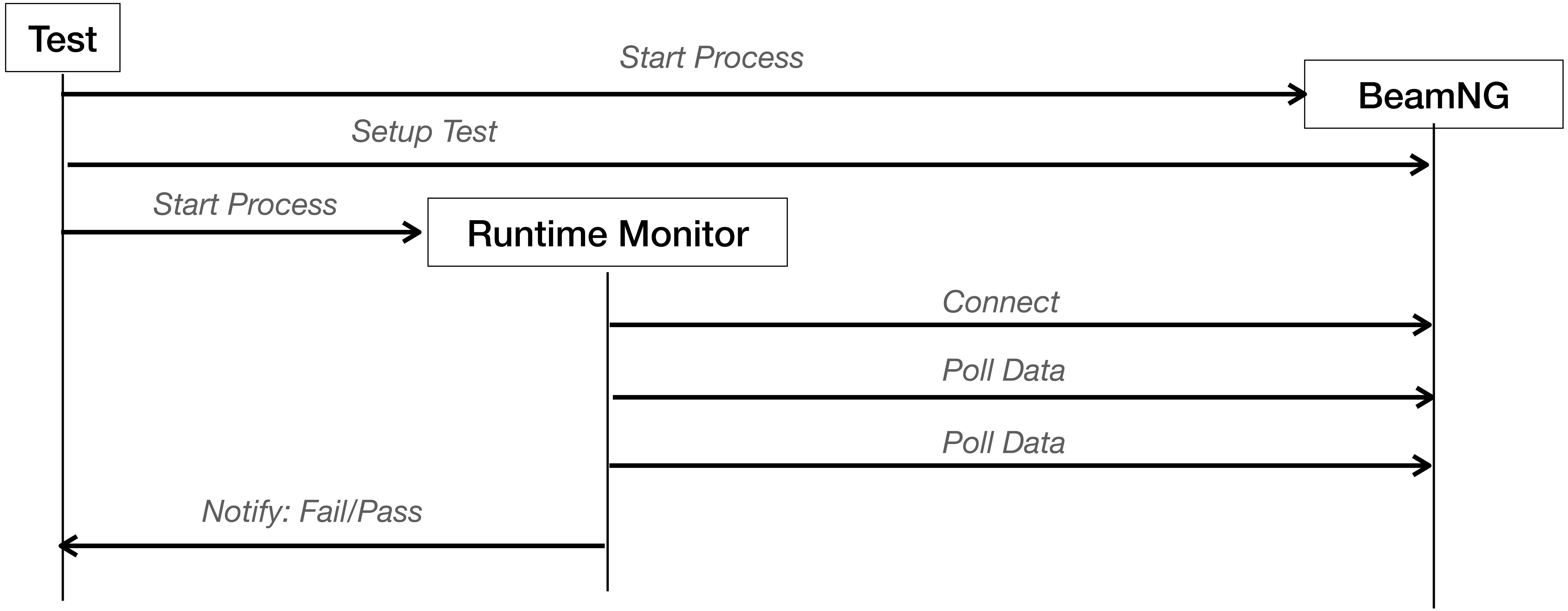
```
# Attach a State sensor to the vehicle
state_sensor = State()
self.ego_vehicle.attach_sensor('state', state_sensor)
# Define the oracle
target_position = (60, 30, ground_level)
radius = 2 * lane_width + 0.2
target_area_reached_oracle = TargetAreaOracle(target_position, radius, state_sensor)

with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER) as bng:
    self.scenario.make(bng)
    bng.load_scenario(self.scenario)
    bng.start_scenario()
    for i in range(1,TIMEOUT):
        sleep(10) # Wait
        self.ego_vehicle.poll_sensors() # Poll Data
        # Check Oracle
        if target_area_reached_oracle.check():
            print("Car reached target location")
            return
```

Runtime Monitoring

- During the simulation execution, data can be gathered directly in the **main process** (i.e., test controller) or in a **background (sub-)process**.

- Gathering data directly in the main process is **simpler to implement** since it does not require to setup complex inter-process communications (as illustrated below)



Synchronous Simulations

- Collecting large amount of data (e.g., Camera images, Point-clouds) at high frequency may introduce large performance overhead, impacting the achievable Frame-per-Second (FPS) and overall quality of the simulation.
- Likewise, performance overhead impact the **quality of control** because it introduces lags/delays in controllers/drivers reaction
- **Synchronous simulations** can be used to reduce the impact of processing data on the critical path by executing a number of **simulation steps** and then **pausing** waiting for the "clients" to read and process the data before continuing
- Synchronous simulation may improves **reproducibility** and reduce noise and *flakyness* (especially when paired with **deterministic** simulations)

Synchronous Simulations

```python
with BeamNGpy('localhost', 64256, home=BNG_HOME, user=BNG_USER) as bng:
    # Define the simulation frequency: 60 FPS
    bng.set_steps_per_second(60)
    bng.set_deterministic()

    # Pause the simulation
    bng.pause()

    for i in range(1,10):
        # Progress it for 30 steps, 30/60=0.5 sec
        bng.step(30)
        # Pretend this is a long-running computation
        sleep(2)

    #Eventually restore the standard simulation behavior
    bng.resume()
```

Anatomy of a Simulation-based Test

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- Configure the **test subject** (connect to ego-car, instruct about test goal/task)
- Add **some dynamism** (NPC, traffic)

The Ego-Car, a.k.a. the Test Subject

- The logic controlling the ego-car can be executed **inside** the simulator (e.g., BeamNG driving agent) or **outside**
- Outside the simulator, the driving agent can run inside the **main** process (e.g., **DeepJanus**, **DeepHyperion**, **Tool Competition Pipeline**) or in **different** process (e.g., **AsFault**)
- As runtime monitors do**, driving agents collect** data using **sensors** attached to the Vehicle(s)
- Different than runtime monitors, driving agent **control** the ego-car (i.e., steering, throttle, brake)

Define the Test Goal

- Simulation-based tests usually take the form of **driving tasks**, such as follow the lane or avoid an obstacle, that the test subject must successfully complete
- Instructing the driving agent/AI on what to do is **problem** and **application specific**
- Sometimes the driving task is **"implicitly"** defined:
    - For testing lane keeping systems, **AsFault**, provides a list of way points for the ego-car to follow, while **DeepJanus** puts the car on a single road, and the ego-car has to following it

Using BeamNG Driving AI

Tool Competition Pipeline

- The logic controlling vehicles is embedded in the simulator and exposed via BeamNGpy
  - Set destination waypoint (must be **reachable** from ego-vehicle current position)
  - Set risk factor, max speed, and other properties

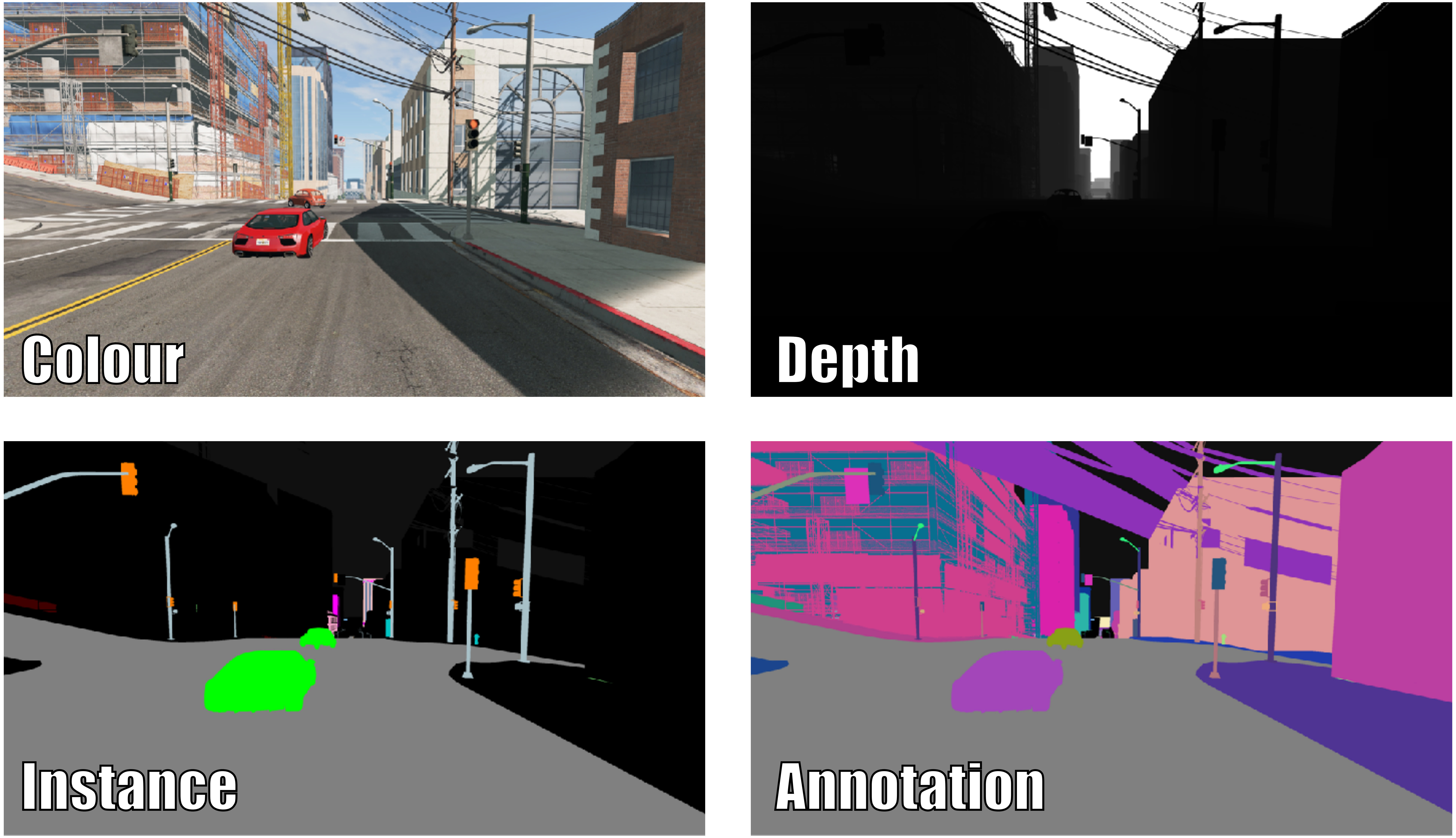
```
r_nodes = generate_road_nodes()
# Define the destination point
dest = (r_nodes[-1][0], r_nodes[-1][1], r_nodes[-1][2])
scenario.add_checkpoints([dest], [(1, 1, 1)], ids=["dest_wp"])
with BeamNGpy('localhost', 64256) as bng:
    # Make and start the scenario
    scenario.make(bng)
    bng.load_scenario(scenario)
    bng.start_scenario()
    bng.pause()
    # Configure BeamNG driving AI to drive to the destination
    ego_vehicle.ai_set_mode('manual')
    ego_vehicle.ai_set_waypoint('dest_wp')
    ego_vehicle.ai_drive_in_lane('true')
    ego_vehicle.ai_set_speed(50.0 / 3.6, mode='limit')
```

End-to-end Driving in Main Process

DeepJanus, DeepHyperion

- The logic controlling the vehicles is executed **inside the main process** along with the runtime monitor/oracles
  - Data are collected using the sensors and sent to the driving agent that uses the API to **drive the vehicle** by setting steering, brake, and throttle.
- Simple setup, but **requires installing the driving agent dependencies** along with the dependencies of the other components
  - For instance, NVidia Dave2 (from Precrime) requires tensorflow, keras, open-cv, and other libraries

Camera Sensor



DeepJanus*
DeepHyperion*

** Code simplified to ease the presentation*

https://github.com/testingautomated-usi/DeepJanus/tree/master/DeepJanus-BNG/self_driving

DeepJanus*
DeepHyperion*

* *Code simplified to ease the presentation*

nvidia_prediction.py

```
class NvidiaPrediction:

  def __init__(self, model, config: Config):
    self.model = model
    self.config = config
    self.speed_limit = config.MAX_SPEED

  def predict(self, image, car_state):
      # Predict the steering angle from the image
      image = np.asarray(image)
      image = preprocess(image)
      image = np.array([image])
      steering_angle = float(self.model.predict(image, batch_size=1))
      # Adjust the speed
      speed = car_state.vel_kmh
      if speed > self.speed_limit:
          self.speed_limit = self.config.MIN_SPEED  # slow down
      else:
          self.speed_limit = self.config.MAX_SPEED
      throttle = 1.0 - steering_angle ** 2 - (speed / self.speed_limit) ** 2
      return steering_angle, throttle
```

https://github.com/testingautomated-usi/DeepJanus/tree/master/DeepJanus-BNG/self_driving

DeepJanus*
DeepHyperion*

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      # Adjust the speed
      speed = car_state.vel_kmh
      if speed > self.speed_limit:
          self.speed_limit = self.config.MIN_SPEED  # slow down
      else:
          self.speed_limit = self.config.MAX_SPEED
      throttle = 1.0 - steering_angle ** 2 - (speed / self.speed_limit) ** 2
      return steering_angle, throttle
```

beamng_nvidia_runner.py

```
def run_simulation(self, nodes):
    # Setup the test
    self.setup_road_nodes(nodes)
    self.vehicle_start_pose = _get_vehicle_start_pose()
    # Define the destination
    waypoint_goal = BeamNGWaypoint('waypoint_goal', get_node_coords(nodes[-1]))
    # Setup runtime monitoring
    vehicle_state_reader = VehicleStateReader(self.vehicle, self.beamng,
                           additional_sensors= BeamNGCarCameras())
    sim_data_collector = SimulationDataCollector(self.vehicle, self.beamng,
                           vehicle_state_reader=vehicle_state_reader)
    # Start runtime monitoring
    sim_data_collector.get_simulation_data().start()
    brewer.bring_up()      # Start simulation
    self.model = load_model(self.model_file) # Load the model
    predict = NvidiaPrediction(self.model, self.config)
    while True:
        # Poll sensors
        sim_data_collector.collect_current_data(oob_bb=False)
        last_state: SimulationDataRecord = sim_data_collector.states[-1]
        # Check oracles
        if points_distance(last_state.pos, waypoint_goal.position) < 6.0 or last_state.is_oob:
          break
        # Make prediction based on camera image
        img = vehicle_state_reader.sensors['cam_center']['colour'].convert('RGB')
        steering_angle, throttle = predict.predict(img, last_state)
        # Apply control command
        self.vehicle.control(throttle=throttle, steering=steering_angle, brake=0)
        # Progress with the simulation
        beamng.step(steps)
```

https://github.com/testingautomated-usi/DeepJanus/tree/master/DeepJanus-BNG/self_driving

Driving the ego-car from Another Process

AsFault + Path Planner

- The logic controlling the vehicles is executed **in a separate process** that uses BeamNGpy to **query** the **map** and **scenario** and **control the vehicle**
- Driving agent dependencies are **kept separated from the test code**, but this setup requires IPC and some form of synchronization between the test controller and the test subjects
- A path planner can control the vehicle by providing the BeamNG driving agent with a **trajectory** to follow (i.e., locations in time)

AsFault

beamer.py

```
def start_controller(self):
    l.info('Calling process: %s', self.ctrl)
    self.ctrl_process = subprocess.Popen(self.ctrl)

def kill_controller(self):
    if self.ctrl_process:
        l.info('Terminating process %s', self.ctrl)
        TestRunner.kill_process(self.ctrl_process)
    self.ctrl_process = None

@staticmethod
def kill_process(process):
    if process:
        if os.name == 'nt':
            subprocess.call(['taskkill',
                             '/F', '/T', '/PID',
                             str(process.pid)])
        else:
            os.kill(process.pid, signal.SIGTERM)
```

drivers.py

```
def run(self):
    self.bng = BeamNGpy('localhost', 64256)
    # Connect to the running BeamNG simulation
    self.bng = self.bng.open(launch=False, deploy=False)
    self.bng.pause()
    # Connect to the ego-car and configure sensors
    active_vehicles = bng.get_current_vehicles()
    self.vehicle = active_vehicles[car_model['id']]
    self.vehicle.attach_sensor('state', State())
      self.bng.connect_vehicle(self.vehicle)
    # Get initial state of the car
    self.bng.poll_sensors(self.vehicle)
    # Get geometry of the road
    road_geometry = self.bng.get_road_edges('the_road_id')
    # Compute the "optimal" trajectory
    driving_path = self._compute_driving_path(self.vehicle.state,
                                              road_geometry)
    self.ai_script = self.compute_ai_script(driving_path, self.car_model)
    # Configure BeamNG driving agent to follow the trajectory
    self.vehicle.ai_set_mode('disabled')
    self.vehicle.ai_set_script(self.script)
    # Resume the simulation (this will cause the car to move)
    self.bng.resume()
```

https://github.com/alessiogambi/AsFault/tree/asfault-deap/src/asfault

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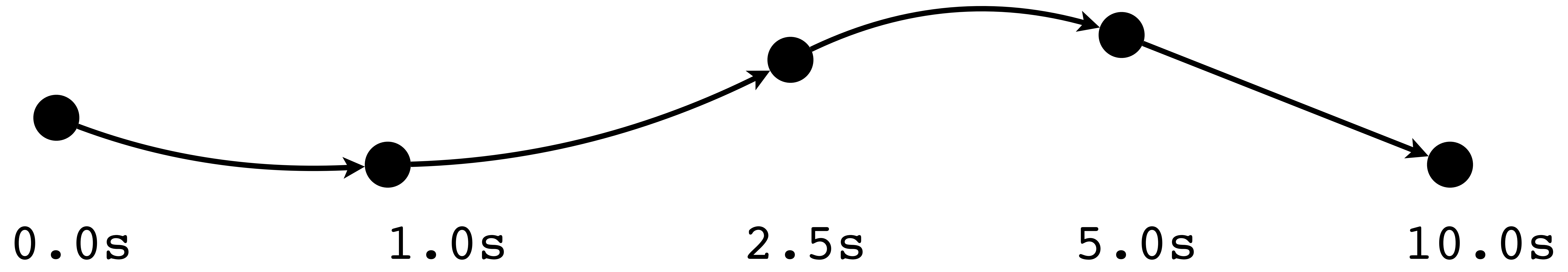
- Configure the **test subject** (connect to ego-car, instruct about test goal/task)
- Add **some dynamism** (NPC, random traffic)

Controlling NPC Vehicles

- Controlling non-playable character can be done using BeamNGpy and the available BeamNG driving AI by
  - **Setting the checkpoints** and the other configurations (e.g., speed limit, risk factor)
  - **Generating** a **script** that defines the trajectory **implicitly** by specifying a sequence of **nodes** (absolute positions) that must be reached by the vehicle at a given time (computed from the beginning of the simulation)



```python
INTER_NODE_DISTANCE = 20.0
# Define a straight trajectory and constant speed
trajectory = []
for i in range(0, 5):
    node = {
        'x': INTER_NODE_DISTANCE * i + INITIAL_DISTANCE,
        'y': 30 - LANE_WIDTH * 0.5,
        'z': GROUND_LEVEL + 1.0,
        't': 2.5 * i
    }
    trajectory.append(node)

heading_vehicle = Vehicle('ego', model='etk800', licence='NPC', color="red")
scenario.add_vehicle(heading_vehicle, pos=initial_position, rot=None, rot_quat=direction_of_the_road)
scenario.make(bng)
bng.load_scenario(scenario)
bng.start_scenario()

# Configure the NPC
heading_vehicle.ai_set_mode('disabled')
heading_vehicle.ai_set_script(trajectory)
```

Part III

Automated test generation

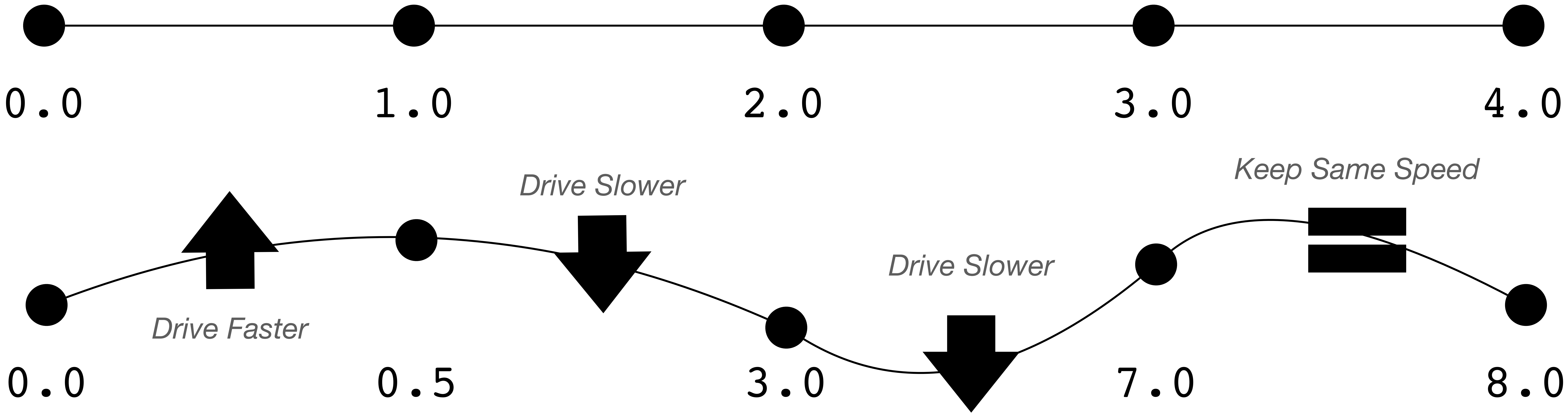
Automated Test Generation

- Automated test generation can take **many** forms depending on the testing goal to achieve and the test subject. Standard examples are:
  - **Parameter exploration** (one abstract scenario, many concrete scenarios)
  - **Procedural content generation** (many abstract scenarios, many concrete scenarios)
- We show two cases:
  - Testing car-following (parameter exploration, inspired by EuroNCAP)
  - Testing lane-keeping (procedural content generation, inspired by AsFault)

automation_example_1.py

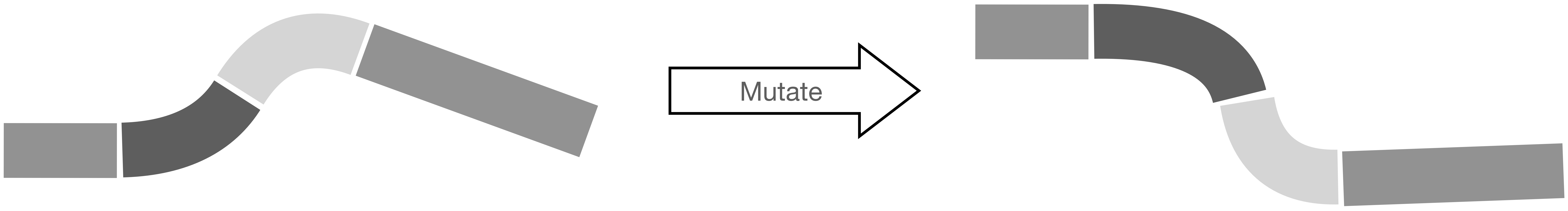
Follow the Drunk Driver

- We start with the ego-car behind a NPC car and configure the NPC to follow a straight trajectory at a constant speed
- We **mutate** the trajectory by changing the **lateral position** of the node and the **inter-time** between consecutive nodes (i.e., the NPC car speed)
- We implement a basic **EA 1+1** (pop size = 1, only mutation)



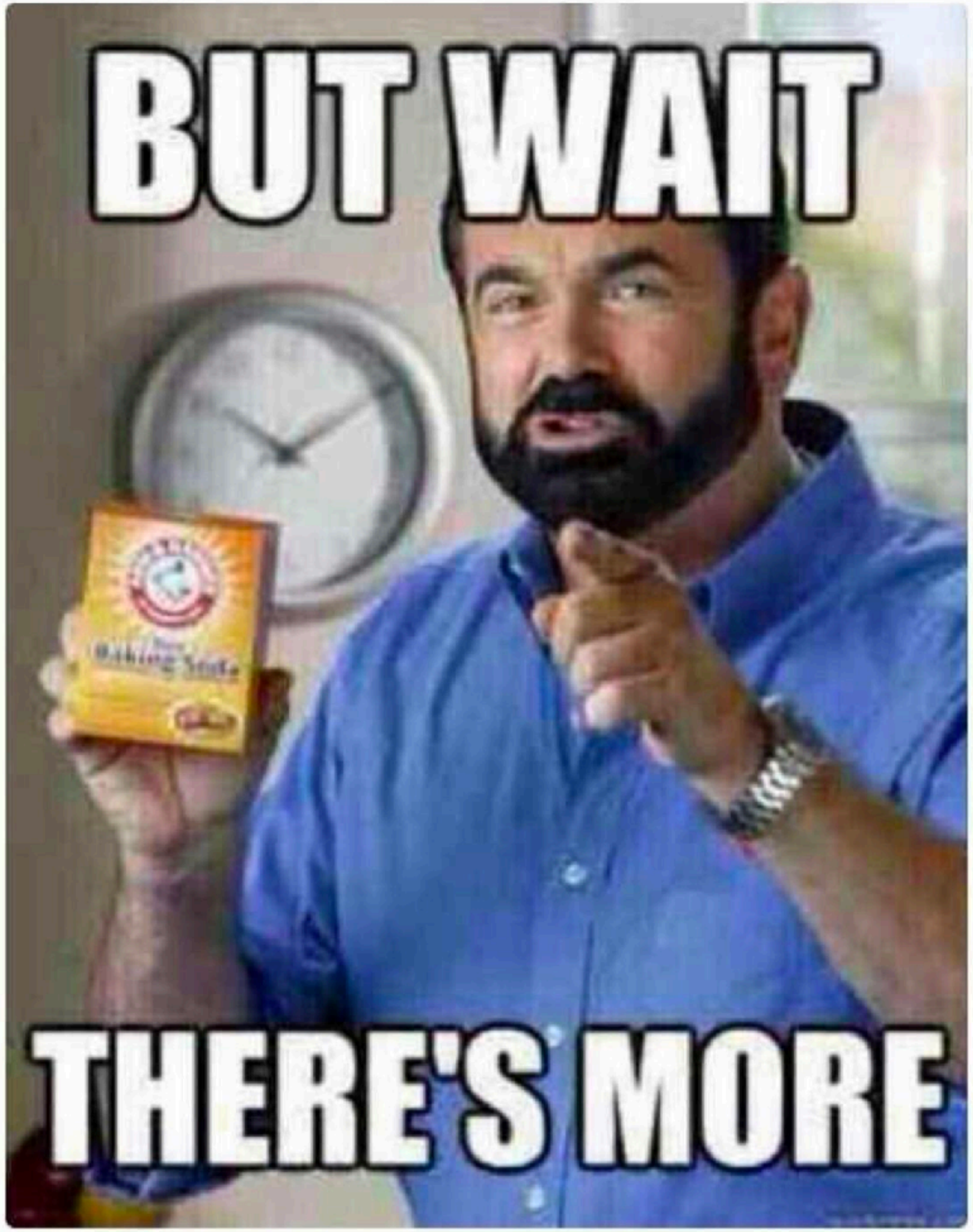
Procedurally Generate Roads

- We abstract roads as sequence of segments (straights, left-turn, right-turn) and procedurally generate "concrete" roads (**AsFault**)
- We implement a simple Genetic Algorithm
- Roads have **fixed** number of segments
- We evolve the roads by **replacing** segments or **mutating** their attributes



Useful Links

- https://sbst21.github.io/
- https://documentation.beamng.com/
- **https://github.com/se2p/sbst-2021-tutorial**
- https://github.com/se2p/tool-competition-av
- https://github.com/BeamNG/BeamNGpy
- https://github.com/alessiogambi/AsFault/tree/asfault-deap/src
- https://github.com/testingautomated-usi/DeepJanus/tree/master/DeepJanus-BNG
- https://github.com/TriHuynh00/AC3R-Demo


BUT WAIT
THERE'S MORE

Additional Use Cases of Simulation-Based Testing with BeamNG.tech

- Injecting Faults: simulate hardware failures (e.g., flat tires) and other *funny* situations
- Testing the effects of load/weight distribution: trailers, heavy loads, etc.
- Creating datasets for AI: noise, randomization, pixel perfect annotated image, Lidar Points clouds, 2D/3D bounding boxes
- Record/Replay: recording *interesting* driving behaviors and replicating them for generating simulation-based tests
- Simulating other CPS systems: drones, cranes/work machines, robots (assuming you can "build them")

Fork me on GitHub

Simulation-based Testing with BeamNG.tech

Tutorial @ SBST 2021

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https://github.com/se2p/sbst-2021-tutorial