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# Nashpy Documentation

*Release 0.0.25*

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**Aug 04, 2021**



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This is a Python library used for the computation of equilibria in 2 player strategic form games.



## TUTORIAL: BUILDING AND FINDING THE EQUILIBRIUM FOR A GAME

### 1.1 Introduction to game theory

Game theory is the study of strategic interactions between rational agents. This means that it is the study of interactions when the involved parties try and do what is best from their point of view.

As an example let us consider [Rock Paper Scissors](#). This is a common game where two players choose one of 3 options (in game theory we call these *strategies*):

- Rock
- Paper
- Scissors

The winner is decided according to the following:

- Rock crushes scissors
- Paper covers Rock
- Scissors cuts paper

We can represent this mathematically using a 3 by 3 matrix:

$$A = \begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}$$

The matrix  $A_{ij}$  shows the utility to the player controlling the rows when they play the  $i$  th row and their opponent (the column player) plays the  $j$  th column. For example, if the row player played Scissors (the 3rd strategy) and the column player played Paper (the 2nd strategy) then the row player gets:  $A_{32} = 1$  because Scissors cuts Paper.

A recommend text book on Game Theory is [\[Maschler2013\]](#).

### 1.2 Installing Nashpy

We are going to study this game using Nashpy, first though we need to install it. Nashpy requires the following things to be on your computer:

- Python 3.5 or greater;
- Scipy 0.19.0 or greater;
- Numpy 1.12.1 or greater.

Assuming you have those installed, to install Nashpy:

- On Mac OSX or linux open a terminal;
- On Windows open the Command prompt or similar

and type:

```
$ python -m pip install nashpy
```

If this does not work, you might not have Python or one of the other dependencies. You might also have problems due to `pip` not being recognised. To overcome these, using the [Anaconda](#) distribution of Python is recommended as it installs straightforwardly on all operating systems and also includes the libraries needed to run Nashpy.

## 1.3 Creating a game

We can create this game using Nashpy:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[0, -1, 1], [1, 0, -1], [-1, 1, 0]])
>>> rps = nash.Game(A)
>>> rps
```

Zero sum game with payoff matrices:

Row player:

```
[[ 0 -1  1]
 [ 1  0 -1]
 [-1  1  0]]
```

Column player:

```
[[ 0  1 -1]
 [-1  0  1]
 [ 1 -1  0]]
```

The string representation of the game also contains some information. For example, it is also showing the matrix that corresponds to the utility of the column player. In this case that is  $-A$  but that does not always have to be the case.

We can in fact pass a pair of matrices to the game class to create the same game:

```
>>> B = - A
>>> rps = nash.Game(A, B)
>>> rps
```

Zero sum game with payoff matrices:

Row player:

```
[[ 0 -1  1]
 [ 1  0 -1]
 [-1  1  0]]
```

Column player:

```
[[ 0  1 -1]
 [-1  0  1]
 [ 1 -1  0]]
```

We get the exact same game, if passed a single game, Nashpy will assume that the game is a *zero sum game*: in other words the utilities of both players are opposite.

## 1.4 Calculating the utility of a pair of strategies

If the row player played Scissors (the 3rd strategy) and the column player played Paper (the 2nd strategy) then the row player gets:  $A_{32} = 1$  because Scissors cuts Paper.

A mathematical approach to representing a strategy is to consider a vector of the size: the number of strategies. For example  $\sigma_r = (0, 0, 1)$  is the row strategy where the row player always plays their third strategy. Similarly  $\sigma_c = (0, 1, 0)$  is the strategy for the column player where they always play their second strategy.

When we represent strategies like this we can get the utility to the row player using the following linear algebraic expression:

$$\sigma_r A \sigma_c^T$$

Similarly, if  $B$  is the utility to the column player their utility is given by:

$$\sigma_r B \sigma_c^T$$

We can use Nashpy to find these utilities:

```
>>> sigma_r = [0, 0, 1]
>>> sigma_c = [0, 1, 0]
>>> rps[sigma_r, sigma_c]
array([ 1, -1])
```

Players can choose to play randomly, in which case the utility corresponds to the long term average. This is where our representation of strategies and utility calculations becomes particularly useful. For example, let us assume the column player decides to play Rock and Paper “randomly”. This corresponds to  $\sigma_c = (1/2, 1/2, 0)$ :

```
>>> sigma_c = [1 / 2, 1 / 2, 0]
>>> rps[sigma_r, sigma_c]
array([0., 0.])
```

The row player might then decide to change their strategy and “randomly” play Paper and Scissors:

```
>>> sigma_r = [0, 1 / 2, 1 / 2]
>>> rps[sigma_r, sigma_c]
array([ 0.25, -0.25])
```

The column player would then probably deviate once more. Whether or not there is a pair of strategies for both players at which they both no longer have a reason to move is going to be answered in the next section.

## 1.5 Computing Nash equilibria

Nash equilibria is (in two player games) a pair of strategies at which both players do not have an incentive to deviate. We can find these using Nashpy:

```
>>> eqs = rps.support_enumeration()
>>> list(eqs)
[(array([0.333..., 0.333..., 0.333...]), array([0.333..., 0.333..., 0.333...]))]
```

*Nash* equilibria is an important concept as it allows to gain an initial understanding of emergent behaviour in complex systems.

## 1.6 Learning in games

Nash equilibria are not always observed during non cooperative play: they correspond to strategies at which no player has an incentive to move but that does not necessarily imply that players can arrive at that equilibria naturally.

We can illustrate this using Nashpy:

```
>>> import numpy as np
>>> iterations = 100
>>> np.random.seed(0)
>>> play_counts = rps.fictitious_play(iterations=iterations)
>>> for row_play_count, column_play_count in play_counts:
...     print(row_play_count, column_play_count)
[0 0 0] [0 0 0]
[1. 0. 0.] [0. 1. 0.]
...
[28. 39. 32.] [37. 26. 36.]
[29. 39. 32.] [37. 26. 37.]
```

Over time we can see the behaviour emerge, as the play counts can be normalised to give strategy vectors. Note that these will not always converge.

## HOW TO

How to:

### 2.1 Install Nashpy

Nashpy currently requires Python 3.5 or above. To install from the Python Package index (PyPi) run the following command:

```
$ python -m pip install nashpy
```

To install a development version from source:

```
$ git clone https://github.com/drvinceknight/Nashpy.git
$ cd nashpy
$ python -m pip install flit
$ python -m flit install --symlink
```

### 2.2 Create a Normal Form Game

A game in Nashpy is created by passing 1 or 2 matrices to the `nash.Game` class. Here is the zero sum game *Matching Pennies*:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[1, -1], [-1, 1]])
>>> matching_pennies = nash.Game(A)
>>> matching_pennies
Zero sum game with payoff matrices:

Row player:
[[ 1 -1]
 [-1  1]]

Column player:
[[-1  1]
 [ 1 -1]]
```

Here is the **non** zero sum game *Prisoners Dilemma*:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 0], [5, 1]])
>>> B = np.array([[3, 5], [0, 1]])
>>> prisoners_dilemma = nash.Game(A, B)
>>> prisoners_dilemma
Bi matrix game with payoff matrices:

Row player:
[[3 0]
 [5 1]]

Column player:
[[3 5]
 [0 1]]
```

## 2.3 Calculate utilities

A game can be passed a pair of *Strategies* to return the utilities. Let us create a game to illustrate this:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 0], [5, 1]])
>>> B = np.array([[3, 5], [0, 1]])
>>> prisoners_dilemma = nash.Game(A, B)
```

The utility for both players when they both play their first action:

```
>>> sigma_r = np.array([1, 0])
>>> sigma_c = np.array([1, 0])
>>> prisoners_dilemma[sigma_r, sigma_c]
array([3, 3])
```

The utility to both players when they play uniformly randomly across both their actions:

```
>>> sigma_r = np.array([1 / 2, 1 / 2])
>>> sigma_c = np.array([1 / 2, 1 / 2])
>>> prisoners_dilemma[sigma_r, sigma_c]
array([2.25, 2.25])
```

## 2.4 Check if a strategy is a best response

A game can be passed a pair of *Strategies* to check if they are best responses to each other. Let us create a game to illustrate this:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 0], [5, 1]])
>>> B = np.array([[3, 5], [0, 1]])
>>> prisoners_dilemma = nash.Game(A, B)
```

The `is_best_response` method returns a pair of booleans. In this instance, the row player strategy is a best response to the column player's but not vice versa:

```
>>> sigma_r = np.array([0, 1])
>>> sigma_c = np.array([1, 0])
>>> prisoners_dilemma.is_best_response(sigma_r, sigma_c)
(True, False)
```

## 2.5 Solve with support enumeration

One of the algorithms implemented in Nashpy is called *Support enumeration*, this is implemented as a method on the `Game` class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[1, -1], [-1, 1]])
>>> matching_pennies = nash.Game(A)
```

This `support_enumeration` method returns a generator of all the equilibria:

```
>>> equilibria = matching_pennies.support_enumeration()
>>> for eq in equilibria:
...     print(eq)
(array([0.5, 0.5]), array([0.5, 0.5]))
```

## 2.6 Solve with vertex enumeration

One of the algorithms implemented in Nashpy is called *Vertex enumeration*, this is implemented as a method on the `Game` class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[1, -1], [-1, 1]])
>>> matching_pennies = nash.Game(A)
```

This `vertex_enumeration` method returns a generator of all the equilibria:

```
>>> equilibria = matching_pennies.vertex_enumeration()
>>> for eq in equilibria:
...     print(eq)
(array([0.5, 0.5]), array([0.5, 0.5]))
```

## 2.7 Solve with Lemke Howson

One of the algorithms implemented in Nashpy is *The Lemke Howson Algorithm*. This algorithm does not return **all** equilibria and takes an input argument:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[1, -1], [-1, 1]])
>>> matching_pennies = nash.Game(A)
>>> matching_pennies.lemke_howson(initial_dropped_label=0)
(array([0.5, 0.5]), array([0.5, 0.5]))
```

The `initial_dropped_label` is an integer between 0 and `sum(A.shape) - 1`. To iterate over all possible labels use the `lemke_howson_enumeration` which returns a generator:

```
>>> equilibria = matching_pennies.lemke_howson_enumeration()
>>> for eq in equilibria:
...     print(eq)
(array([0.5, 0.5]), array([0.5, 0.5]))
(array([0.5, 0.5]), array([0.5, 0.5]))
(array([0.5, 0.5]), array([0.5, 0.5]))
(array([0.5, 0.5]), array([0.5, 0.5]))
```

Note that this algorithm is not guaranteed to find **all** equilibria but is an efficient way of finding **an** equilibrium.

## 2.8 Use fictitious play

One of the learning algorithms implemented in Nashpy is called *Fictitious play*, this is implemented as a method on the Game class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 1], [0, 2]])
>>> B = np.array([[2, 0], [1, 3]])
>>> game = nash.Game(A, B)
```

The `fictitious_play` method returns a generator of a given collection of learning steps:

```
>>> np.random.seed(0)
>>> iterations = 500
>>> play_counts = game.fictitious_play(iterations=iterations)
>>> for row_play_counts, column_play_counts in play_counts:
...     print(row_play_counts, column_play_counts)
[0 0] [0 0]
[1. 0.] [0. 1.]
...
[498.  1.] [497.  2.]
[499.  1.] [498.  2.]
```

Note that this process is stochastic:

```
>>> np.random.seed(1)
>>> play_counts = game.fictitious_play(iterations=iterations)
>>> for row_play_counts, column_play_counts in play_counts:
...     print(row_play_counts, column_play_counts)
[0 0] [0 0]
[0. 1.] [0. 1.]
...
[ 0. 499.] [ 0. 499.]
[ 0. 500.] [ 0. 500.]
```

It is also possible to pass a `play_counts` variable to give a starting point for the algorithm:

```
>>> np.random.seed(1)
>>> play_counts = (np.array([0., 500.]), np.array([0., 500.]))
>>> play_counts = game.fictitious_play(iterations=iterations, play_counts=play_counts)
>>> for row_play_counts, column_play_counts in play_counts:
...     print(row_play_counts, column_play_counts)
[ 0. 500.] [ 0. 500.]
[ 0. 501.] [ 0. 501.]
...
[ 0. 999.] [ 0. 999.]
[ 0. 1000.] [ 0. 1000.]
```

## 2.9 Use stochastic fictitious play

One of the learning algorithms implemented in Nashpy is called *Stochastic fictitious play*, this is implemented as a method on the `Game` class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 1], [0, 2]])
>>> B = np.array([[2, 0], [1, 3]])
>>> game = nash.Game(A, B)
```

The `stochastic_fictitious_play` method returns a generator of a given collection of learning steps, comprising of the play counts and the mixed strategy of each player:

```
>>> np.random.seed(0)
>>> iterations = 500
>>> play_counts_and_distributions = game.stochastic_fictitious_
    play(iterations=iterations)
>>> for play_counts, distributions in play_counts_and_distributions:
...     row_play_counts, column_play_counts = play_counts
...     row_distributions, column_distributions = distributions
...     print(row_play_counts, column_play_counts, row_distributions, column_
    distributions)
[0 0] [0 0] None None
[1. 0.] [0. 1.] [9.99953841e-01 4.61594628e-05] [0.501447 0.498553]
...
[498. 1.] [497. 2.] [1.00000000e+00 1.07557011e-13] [9.99999998e-01 2.32299935e-09]
[499. 1.] [498. 2.] [1.00000000e+00 1.17304491e-13] [9.99999998e-01 2.18403537e-09]
```

Note that this process is stochastic:

```
>>> np.random.seed(1)
>>> play_counts_and_distributions = game.stochastic_fictitious_
↳play(iterations=iterations)
>>> for play_counts, distributions in play_counts_and_distributions:
...     row_play_counts, column_play_counts = play_counts
...     row_distributions, column_distributions = distributions
...     print(row_play_counts, column_play_counts)
[0 0] [0 0]
[1. 0.] [1. 0.]
...
[499. 0.] [499. 0.]
[500. 0.] [500. 0.]
```

It is also possible to pass a `play_counts` variable to give a starting point for the algorithm:

```
>>> np.random.seed(0)
>>> play_counts = (np.array([0., 500.]), np.array([0., 500.]))
>>> play_counts_and_distributions = game.stochastic_fictitious_
↳play(iterations=iterations, play_counts=play_counts)
>>> for play_counts, distributions in play_counts_and_distributions:
...     row_play_counts, column_play_counts = play_counts
...     row_distributions, column_distributions = distributions
...     print(row_play_counts, column_play_counts)
...
[ 0. 500.] [ 0. 500.]
[ 0. 501.] [ 0. 501.]
...
[ 0. 999.] [ 0. 999.]
[ 0. 1000.] [ 0. 1000.]
```

A value of `etha` and `epsilon_bar` can be passed. See the [Stochastic fictitious play](#) reference section for more information. The default values for `etha` and `epsilon_bar` are  $10^{-1}$  and  $10^{-2}$  respectively:

```
>>> np.random.seed(0)
>>> etha = 10**-2
>>> epsilon_bar = 10**-3
>>> play_counts_and_distributions = game.stochastic_fictitious_
↳play(iterations=iterations, etha=etha, epsilon_bar=epsilon_bar)
>>> for play_counts, distributions in play_counts_and_distributions:
...     row_play_counts, column_play_counts = play_counts
...     row_distributions, column_distributions = distributions
...     print(row_play_counts, column_play_counts)
...
[0 0] [0 0]
[1. 0.] [0. 1.]
...
[498. 1.] [497. 2.]
[499. 1.] [498. 2.]
```

## 2.10 Use replicator dynamics

One of the learning algorithms implemented in Nashpy is called *Replicator dynamics*, this is implemented as a method on the Game class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 2], [4, 2]])
>>> game = nash.Game(A)
```

The `replicator_dynamics` method returns the strategies of the row player over time:

```
>>> game.replicator_dynamics()
array([[0.5         , 0.5         ],
       [0.49875032, 0.50124968],
       [0.49750377, 0.50249623],
       ...,
       [0.10199196, 0.89800804],
       [0.10189853, 0.89810147],
       [0.10180527, 0.89819473]])
```

It is also possible to pass a `y0` variable in order to assign a starting strategy. Otherwise the probability is divided equally amongst all possible actions. Passing a `timepoints` variable gives the algorithm a sequence of timepoints over which to calculate the strategies:

```
>>> y0 = np.array([0.9, 0.1])
>>> timepoints = np.linspace(0, 10, 1000)
>>> game.replicator_dynamics(y0=y0, timepoints=timepoints)
array([[0.9         , 0.1         ],
       [0.89918663, 0.10081337],
       [0.89836814, 0.10163186],
       ...,
       [0.14109126, 0.85890874],
       [0.1409203 , 0.8590797 ],
       [0.14074972, 0.85925028]])
```

## 2.11 Use asymmetric replicator dynamics

This algorithm that is implemented in Nashpy is called *Asymmetric replicator dynamics* and is implemented as a method on the Game class:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 2], [4, 2]])
>>> B = np.array([[1, 3], [2, 4]])
>>> game = nash.Game(A, B)
```

The `asymmetric_replicator_dynamics` method returns the strategies of both the row player and the column player over time:

```
>>> xs, ys = game.asymmetric_replicator_dynamics()
>>> xs
array([[0.5          , 0.5          ],
       [0.49875..., 0.50124...],
       [0.49752..., 0.50247...],
       ...,
       [0.41421..., 0.58578...],
       [0.41421..., 0.58578...],
       [0.41421..., 0.58578...]])
>>> ys
array([[5.00000...e-01, 5.00000...e-01],
       [4.94995...e-01, 5.05004...e-01],
       [4.89991...e-01, 5.10008...e-01],
       ...,
       [2.28749...e-09, 9.99999...e-01],
       [2.24298...e-09, 9.99999...e-01],
       [2.19926...e-09, 9.99999...e-01]])
```

It is also possible to pass `x0` and `y0` arguments to assign the initial strategy to be played. Otherwise the probability is divided equally amongst all possible actions for both `x0` and `y0`. Additionally, a `timepoints` argument may be passed that gives the algorithm a sequence of timepoints over which to calculate the strategies.

```
>>> x0 = np.array([0.4, 0.6])
>>> y0 = np.array([0.9, 0.1])
>>> timepoints = np.linspace(0, 10, 1000)
>>> xs, ys = game.asymmetric_replicator_dynamics(x0=x0, y0=y0, timepoints=timepoints)
>>> xs
array([[0.4          , 0.6          ],
       [0.39784..., 0.60215...],
       [0.39569..., 0.60430...],
       ...,
       [0.17411..., 0.82588...],
       [0.17411..., 0.82588...],
       [0.17411..., 0.82588...]])
>>> ys
array([[9.00000...e-01, 1.00000...e-01],
       [8.98183...e-01, 1.01816...e-01],
       [8.96338...e-01, 1.03661...e-01],
       ...,
       [1.86696...e-08, 9.99999...e-01],
       [1.82868...e-08, 9.99999...e-01],
       [1.79139...e-08, 9.99999...e-01]])
```

## DISCUSSION

### 3.1 Normal Form Games

#### 3.1.1 Motivating example: Coordination Game

Game theory is the study of interactive decision making. One example of this is the following situation:

Two friends must decide what movie to watch at the cinema. Alice would like to watch a sport movie and Bob would like to watch a comedy. Importantly, they would both rather spend their evening together than apart.

To quantify this mathematically, numeric values are associated to the 4 possible outcomes:

1. Alice watches a sport movie, Bob watches a comedy: Alice receives a utility of 1 and Bob a utility of 1.
2. Alice watches a comedy, Bob watches a sport movie: Alice receives a utility of 0 and Bob a utility of 0.
3. Alice and Bob both watch a sport movie: Alice receives a utility of 3 and Bob a utility of 2.
4. Alice and Bob both watch a comedy: Alice receives a utility of 2 and Bob a utility of 3.

This particular example will be represented using two matrices.

$A$  will represent the utilities of Alice:

$$A = \begin{pmatrix} 3 & 1 \\ 0 & 2 \end{pmatrix}$$

$B$  will represent the utilities of Bob

$$B = \begin{pmatrix} 2 & 1 \\ 0 & 3 \end{pmatrix}$$

Alice is referred to as the row player and Bob as the column player:

- The row player chooses which row of the matrices the player will gain their utilities.
- The column player chooses which column of the matrices the player will gain their utilities.

This representation of the strategic interaction between Alice and Bob is called a *Normal Form Game*

### 3.1.2 Definition of Normal Form Game

An  $N$  play normal form game consists of:

- A finite set of  $N$  players.
- Action set for the players:  $\{\mathcal{A}_1, \mathcal{A}_2, \dots, \mathcal{A}_N\}$
- Payoff functions for the players:  $u_i : \mathcal{A}_1 \times \mathcal{A}_2 \cdots \times \mathcal{A}_N \rightarrow \mathbb{R}$

---

#### Question

For the *Coordination game*:

1. What is the finite set of players?
  2. What are the action sets?
  3. What are the payoff functions?
- 

---

#### Answer

1. The two players are Alice and Bob ( $N = 2$ ).
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Sport, Comedy}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Sport and the second row or column corresponds to Comedy.

$$u_1(\neg_1, \neg_2) = A_{\neg_1, \neg_2} \quad u_2(\neg_1, \neg_2) = B_{\neg_1, \neg_2}$$

where  $\neg_1 \in \mathcal{A}_1$  and  $\neg_2 \in \mathcal{A}_2$ .

---

### 3.1.3 Definition of a Zero Sum Game

A two player normal form game with payoff matrices  $A, B$  is called zero sum if and only if:

$$A = -B$$

---

#### Question

Is the *Coordination game* zero sum?

---



---

#### Answer

$A \neq -B$  so the Coordination game is not Zero sum.

---

### 3.1.4 Examples of other Normal Form Games

#### Prisoners Dilemma

Assume two thieves have been caught by the police and separated for questioning. If both thieves cooperate and do not divulge any information they will each get a short sentence (with a utility value of 3). If one defects they are offered a deal (utility value of 5) while the other thief will get a long sentence (utility value of 0). If they both defect they both get a medium length sentence (utility value of 1).

---

#### Question

For the Prisoners Dilemma

1. What is the finite set of players?
  2. What are the action sets?
  3. What are the payoff functions?
  4. Is the game zero sum?
- 

---

#### Answer

1. The two players are the two thieves ( $N = 2$ ).
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Cooperate, Defect}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Cooperate and the second row or column corresponds to Defect.

$$A = \begin{pmatrix} 3 & 0 \\ 5 & 1 \end{pmatrix} \quad B = \begin{pmatrix} 3 & 5 \\ 0 & 1 \end{pmatrix}$$

$$u_1(\neg_1, \neg_2) = A_{\neg_1, \neg_2} \quad u_2(\neg_1, \neg_2) = B_{\neg_1, \neg_2}$$

where  $\neg_1 \in \mathcal{A}_1$  and  $\neg_2 \in \mathcal{A}_2$ .

4. The game is not Zero sum as  $A \neq -B$ .
- 

#### Hawk Dove Game

Suppose two birds of prey must share a limited resource. The birds can act like a hawk or a dove. Hawks always act aggressively over the resource to the point of exterminating another hawk (both hawks get a utility value of 0) and/or take a majority of the resource from a dove (the hawk gets a utility value of 3 and the dove a utility value of 1). Two doves can share the resource (both getting a utility value of 2).

---

#### Question

For the Hawk Dove Game

1. What is the finite set of players?
  2. What are the action sets?
  3. What are the payoff functions?
  4. Is the game zero sum?
-

### Answer

1. The two players are two birds  $N = 2$ .
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Hawk}, \text{Dove}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Hawk and the second row or column corresponds to Dove.

$$A = \begin{pmatrix} 0 & 3 \\ 1 & 2 \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 3 & 2 \end{pmatrix}$$

$$u_1(\neg_1, \neg_2) = A_{\neg_1, \neg_2} \quad u_2(\neg_1, \neg_2) = B_{\neg_1, \neg_2}$$

where  $\neg_1 \in \mathcal{A}_1$  and  $\neg_2 \in \mathcal{A}_2$ .

4. The game is not Zero sum as  $A \neq -B$ .
- 

### Pigs

Consider two pigs. One dominant pig and one subservient pig. These pigs share a pen. There is a lever in the pen that delivers food but if either pig pushes the lever it will take them a little while to get to the food.

- If the dominant pig pushes the lever, the subservient pig has some time to eat most of the food before being pushed out of the way. The dominant pig gets a utility value of 2 and the subservient pig gets a utility value of 3.
  - If the subservient pig pushes the lever, the dominant pig will eat all the food. The dominant pig gets a utility value of 6 and the subservient pig gets a utility value of -1.
  - If both pigs push the lever, the subservient pig will a small amount of the food. The dominant pig gets a utility value of 4 and the subservient pig gets a utility value of 2.
  - If both pigs do not push the lever they both get a utility value of 0.
- 

### Question

For the Pigs Game

1. What is the finite set of players?
  2. What are the action sets?
  3. What are the payoff functions?
  4. Is the game zero sum?
- 

### Answer

1. The two players are dominant and a subservient pig  $N = 2$ .
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Push}, \text{Do not push}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Push and the second row or column corresponds to Do not push.

$$A = \begin{pmatrix} 4 & 2 \\ 6 & 0 \end{pmatrix} \quad B = \begin{pmatrix} 2 & 3 \\ -1 & 0 \end{pmatrix}$$

$$u_1(\neg_1, \neg_2) = A_{\neg_1, \neg_2} \quad u_2(\neg_1, \neg_2) = B_{\neg_1, \neg_2}$$

where  $\neg_1 \in \mathcal{A}_1$  and  $\neg_2 \in \mathcal{A}_2$ .

4. The game is not Zero sum as  $A \neq -B$ .

## Matching Pennies

Consider two players who can choose to display a coin either Heads facing up or Tails facing up. If both players show the same face then player 1 wins, if not then player 2 wins. Winning corresponds to a numeric value of 1 and losing a numeric value of -1.

### Question

For the Matching Pennies game:

1. What is the finite set of players?
2. What are the action sets?
3. What are the payoff functions?
4. Is the game zero sum?

### Answer

1. There are two players  $N = 2$ .
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Heads, Tails}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Heads and the second row or column corresponds to Tails.

$$A = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \quad B = \begin{pmatrix} -1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$u_1(\neg_1, \neg_2) = A_{\neg_1, \neg_2} \quad u_2(\neg_1, \neg_2) = B_{\neg_1, \neg_2}$$

where  $\neg_1 \in \mathcal{A}_1$  and  $\neg_2 \in \mathcal{A}_2$ .

4. The game is Zero sum as  $A = -B$ .

## 3.1.5 Using Nashpy

See [Create a Normal Form Game](#) for guidance of how to use Nashpy to create a Normal form game.

## 3.2 Strategies

### 3.2.1 Motivating example: Strategy for Rock Paper Scissors

The game of Rock Paper Scissors is a common parlour game between two players who pick 1 of 3 options simultaneously:

1. Rock which beats Scissors;
2. Paper which beats Rock;
3. Scissors which beats Paper

Thus, this corresponds to a Normal Form Game with:

1. Two players ( $N = 2$ ).
2. The action sets are:  $\mathcal{A}_1 = \mathcal{A}_2 = \{\text{Rock, Paper, Scissors}\}$
3. The payoff functions are given by the matrices  $A, B$  where the first row or column corresponds to Rock, the second to Paper and the third to Scissors.

$$A = \begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}$$

$$B = -A = \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix}$$

If we consider two players, assume the row player always chooses Paper and the column player randomly chooses from Rock and Paper (with equal probability) what is the expected outcome of any one game between them?

- The expected score of the row player will be:  $-1 \times 1/2 + 0 \times 1/2 = -1/2$ .
- The expected score of the column player will be:  $1 \times 1/2 + 0 \times 1/2 = 1/2$ .

In Game theoretic terms, the behaviours described above are referred to as **strategies**. **Strategies map information to actions**. In this particular case, the only available information is the game itself and the actions are  $\mathcal{A}_1 = \mathcal{A}_2$ .

### 3.2.2 Definition of a strategy in a normal form game

A strategy for a player with action set  $\mathcal{A}$  is a probability distribution over elements of  $\mathcal{A}$ .

Typically a strategy is denoted by  $\sigma \in [0, 1]_{\mathbb{R}}^{|\mathcal{A}|}$  so that:

$$\sum_{i=1}^S \sigma_i = 1$$

---

#### Question

For *Rock Paper Scissors*:

1. What is the strategy  $\sigma_r$  that corresponds to the row player's behaviour of always choosing Paper?
2. What is the strategy  $\sigma_c$  that corresponds to the column player's behaviour of always randomly choosing between Rock and Paper?

**Answer**

1.  $\sigma_r = (0, 1, 0)$
2.  $\sigma_c = (1/2, 1/2, 0)$

**3.2.3 Calculation of expected utilities**

Considering a game  $(A, B) \in \mathbb{R}^{(m \times n)^2}$ , if  $\sigma_r$  and  $\sigma_c$  are the strategies for the row/column player, the expected utilities are:

- For the row player:  $u_r(\sigma_r, \sigma_c) = \sum_{i=1}^m \sum_{j=1}^n A_{ij} \sigma_{r_i} \sigma_{c_j}$
- For the column player:  $u_c(\sigma_r, \sigma_c) = \sum_{i=1}^m \sum_{j=1}^n B_{ij} \sigma_{r_i} \sigma_{c_j}$

This corresponds to taking the expectation over the probability distributions  $\sigma_r$  and  $\sigma_c$ .

**Question**

For the *Rock Paper Scissors*:

What are the expected utilities to both players if  $\sigma_r = (1/3, 0, 2/3)$  and  $\sigma_c = (1/3, 1/3, 1/3)$ .

**Answer**

$$\begin{aligned} u_r(\sigma_r, \sigma_c) &= 1/3(1/3 \times 0 + 1/3 \times -1 + 1/3 \times 1) \\ &\quad + 0(1/3 \times 1 + 1/3 \times 0 + 1/3 \times -1) \\ &\quad + 2/3(1/3 \times -1 + 1/3 \times 1 + 1/3 \times 0) \\ &= 0 \end{aligned} \tag{3.1}$$

$$\begin{aligned} u_c(\sigma_r, \sigma_c) &= 1/3(1/3 \times 0 + 1/3 \times 1 + 1/3 \times -1) \\ &\quad + 0(1/3 \times -1 + 1/3 \times 0 + 1/3 \times 1) \\ &\quad + 2/3(1/3 \times 1 + 1/3 \times -1 + 1/3 \times 0) \\ &= 0 \end{aligned} \tag{3.5}$$

**3.2.4 Linear algebraic calculation of expected utilities**

Given a game  $(A, B) \in \mathbb{R}^{(m \times n)^2}$ , considering  $\sigma_r$  and  $\sigma_c$  as vectors in  $\mathbb{R}^m$  and  $\mathbb{R}^n$ . The expected utilities can be written as the matrix vector product:

- For the row player:  $u_r(\sigma_r, \sigma_c) = \sigma_r A \sigma_c^T$
- For the column player:  $u_c(\sigma_r, \sigma_c) = \sigma_r B \sigma_c^T$

**Question**

For *Rock Paper Scissors*:

Calculate the expected utilities to both players if  $\sigma_r = (1/3, 0, 2/3)$  and  $\sigma_c = (1/3, 1/3, 1/3)$  using a linear algebraic approach.

---

**Answer**

$$u_r(\sigma_r, \sigma_c) = (1/3, 0, 2/3)A \begin{pmatrix} 1/3 \\ 1/3 \\ 1/3 \end{pmatrix} = (-2/3, 1/3, 1/3) \begin{pmatrix} 1/3 \\ 1/3 \\ 1/3 \end{pmatrix} = 0$$

$$u_c(\sigma_r, \sigma_c) = (1/3, 0, 2/3)B \begin{pmatrix} 1/3 \\ 1/3 \\ 1/3 \end{pmatrix} = (2/3, -1/3, -1/3) \begin{pmatrix} 1/3 \\ 1/3 \\ 1/3 \end{pmatrix} = 0$$


---

### 3.2.5 Strategy spaces for Normal form Games

### 3.2.6 Using Nashpy

See [Calculate utilities](#) for guidance of how to use Nashpy to calculate utilities.

## 3.3 Best responses

### 3.3.1 Motivating example: Best Responses in Matching Pennies

Considering the game *Matching Pennies*:

$$A = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \quad B = \begin{pmatrix} -1 & 1 \\ 1 & -1 \end{pmatrix}$$

If the row player knows that the column player is playing the *strategy*  $\sigma_c = (0, 1)$  the utility of the row player is maximised by playing  $\sigma_r = (0, 1)$ .

In this case  $\sigma_r$  is referred to as a **best response** to  $\sigma_c$ .

Alternatively, if the column player knows that the row player is playing the *strategy*  $\sigma_r = (0, 1)$  the column player's best response is  $\sigma_c = (1, 0)$ .

### 3.3.2 Definition of a best response in a normal form game

In a two player game  $(A, B) \in \mathbb{R}^{m \times n^2}$  a strategy  $\sigma_r^*$  of the row player is a best response to a column players' strategy  $\sigma_c$  if and only if:

$$\sigma_r^* = \operatorname{argmax}_{\sigma_r \in S_1} \sigma_r A \sigma_c^T.$$

Similarly a mixed strategy  $\sigma_c^*$  of the column player is a best response to a row players' strategy  $\sigma_r$  if and only if:

$$\sigma_c^* = \operatorname{argmax}_{\sigma_c \in S_2} \sigma_r B \sigma_c^T.$$

---

**Question**

For the *Prisoners Dilemma*:

What is the row player's best response to either of the actions of the column player?

---

### Answer

Recalling that  $A$  is given by:

$$A = \begin{pmatrix} 3 & 0 \\ 5 & 1 \end{pmatrix}$$

Against the first action of the column player the best response is to choose the second action which gives a utility of 5. This can be expressed as:

$$\operatorname{argmax}_{i \in \mathcal{S}_1} A_{i1} = 2$$

Against the second action of the column player the best response is to choose the second action which gives a utility of 1. This can be expressed as:

$$\operatorname{argmax}_{i \in \mathcal{S}_1} A_{i2} = 2$$

The row player's best response to either of the actions of the column player is  $\sigma_r^* = (1, 0)$ . This can be expressed as:

$$\operatorname{argmax}_{i \in \mathcal{S}_1} A_{ij} = 2 \text{ for all } j \in \mathcal{A}_2$$


---

### 3.3.3 Generic best responses in 2 by 2 games

In two player normal form games with  $|\mathcal{A}_1| = |\mathcal{A}_2| = 2$ : a 2 by 2 game, the utility of a row player playing  $\sigma_r = (x, 1-x)$  against a strategy  $\sigma_c = (y, 1-y)$  is linear in  $x$ :

$$\begin{aligned} u_r(\sigma_r, \sigma_c) &= (x, 1-x)A(y, 1-y)^T \\ &= A_{11}xy + A_{12}x(1-y) + A_{21}(1-x)y + A_{22}(1-x)(1-y) \\ &= ax + b \end{aligned}$$

where:

$$\begin{aligned} a &= A_{11}y + A_{12}(1-y) - A_{21}y - A_{22}(1-y) \\ b &= A_{21}y + A_{22}(1-y) \end{aligned}$$

This observation allows us to obtain the best response  $\sigma_r^*$  against any  $\sigma_c = (y, 1-y)$ .

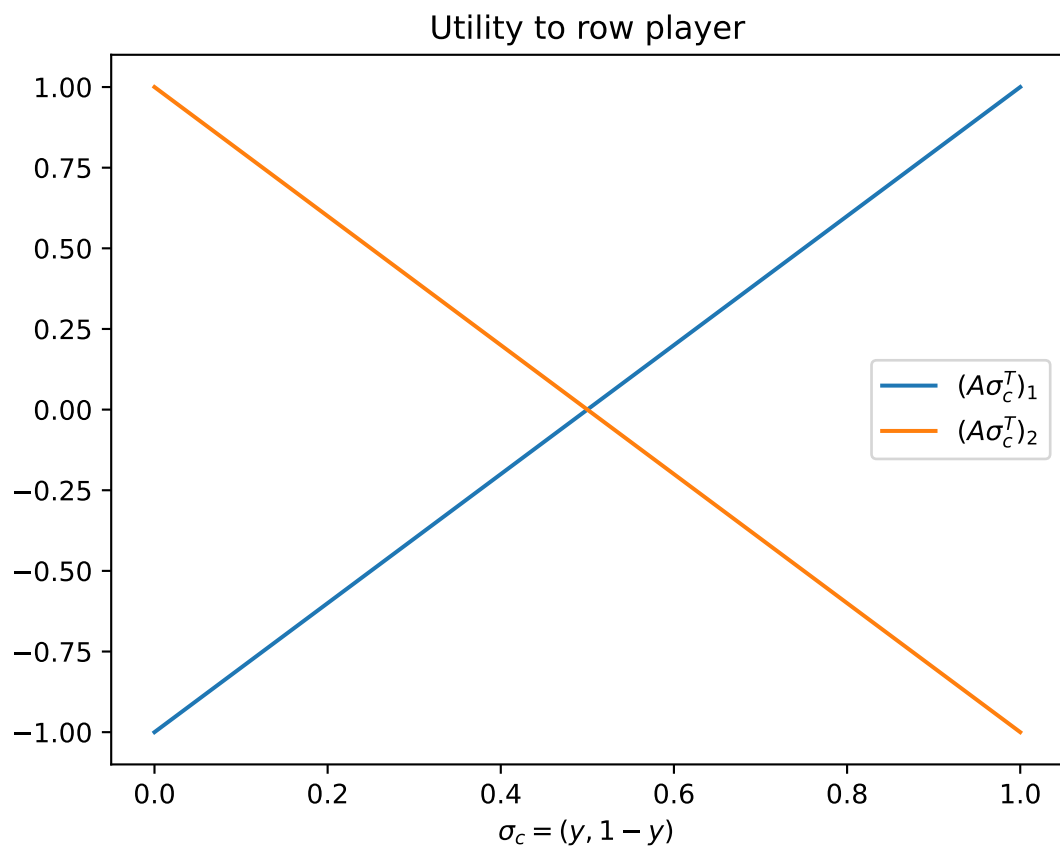
For example, consider *Matching Pennies*. Below is a plot of  $u_r(\sigma_r, \sigma_c)$  as a function of  $y$  for  $\sigma_r \in \{(1, 0), (0, 1)\}$ .

Given that the utilities in both cases are linear, the best response to any value of  $y \neq 1/2$  is either  $(1, 0)$  or  $(0, 1)$ . The best response  $\sigma_r^*$  is given by:

$$\sigma_r^* = \begin{cases} (1, 0), & \text{if } y > 1/2 \\ (0, 1), & \text{if } y < 1/2 \\ \text{indifferent}, & \text{if } y = 1/2 \end{cases}$$

---

### Question



For the *Matching Pennies* game:

What is the column player's best response as a function of  $x$  where  $\sigma_r = (x, 1 - x)$ .

### Answer

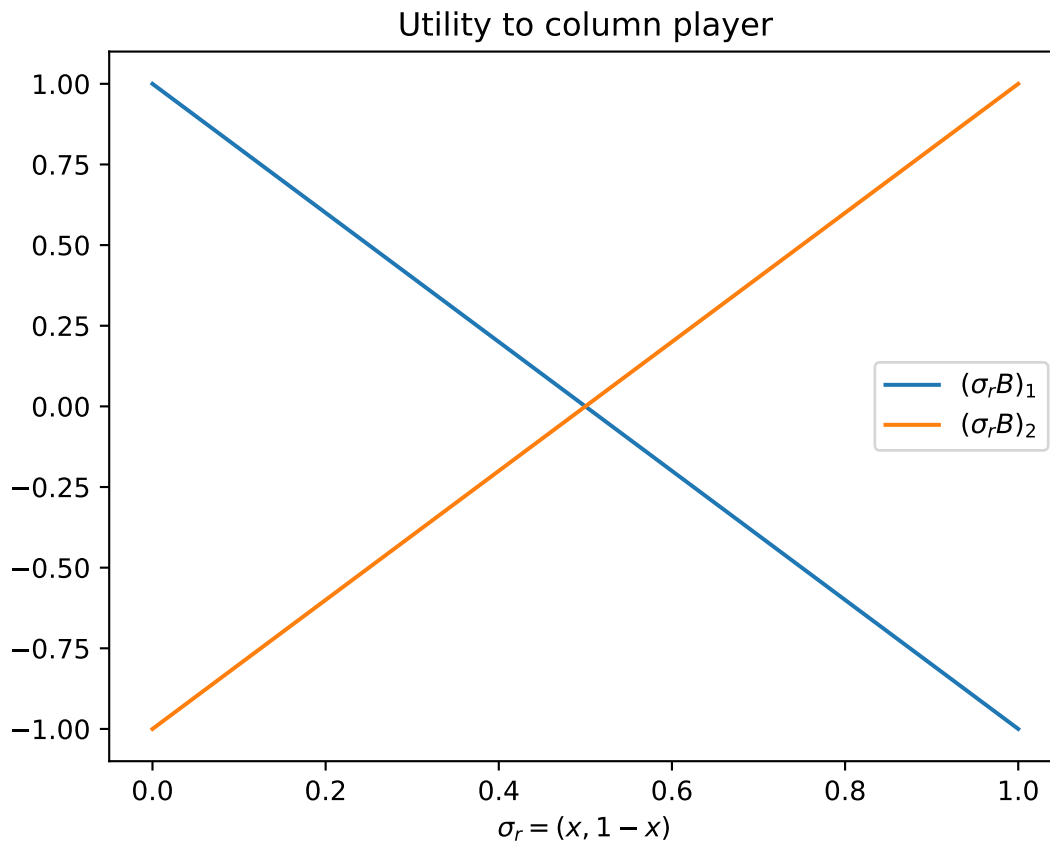
Recalling that  $B$  is given by:

$$B = \begin{pmatrix} -1 & 1 \\ 1 & -1 \end{pmatrix}$$

This gives:

$$\begin{aligned} u_c(\sigma_r, (1, 0)) &= -x + (1 - x) = 1 - 2x \\ &= x - (1 - x) = -1 + 2x \end{aligned}$$

Here is a plot of the utilities:



### 3.3.4 General condition for a best response

In a two player game  $(A, B) \in \mathbb{R}^{m \times n^2}$  a strategy  $\sigma_r^*$  of the row player is a best response to a column players' strategy  $\sigma_c$  if and only if:

$$\sigma_{r^*i} > 0 \Rightarrow (A\sigma_c^T)_i = \max_{k \in \mathcal{A}_2} (A\sigma_c^T)_k \text{ for all } i \in \mathcal{A}_1$$

#### Proof

$(A\sigma_c^T)_i$  is the utility of the row player when they play their  $i^{\text{th}}$  action. Thus:

$$\sigma_r A \sigma_c^T = \sum_{i=1}^m \sigma_{ri} (A\sigma_c^T)_i$$

Let  $u = \max_k (A\sigma_c^T)_k$  giving:

$$\begin{aligned} \sigma_r A \sigma_c^T &= \sum_{i=1}^m \sigma_{ri} (u - u + (A\sigma_c^T)_i) \\ &= \sum_{i=1}^m \sigma_{ri} u - \sum_{i=1}^m \sigma_{ri} (u - (A\sigma_c^T)_i) \\ &= u - \sum_{i=1}^m \sigma_{ri} (u - (A\sigma_c^T)_i) \end{aligned}$$

We know that  $u - (A\sigma_c^T)_i \geq 0$ , thus the largest  $\sigma_r A \sigma_c^T$  can be is  $u$  which occurs if and only if  $\sigma_{ri} > 0 \Rightarrow (A\sigma_c^T)_i = u$  as required.

---

#### Question

For the *Rock Paper Scissors* game:

Which of the following pairs of strategies are best responses to each other:

1.  $\sigma_r = (0, 0, 1)$  and  $\sigma_c = (0, 1/2, 1/2)$
  2.  $\sigma_r = (1/3, 1/3, 1/3)$  and  $\sigma_c = (0, 1/2, 1/2)$
  3.  $\sigma_r = (1/3, 1/3, 1/3)$  and  $\sigma_c = (1/3, 1/3, 1/3)$
- 

#### Answer

Recalling that  $A$  and  $B$  are given by:

$$A = \begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix}$$

$$B = -A = \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix}$$

We can apply the best response condition to each pairs of strategies:

1.  $A\sigma_c^T = \begin{pmatrix} 0 \\ -1/2 \\ 1/2 \end{pmatrix}$ .  $\max(A\sigma_c^T) = 1/2$ . The only  $i$  for which  $\sigma_{ri} > 0$  is  $i = 3$  and  $(A\sigma_c^T)_3 = \max(A\sigma_c^T)$  thus  $\sigma_r$  **is a best response to**  $\sigma_c$ .  $\sigma_r B = (1, -1, 0)$ .  $\max(\sigma_r B) = 1$ . The values of  $i$  for which  $\sigma_{ci} > 0$  are  $i = 2$  and  $i = 3$  but  $(\sigma_r B)_2 \neq \max(\sigma_r B)$  thus  $\sigma_c$  **is not a best response to**  $\sigma_r$ .
2.  $A\sigma_c^T = \begin{pmatrix} 0 \\ -1/2 \\ 1/2 \end{pmatrix}$ .  $\max(A\sigma_c^T) = 1/2$ . The values of  $i$  for which  $\sigma_{ri} > 0$  are  $i = 1$ ,  $i = 2$  and  $i = 3$  however,  $(A\sigma_c^T)_2 \neq \max(A\sigma_c^T)$  thus  $\sigma_r$  **is not a best response to**  $\sigma_c$ .  $\sigma_r B = (0, 0, 0)$ .  $\max(\sigma_r B) = 0$ . The values of  $i$  for which  $\sigma_{ci} > 0$  are  $i = 2$  and  $i = 3$  and  $(\sigma_r B)_2 = (\sigma_r B)_3 = \max(\sigma_r B)$  thus  $\sigma_c$  **is a best response to**  $\sigma_r$ .
3.  $A\sigma_c^T = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$ .  $\max(A\sigma_c^T) = 0$ . The values of  $i$  for which  $\sigma_{ri} > 0$  are  $i = 1$ ,  $i = 2$  and  $i = 3$  and  $(A\sigma_c^T)_1 = (A\sigma_c^T)_2 = (A\sigma_c^T)_3 = \max(A\sigma_c^T)$  thus  $\sigma_r$  **is a best response to**  $\sigma_c$ .  $\sigma_r B = (0, 0, 0)$ .  $\max(\sigma_r B) = 0$ . The values of  $i$  for which  $\sigma_{ci} > 0$  are  $i = 1$ ,  $i = 2$  and  $i = 3$  and  $(\sigma_r B)_1 = (\sigma_r B)_2 = (\sigma_r B)_3 = \max(\sigma_r B)$  thus  $\sigma_c$  **is a best response to**  $\sigma_r$ .

### 3.3.5 Using Nashpy

See [Check if a strategy is a best response](#) for guidance of how to use Nashpy to check if a strategy is a best response.

## 3.4 Support enumeration

The support enumeration algorithm implemented in Nashpy is based on the one described in [Nisan2007].

The algorithm is as follows:

For a degenerate 2 player game  $(A, B) \in \mathbb{R}^{m \times n^2}$  the following algorithm returns all nash equilibria:

1. For all  $1 \leq k_1 \leq m$  and  $1 \leq k_2 \leq n$ ;
2. For all pairs of support  $(I, J)$  with  $|I| = k_1$  and  $|J| = k_2$ .
3. Solve the following equations (this ensures we have best responses):

$$\sum_{i \in I} \sigma_{ri} B_{ij} = v \text{ for all } j \in J$$

$$\sum_{j \in J} A_{ij} \sigma_{cj} = u \text{ for all } i \in I$$

4. Solve
  - $\sum_{i=1}^m \sigma_{ri} = 1$  and  $\sigma_{ri} \geq 0$  for all  $i$
  - $\sum_{j=1}^n \sigma_{cj} = 1$  and  $\sigma_{cj} \geq 0$  for all  $j$
5. Check the best response condition.

Repeat steps 3,4 and 5 for all potential support pairs.

### 3.4.1 Discussion

1. Step 1 is a complete enumeration of all possible strategies that the equilibria could be.
2. Step 2 can be modified to only consider degenerate games ensuring that only supports of equal size are considered  $|I| = |J|$ . This is described further in [Degenerate games](#).
3. Step 3 are the linear equations that are to be solved, for a given pair of supports these ensure that neither player has an incentive to move to another strategy on that support.
4. Step 4 is to ensure we have mixed strategies.
5. Step 5 is a final check that there is no better utility outside of the supports.

In Nashpy this is all implemented algebraically using Numpy to solve the linear equations.

## 3.5 Vertex enumeration

The vertex enumeration algorithm implemented in Nashpy is based on the one described in [Nisan2007].

The algorithm is as follows:

For a nondegenerate 2 player game  $(A, B) \in \mathbb{R}^{m \times n^2}$  the following algorithm returns all nash equilibria:

1. Obtain the best response Polytopes  $P$  and  $Q$ .
2. For all pairs of vertices of  $P$  and  $Q$ .
3. Check if the pair is fully labeled and return the normalised probability vectors.

Repeat steps 2 and 3 for all pairs of vertices.

### 3.5.1 Discussion

1. Before creating the best response Polytope we need to consider the best response Polyhedron. For the row player, this corresponds to the set of all the mixed strategies available to the row player as well as an upper bound on the utilities to the column player. Analogously for the column player:

$$\begin{aligned}\bar{P} &= \{(x, v) \in \mathbb{R}^m \times \mathbb{R} \mid x \geq 0, \mathbb{1}^T x = 1, B^T x \leq \mathbb{1}^T v\} \\ \bar{Q} &= \{(y, u) \in \mathbb{R}^n \times \mathbb{R} \mid y \geq 0, \mathbb{1}^T y = 1, Ay \leq \mathbb{1}^T u\}\end{aligned}$$

Note that in both definitions above we have a total of  $m + n$  inequalities in the constraints.

For  $P$ , the first  $m$  of those constraints correspond to the elements of  $x$  being greater or equal to 0. For a given  $x$ , if  $x_i = 0$ , we say that  $x$  has label  $i$ . This corresponds to strategy  $i$  not being in the support of  $x$ .

For the last  $n$  of these inequalities, when they are equalities they correspond to whether or not strategy  $1 \leq j \leq n$  of the other player is a best response to  $x$ . Similarly, if strategy  $j$  is a best response to  $x$  then we say that  $x$  has label  $m + j$ .

This all holds analogously for the column player. If the labels of a pair of elements of  $\bar{P}$  and  $\bar{Q}$  give the full set of integers from 1 to  $m + n$  then they represent strategies that are best responses to each other. Since, this would imply that either a pure strategy is not played or it is a best response to the other players strategy.

The difficulty with using the best response Polyhedron is that the upper bound on the utilities of both players  $(u, v)$  is not known. Importantly, we do not need to know it. Thus, we assume that in both cases:  $u = v = 1$  (this corresponds to a scaling of our strategy vectors).

This allows us to define the best response Polytopes:

$$P = \{(x, v) \in \mathbb{R}^m \times \mathbb{R} \mid x \geq 0, B^T x \leq 1\}$$

$$Q = \{(y, u) \in \mathbb{R}^n \times \mathbb{R} \mid y \geq 0, Ay \leq 1\}$$

2. Step 2: The vertices of these polytopes are the points that will have labels (they are the points that are at the intersection of the underlying halfspaces [Ziegler2012]).

To find these vertices, `nashpy` uses `scipy` which has a handy class for creating Polytopes using the inequality definitions and being able to return the vertices. Here is the wrapper written in `nashpy` that is used by the vertex enumeration algorithm to give the vertices and corresponding labels:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[3, 1], [1, 3]])
>>> halfspaces = nash.polytope.build_halfspaces(A)
>>> vertices = nash.polytope.non_trivial_vertices(halfspaces)
>>> for vertex in vertices:
...     print(vertex)
(array([0.333..., 0...]), {0, 3})
(array([0..., 0.333...]), {1, 2})
(array([0.25, 0.25]), {0, 1})
```

3. Step 3, we iterate over all pairs of the vertices of both polytopes and pick out the ones that are fully labeled. Because of the scaling that took place to create the Polytope from the Polyhedron, we will need to return a normalisation of both vertices.

## 3.6 The Lemke Howson Algorithm

The Lemke Howson algorithm implemented in `Nashpy` is based on the one described in [Nisan2007] originally introduced in [Lemke1964].

The algorithm is as follows:

For a nondegenerate 2 player game  $(A, B) \in \mathbb{R}^{m \times n^2}$  the following algorithm returns a single Nash equilibria:

1. Obtain the best response Polytopes  $P$  and  $Q$ .
2. Choose a starting label to drop, this will correspond to a vertex of  $P$  or  $Q$ .
3. In that polytope, remove the label from the corresponding vertex and move to the vertex that shared that label. A new label will be picked up and duplicated in the other polytope.
4. In the other polytope drop the duplicate label and move to the vertex that shared that label.

Repeat steps 3 and 4 until there are no duplicate labels.

### 3.6.1 Discussion

This algorithm is implemented using integer pivoting.

1. Step 1, the best response polytopes  $P$  and  $Q$  are represented by a tableau. For example for:

$$A = \begin{pmatrix} 3 & 1 \\ 1 & 3 \end{pmatrix}$$

$$B = \begin{pmatrix} 1 & 3 \\ 2 & 1 \end{pmatrix}$$

This is represented as a pair of tableau:

$$T_c = \begin{pmatrix} 3 & 1 & 1 & 0 & 1 \\ 1 & 3 & 0 & 1 & 1 \end{pmatrix}$$

For reasons that will become clear, we infact shift this tableau so that the labelling is coherent across both polytopes:

$$T_c = \begin{pmatrix} 1 & 0 & 3 & 1 & 1 \\ 0 & 1 & 1 & 3 & 1 \end{pmatrix}$$

Here it is as a `numpy` array:

```
>>> import numpy as np
>>> col_tableau = np.array([[1, 0, 3, 1, 1],
...                          [0, 1, 1, 3, 1]])
```

Here is the tableau that corresponds to  $B$ :

$$T_r = \begin{pmatrix} 1 & 2 & 1 & 0 & 1 \\ 3 & 1 & 0 & 1 & 1 \end{pmatrix}$$

Here it is as a `numpy` array:

```
>>> row_tableau = np.array([[1, 2, 1, 0, 1],
...                          [3, 1, 0, 1, 1]])
```

2. Step 2, choosing a starting label is choosing an integer from  $0 \leq k < m + n$  (we start our indices at 0). As an example, let us choose the label 1.

First we need to identify which vertex has that label. The labels of a tableau correspond to the non basic variables: these are the columns with more than a single non zero variable:

- The labels of  $T_c$  are thus  $\{2, 3\}$ :

```
>>> import nashpy as nash
>>> nash.integer_pivoting.non_basic_variables(col_tableau)
{2, 3}
```

- The labels of  $T_r$  are thus  $\{0, 1\}$ :

```
>>> nash.integer_pivoting.non_basic_variables(row_tableau)
{0, 1}
```

So we are going to drop label 1 from  $T_r$ .

3. Step 3, removing a label and moving from one vertex to another corresponds to integer pivoting [Dantzig2016]. This is a manipulation of  $T$ , dropping label 1 corresponds to pivoting the second column.

To do this we need to identify which row will not change (the “pivot row”), this is done by finding the smallest ratio of value in that column over the value in the last column:  $(T_r)_{i4}/(T_r)_{ik}$ .

In our case the first row has corresponding ratio:  $1/2$  and the second ratio  $1/1$ . So our pivot row is the first row:

```
>>> nash.integer_pivoting.find_pivot_row(row_tableau, column_index=1)
0
```

What we now do is row operations so as to make the second column correspond to a basic variable. We will do this by multiplying the second row by 2 and then subtracting the first row by it:

$$T_r = \begin{pmatrix} 1 & 2 & 1 & 0 & 1 \\ 5 & 0 & -1 & 2 & 1 \end{pmatrix}$$

Our resulting tableau has labels:  $\{0, 2\}$  so it has “picked up” label 2:

```
>>> nash.integer_pivoting.pivot_tableau(row_tableau, column_index=1)
{2}
>>> row_tableau
array([[ 1,  2,  1,  0,  1],
       [ 5,  0, -1,  2,  1]])
```

4. Step 4, we will now repeat the previous manipulation on  $T_c$  where we now need to drop the duplicate label 2. We do this by pivoting the third column.

The ratios are:  $1/3$  for the first row and  $1/1$  for the second, thus the pivot row is the first row:

```
>>> nash.integer_pivoting.find_pivot_row(col_tableau, column_index=2)
0
```

Using similar row operations we obtain:

$$T_c = \begin{pmatrix} 1 & 0 & 3 & 1 & 1 \\ -1 & 3 & 0 & 8 & 2 \end{pmatrix}$$

Our resulting tableau has labels:  $\{0, 3\}$ , so it has picked up label 0:

```
>>> nash.integer_pivoting.pivot_tableau(col_tableau, column_index=2)
{0}
>>> col_tableau
array([[ 1,  0,  3,  1,  1],
       [-1,  3,  0,  8,  2]])
```

We now need to drop 0 from  $T_r$ , we do this by pivoting the first column. The ratio test:  $1/1 > 1/5$  implies that the second row is the pivot row. Using similar algebraic manipulations we obtain:

$$T_r = \begin{pmatrix} 0 & 10 & 6 & -2 & 4 \\ 5 & 0 & -1 & 2 & 1 \end{pmatrix}$$

Our resulting tableau has labels:  $\{2, 3\}$ , so it has picked up label 3:

```
>>> nash.integer_pivoting.pivot_tableau(row_tableau, column_index=0)
{3}
>>> row_tableau
array([[ 0, 10,  6, -2,  4],
       [ 5,  0, -1,  2,  1]])
```

We now need to drop 3 from  $T_c$ , we do this by pivoting the fourth column. The ratio test:  $1/1 > 2/8$  indicates that we pivot on the second row which gives:

$$T_c = \begin{pmatrix} 9 & -1 & 24 & 0 & 6 \\ -1 & 3 & 0 & 8 & 2 \end{pmatrix}$$

Our resulting tableau has labels:  $\{0, 1\}$ :

```
>>> nash.integer_pivoting.pivot_tableau(col_tableau, column_index=3)
{1}
>>> col_tableau
array([[ 9, -3, 24,  0,  6],
       [-1,  3,  0,  8,  2]])
```

The union of the labels of  $T_r$  and  $T_c$  is:  $\{0, 1, 2, 3\}$  which implies that we have a fully labeled vertex pair.

The vertex corresponding to  $T_r$  are obtained by setting the non basic variables to 0 and looking at the corresponding values of the first two columns:

$$v_r = (1/5, 4/10) = (1/5, 2/5)$$

The vertex corresponding to  $T_c$  are obtained from the last 2 columns:

$$v_c = (6/24, 2/8) = (1/4, 1/4)$$

The final step of the algorithm is to return the normalised probabilities that correspond to these vertices:

$$((1/3, 2/3), (1/2, 1/2))$$

## 3.7 Degenerate games

A two player game is called nondegenerate if no mixed strategy of support size  $k$  has more than  $k$  pure best responses.

For example, the zero sum game defined by the following matrix is degenerate:

$$A = \begin{pmatrix} 0 & -1 & 1 \\ -1 & 0 & 1 \\ -1 & 1 & 0 \end{pmatrix}$$

The third column has two pure best responses.

When dealing with *degenerate* games unexpected results can occur:

```
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[0, -1, 1], [-1, 0, 1], [-1, 0, 1]])
>>> game = nash.Game(A)
```

Here is the output when using *Support enumeration*:

```
>>> for eq in game.support_enumeration():
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[0.5 0.5 0. ] [0.5 0.5 0. ]
[0.5 0.  0.5] [0.5 0.5 0. ]
```

Here is the output when using *Vertex enumeration*:

```
>>> for eq in game.vertex_enumeration():
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[0.5 0.  0.5] [ 0.5  0.5 -0. ]
[ 0.5  0.5 -0. ] [ 0.5  0.5 -0. ]
```

Here is the output when using the *The Lemke Howson Algorithm*:

```
>>> for eq in game.lemke_howson_enumeration():
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[0.33... 0.33... 0.33...] [nan]
```

We see that the *lemke-howson* algorithm fails but also that the *Support enumeration* and *Vertex enumeration* fail to find some equilibria: there is in fact a range of strategies the row player can play against [ 0.5 0.5 0] that is still a best response.

The *Support enumeration* algorithm can be run with two optional arguments:

- `non_degenerate=True` (False is the default) will only consider supports of equal size. If you know your game is non degenerate this will make support enumeration make less checks.
- `tol=0` (10 \*\* -16 is the default), when considering the underlying linear system `tol` is considered to be a lower bound for difference between two real numbers. Using `tol=0` ensures a strict run of the algorithm.

Here is an example:

```
>>> A = np.array([[4, 9, 9], [9, 1, 6], [9, 2, 3]])
>>> B = np.array([[2, 2, 5], [7, 4, 4], [1, 6, 4]])
>>> game = nash.Game(A, B)
>>> for eq in game.support_enumeration():
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[1. 0. 0.] [0. 0. 1.]
[0. 1. 0.] [1. 0. 0.]
[0.5 0.5 0. ] [0.38 0.  0.62]
[0.2 0.5 0.3] [0.57 0.32 0.11]
>>> for eq in game.support_enumeration(non_degenerate=True):
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[1. 0. 0.] [0. 0. 1.]
[0. 1. 0.] [1. 0. 0.]
[0.2 0.5 0.3] [0.57 0.32 0.11]
>>> for eq in game.support_enumeration(non_degenerate=False, tol=0):
...     print(np.round(eq[0], 2), np.round(eq[1], 2))
[1. 0. 0.] [0. 0. 1.]
[0. 1. 0.] [1. 0. 0.]
[0.2 0.5 0.3] [0.57 0.32 0.11]
```

## 3.8 Fictitious play

The fictitious play algorithm implemented in Nashpy is based on the one described in [Fudenberg1998].

The algorithm is as follows:

For a game  $(A, B) \in \mathbb{R}^{m \times n}$  define  $\kappa_t^i : S^{-1} \rightarrow \mathbb{N}$  to be a function that in a given time interval  $t$  for a player  $i$  maps a strategy  $s$  from the opponent's strategy space  $S^{-1}$  to a number of total times the opponent has played  $s$ .

Thus:

$$\kappa_t^i(s^{-i}) = \kappa_{t-1}(s^{-i}) + \begin{cases} 1, & \text{if } s_{t-1}^{-i} = s^{-i} \\ 0, & \text{otherwise} \end{cases}$$

In practice:

$$\kappa_t^1 \in \mathbb{Z}^n \quad \kappa_t^2 \in \mathbb{Z}^m$$

At stage  $t$ , each player assumes their opponent is playing a mixed strategy based on  $\kappa_{t-1}$ :

$$\frac{\kappa_{t-1}}{\sum \kappa_{t-1}}$$

They calculate the expected value of each strategy, which is equivalent to:

$$s_t^1 \in \operatorname{argmax}_{s \in S_1} A \kappa_{t-1}^2 \quad s_t^2 \in \operatorname{argmax}_{s \in S_2} B^T \kappa_{t-1}^1$$

In the case of multiple best responses, a random choice is made.

### 3.8.1 Discussion

Note that this algorithm will not always converge and sometimes it depends on the form of the game.

For example:

```
>>> import numpy as np
>>> import nashpy as nash
>>> A = np.array([[0, 1, 0], [0, 0, 1], [1, 0, 0]])
>>> B = np.array([[0, 0, 1], [1, 0, 0], [0, 1, 0]])
>>> game = nash.Game(A, B)
>>> iterations = 10000
>>> np.random.seed(0)
>>> play_counts = tuple(game.fictitious_play(iterations=iterations))
>>> play_counts[-1]
[array([5464., 1436., 3100.]), array([2111., 4550., 3339.])]
```

We can visualise the lack of convergence:

```
>>> import matplotlib.pyplot as plt
>>> plt.figure()
>>> probabilities = [row_play_counts / np.sum(row_play_counts) for row_play_counts, col_
    ↪ play_counts in play_counts]
>>> for number, strategy in enumerate(zip(*probabilities)):
...     plt.plot(strategy, label=f"$s_{number}$")
>>> plt.xlabel("Iteration")
>>> plt.ylabel("Probability")
>>> plt.title("Actions taken by row player")
>>> plt.legend()
```

If we modify the game slightly we obtain a different outcome:

```
>>> A = np.array([[1 / 2, 1, 0], [0, 1 / 2, 1], [1, 0, 1 / 2]])
>>> B = np.array([[1 / 2, 0, 1], [1, 1 / 2, 0], [0, 1, 1 / 2]])
>>> game = nash.Game(A, B)
>>> np.random.seed(0)
>>> play_counts = tuple(game.fictitious_play(iterations=iterations))
>>> play_counts[-1]
(array([3290., 3320., 3390.]), array([3356., 3361., 3283.]])
```

With a clear convergence now visible:

```
>>> import matplotlib.pyplot as plt
>>> plt.figure()
>>> probabilities = [row_play_counts / np.sum(row_play_counts) for row_play_counts, col_
    ↪ play_counts in play_counts]
>>> for number, strategy in enumerate(zip(*probabilities)):
...     plt.plot(strategy, label=f"$s_{number}$")
>>> plt.xlabel("Iteration")
>>> plt.ylabel("Probability")
>>> plt.title("Actions taken by row player")
>>> plt.legend()
```

## 3.9 Stochastic fictitious play

The stochastic fictitious play algorithm implemented in Nashpy is based on the one given in [Hofbauer2002].

As explained in [Fudenberg1998] stochastic fictitious play “avoids the discontinuity inherent in standard fictitious play, where a small change in the data can lead to an abrupt change in behaviour.”

The algorithm is designed to converge in cases where fictitious play does not converge. Note that in some cases this will require a thoughtful choice of the `etha` and `epsilon_bar` parameters.

For a game  $(A, B) \in \mathbb{R}^{m \times n}$  define  $\kappa_t^i : S^{-1} \rightarrow \mathbb{N}$  to be a function that in a given time interval  $t$  for a player  $i$  maps a strategy  $s$  from the opponent’s strategy space  $S^{-1}$  to a number of total times the opponent has played  $s$ .

As per standard *Fictitious play*, each player assumes their opponent is playing a mixed strategy based on  $\kappa_{t-1}$ . If no play has taken place, then the probability of playing each action is assumed to be equal. The assumed mixed strategies of a player’s opponent are multiplied by the player’s own payoff matrices to calculate the expected payoff of each action.

A stochastic perturbation  $\epsilon_i$  is added to each expected payoff  $\pi_i$  to give a perturbed payoff. Each  $\epsilon_i$  is independent of each  $\pi_i$  and is a random number between 0 and `epsilon_bar`.

A logit choice function is used to map the perturbed payoff to a non-negative probability distribution, corresponding to the probability with which each strategy is chosen by the player. The logit choice function can be seen below:

$$L_i(\pi) = \frac{\exp(\eta^{-1}\pi_i)}{\sum_j \exp(\eta^{-1}\pi_j)}$$

### 3.9.1 Discussion

Using the same game from the fictitious play discussion section, we can visualise a lack of convergence when using the default value of `epsilon_bar`:

```
>>> import numpy as np
>>> import nashpy as nash
>>> A = np.array([[0, 1, 0], [0, 0, 1], [1, 0, 0]])
>>> B = np.array([[0, 0, 1], [1, 0, 0], [0, 1, 0]])
>>> game = nash.Game(A, B)
>>> iterations = 10000
>>> np.random.seed(0)
>>> play_counts_and_distributions = tuple(game.stochastic_fictitious_
↳ play(iterations=iterations))
>>> play_counts, distributions = play_counts_and_distributions[-1]
>>> print(play_counts)
[array([3937., 1907., 4156.]), array([2823., 5458., 1719.])]

>>> import matplotlib.pyplot as plt
>>> plt.figure()
>>> probabilities = [
...     row_play_counts / np.sum(row_play_counts)
...     if np.sum(row_play_counts) != 0
...     else row_play_counts + 1 / len(row_play_counts)
...     for (row_play_counts, col_play_counts), _ in play_counts_and_distributions]
>>> for number, strategy in enumerate(zip(*probabilities)):
...     plt.plot(strategy, label=f"$s_{number}$")
>>> plt.xlabel("Iteration")
>>> plt.ylabel("Probability")
>>> plt.title("Actions taken by row player")
>>> plt.legend()
```

Observe below that the game converges when passing values for `etha` and `epsilon_bar`:

```
>>> A = np.array([[1 / 2, 1, 0], [0, 1 / 2, 1], [1, 0, 1 / 2]])
>>> B = np.array([[1 / 2, 0, 1], [1, 1 / 2, 0], [0, 1, 1 / 2]])
>>> game = nash.Game(A, B)
>>> iterations = 10000
>>> etha = 0.1
>>> epsilon_bar = 10**-1
>>> np.random.seed(0)
>>> play_counts_and_distributions = tuple(game.stochastic_fictitious_
↳ play(iterations=iterations, etha=etha, epsilon_bar=epsilon_bar))
>>> play_counts_and_distributions[-1]
([array([3300., 3293., 3407.]), array([3320., 3372., 3308.]), [array([0.33502382, 0.
↳ 41533594, 0.24964024]), array([0.18890743, 0.42793694, 0.38315563])])])
>>> import matplotlib.pyplot as plt
>>> plt.figure()
>>> probabilities = [
...     row_play_counts / np.sum(row_play_counts)
...     if np.sum(row_play_counts) != 0
...     else row_play_counts + 1 / len(row_play_counts)
```

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```

...     for (row_play_counts, col_play_counts), _ in play_counts_and_distributions]
>>> for number, strategy in enumerate(zip(*probabilities)):
...     plt.plot(strategy, label=f"$s_{number}$")
>>> plt.xlabel("Iteration")
>>> plt.ylabel("Probability")
>>> plt.title("Actions taken by row player")
>>> plt.legend()

```

## 3.10 Replicator dynamics

The replicator dynamic algorithm implemented in Nashpy is based on the one described in [Fudenberg1998].

Strategies are assigned amongst the population. Individuals randomly encounter other individuals and play their assigned strategy.

As the game continues, the proportion of the population playing each strategy increases or decreases depending on whether the payoff of the strategy is higher or lower respectively than the mean payoff of the population.

The row player represents a given individual and the column player is the population.

Given a matrix  $A \in \mathbb{R}^{m \times n}$  that corresponds to the utilities of the row player, we have:

$$f = Ax$$

Where  $f \in \mathbb{R}^{m \times 1}$  corresponds to the fitness of each strategy and  $x \in \mathbb{R}^{m \times 1}$  corresponds to the population size of each strategy

Equivalently, where  $\phi$  equals the average fitness of the population, we have:

$$\phi = f^T x$$

In matrix formation we can calculate the rate of change of the strategies:

$$\frac{dx}{dt}_i = x_i(f_i - \phi) \text{ for all } i$$

### 3.10.1 Discussion

Stability is achieved in replicator dynamics when  $\frac{dx}{dt} = 0$ . Every stable steady state is a Nash equilibria, and every Nash equilibria is a steady state in replicator dynamics.

A steady state is when the population shares of all strategies are constant.

Steady states are reached when either:

- An entire population plays the same strategy
- A population plays a mixture of the strategies (such that there is indifference between the fitness)

It is possible that the game does not converge to a steady state. See below an example of a game of Rock, Paper, Scissors that does not converge:

```
>>> import numpy as np
>>> import nashpy as nash
>>> import matplotlib.pyplot as plt
>>> A = np.array([[0, -1, 1], [1, 0, -1], [-1, 1, 0]])
>>> game = nash.Game(A)
>>> y0 = np.array([0.3, 0.35, 0.35])

>>> plt.plot(game.replicator_dynamics(y0=y0))
>>> plt.xlabel("Timepoints")
>>> plt.ylabel("Probability")
>>> plt.title("Probability distribution of strategies over time")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$", f"$s_{2}$"], loc='upper left')
```

Below shows an example of a stable steady state:

```
>>> import numpy as np
>>> import nashpy as nash
>>> import matplotlib.pyplot as plt
>>> A = np.array([[4, 3], [2, 3]])
>>> game = nash.Game(A)
>>> y0 = np.array([1 / 2, 1 / 2])
>>> timepoints = np.linspace(0, 10, 1000)

>>> plt.plot(game.replicator_dynamics(y0=y0, timepoints=timepoints))
>>> plt.xlabel("Timepoints")
>>> plt.ylabel("Probability")
>>> plt.title("Probability distribution of strategies over time")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$"])
```

Evolutionary stable strategies (ESS) stay stable subject to small evolutionary change. This means that the strategy cannot be invaded by any of the other strategies in the population. Every ESS is an asymptotically stable steady state of the replicator dynamic, but the converse does not necessarily hold.

To visualise an example of ESS consider the matrix  $A = \begin{pmatrix} 4 & 3 \\ 2 & 3 \end{pmatrix}$ . It can be shown that  $(1, 0)$  is an ESS for this game. Below we take a small change from this strategy and note that the replicator dynamics guide us back to it.

```
>>> import numpy as np
>>> import nashpy as nash
>>> import matplotlib.pyplot as plt
>>> A = np.array([[4, 3], [2, 3]])
>>> game=nash.Game(A)
>>> epsilon = 1 / 10
>>> y0 = np.array([1 - epsilon, 0 + epsilon])
>>> timepoints = np.linspace(0, 10, 1000)
>>> timepoints[-1]
10.0

>>> plt.plot(game.replicator_dynamics(y0=y0, timepoints=timepoints))
>>> plt.xlabel("Timepoints")
```

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```
>>> plt.ylabel("Probability")
>>> plt.title("Probability distribution of strategies over time")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$"])
```

## 3.11 Asymmetric replicator dynamics

The asymmetric replicator dynamics algorithm is implemented in **Nashpy** based on the work presented in [Elvio2011]. This is considered as the asymmetric version of the symmetric *Replicator dynamics*.

There exists a population with two types of individuals where each type has their own strategy set. Strategies are assigned amongst the population. Individuals randomly encounter individuals of the opposite type and play their assigned strategies.

As the game progresses the proportion of each type playing each strategy changes based on their previous interactions.

The row player represents the first type of individuals and the column player represents the other one.

Given two matrices  $A \in \mathbb{R}^{m \times n}$  and  $B \in \mathbb{R}^{m \times n}$  that correspond to the utilities of the row player and column player respectively, we define:

$$\begin{aligned} f_x &= Ay \\ f_y &= x^T B \end{aligned}$$

Where  $x \in \mathbb{R}^{m \times 1}$  and  $y \in \mathbb{R}^{n \times 1}$  corresponds to the population size of the strategies of the two players and  $f_x \in \mathbb{R}^{n \times 1}$  and  $f_y \in \mathbb{R}^{1 \times m}$  corresponds to the fitness of the strategies of the row player and the column player respectively.

Similarly, the average fitness for the two types of populations is given by  $\phi_x$  and  $\phi_y$  where:

$$\begin{aligned} \phi_x &= f_x x^T \\ \phi_y &= f_y y \end{aligned}$$

In matrix notation the rate of change of the strategies of both types of individuals is captured by:

$$\begin{aligned} \frac{dx}{dt}_i &= x_i((f_x)_i - \phi_x) \text{ for all } i \\ \frac{dy}{dt}_i &= y_i((f_y)_i - \phi_y) \text{ for all } i \end{aligned}$$

### 3.11.1 Discussion

Stability is achieved in asymmetric replicator dynamics when both  $\frac{dx}{dt} = 0$  and  $\frac{dy}{dt} = 0$ . Every stable steady state is a Nash equilibria, and every Nash equilibria is a steady state in asymmetric replicator dynamics.

Similarly to *Replicator dynamics*, a game is not guaranteed to converge to a steady state. Find below the probability distributions for both the row player and the column player over time, of a game that does not converge:

```
>>> import matplotlib.pyplot as plt
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[0, -1, 1], [1, 0, -1], [-1, 1, 0]])
>>> B = A.transpose()
```

(continues on next page)

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```
>>> game = nash.Game(A, B)
>>> x0 = np.array([0.3, 0.35, 0.35])
>>> y0 = np.array([0.3, 0.35, 0.35])
>>> xs, ys = game.asymmetric_replicator_dynamics(x0=x0, y0=y0)
```

```
>>> plt.figure(figsize=(15, 5))
>>> plt.subplot(1, 2, 1)
>>> plt.plot(xs)
>>> plt.title("Probability distribution of strategies over time for row player")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$", f"$s_{2}$"])
>>> plt.subplot(1, 2, 2)
>>> plt.plot(ys)
>>> plt.xlabel("Timepoints")
>>> plt.ylabel("Probability")
>>> plt.title("Probability distribution of strategies over time for column player")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$", f"$s_{2}$"])
```

Find below an example of a game that is able to reach a stable steady state:

```
>>> import matplotlib.pyplot as plt
>>> import nashpy as nash
>>> import numpy as np
>>> A = np.array([[2, 2], [3, 4]])
>>> B = np.array([[4, 3], [3, 2]])
>>> game = nash.Game(A, B)
>>> x0 = np.array([0.9, 0.1])
>>> y0 = np.array([0.3, 0.7])
>>> xs, ys = game.asymmetric_replicator_dynamics(x0=x0, y0=y0)
```

```
>>> plt.figure(figsize=(15, 5))
>>> plt.subplot(1, 2, 1)
>>> plt.plot(xs)
>>> plt.title("Probability distribution of strategies over time for row player")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$"])
>>> plt.subplot(1, 2, 2)
>>> plt.plot(ys)
>>> plt.xlabel("Timepoints")
>>> plt.ylabel("Probability")
>>> plt.title("Probability distribution of strategies over time for column player")
>>> plt.legend([f"$s_{0}$", f"$s_{1}$"])
```

## REFERENCE

### 4.1 John Nash

This library is named after the mathematician John Nash. He is most famous for his work in Game Theory that culminated in him winning a Noble prize in Economics. The book [Nasar2011] (popularized in a 2001 movie) gives a good overview of his life.

The work he received a Noble prize for was a proof that a game **always** has an equilibrium [Nash1950]. His proof is an exceptional piece of mathematics where he uses a fixed point theorem by showing that an equilibrium is equivalent to a fixed point of a function.

Subsequently, these equilibria have been referred to as Nash equilibria.

### 4.2 How does Nashpy relate to Gambit

**Gambit** is the state of the art software library for Game Theory [McKelvey2016]. It also has a Python interface. It handles  $N \geq 2$  player games and is computationally efficient. It is a much more mature piece of software than Nashpy.

It does **however** sometimes prove difficult to install (because of the required C libraries), in particular installation is not supported on Windows. In those instances you can use **Game Theory Explorer** which is a great web point and click Graphical User Interface (GUI) to Gambit.

The main mission statement of Nashpy is to provide a Python library that implements algorithms that are implemented using the scientific Python stack (**numpy** and **scipy**).

This is motivated by the fact that I wanted a Python library (not a GUI as I am keen to teach reproducibly research methodologies) for teaching my Mathematics students. Using the Gambit Python interface is not sufficient for this as students need to be able to install it on their own machines (without difficulty).

All the algorithms in Nashpy are implemented with readability as the main motivation. This at times comes at an efficiency cost. For example, *Support enumeration* builds the entire Polytope representation (using functionality of **scipy**) which is not efficient.

#### To summarise:

- If you want to do sophisticated efficient game theoretic computations, use **Gambit**.
- If you are happy to use a GUI use **Game Theory Explorer**.
- If you would like a Python library that only requires the common scientific python stack for two player games you can use **Nashpy**.

## 4.3 Other Python Game theory libraries

- **Axelrod**: a research library aimed at the study of the Iterated Prisoners dilemma [Knight2016].
- **Gambit**: a C library with a Python interface for the computation of equilibria [McKelvey2016]. *How does Nashpy relate to Gambit.*
- **Game theory explorer** a web interface to gambit useful for teaching. [Savani2015]
- **PyNFG**: PyNFG is a Python package for modeling and solving Network Form Games.
- **lrslib**: A C implementation of a reverse search algorithm with modules for Nash equilibria computation.
- **sagemath**: The mathematical software package Sage has various algorithms for the computation of Nash equilibria.

## 4.4 Bibliography

This is a collection of various bibliographic items referenced in the documentation.

## 4.5 Source files

### 4.5.1 Subpackages

**nash.algorithms package**

**Submodules**

**nashpy.algorithms.support\_enumeration module**

A class for a normal form game

`nashpy.algorithms.support_enumeration.indifference_strategies(A, B, non_degenerate=False, tol=1e-16)`

A generator for the strategies corresponding to the potential supports

#### Parameters

- **A** (*array*) – The row player utility matrix.
- **B** (*array*) – The column player utility matrix
- **non\_degenerate** (*bool*) – Whether or not to consider supports of equal size. By default (False) only considers supports of equal size.
- **tol** (*float*) – A tolerance parameter for equality.

**Yields** *tuple* – A generator of all potential strategies that are indifferent on each potential support. Return False if they are not valid (not a probability vector OR not fully on the given support).

`nashpy.algorithms.support_enumeration.is_ne(strategy_pair, support_pair, payoff_matrices)`

Test if a given strategy pair is a pair of best responses

#### Parameters

- **strategy\_pair** (*tuple*) – a 2-tuple of numpy arrays.

- **support\_pair** (*tuple*) – a 2-tuple of numpy arrays of integers.
- **payoff\_matrices** (*tuple*) – a 2-tuple of numpy array of payoff matrices.

**Returns** True if a given strategy pair is a pair of best responses.

**Return type** bool

`nashpy.algorithms.support_enumeration.obey_support(strategy, support, tol=1e-16)`  
Test if a strategy obeys its support

**Parameters**

- **strategy** (*array*) – A given strategy vector
- **support** (*array*) – A strategy support
- **tol** (*float*) – A tolerance parameter for equality.

**Returns** whether or not that strategy does indeed have the given support

**Return type** bool

`nashpy.algorithms.support_enumeration.potential_support_pairs(A, B, non_degenerate=False)`  
A generator for the potential support pairs

**Parameters**

- **A** (*array*) – The row player utility matrix.
- **B** (*array*) – The column player utility matrix
- **non\_degenerate** (*bool*) – Whether or not to consider supports of equal size. By default (False) only considers supports of equal size.

**Yields** *tuple* – A pair of possible supports.

`nashpy.algorithms.support_enumeration.powerset(n)`  
A power set of range(n)

Based on recipe from python itertools documentation:

<https://docs.python.org/2/library/itertools.html#recipes>

**Parameters** **n** (*int*) – The defining parameter of the powerset.

**Returns** The powerset

**Return type** generator

`nashpy.algorithms.support_enumeration.solve_indifference(A, rows=None, columns=None)`  
Solve the indifference for a payoff matrix assuming support for the strategies given by columns

Finds vector of probabilities that makes player indifferent between rows. (So finds probability vector for corresponding column player)

**Parameters**

- **A** (*array*) – The row player utility matrix.
- **rows** (*array*) – Array of integers corresponding to rows to consider.
- **columns** (*array*) – Array of integers corresponding to columns to consider.

**Returns** The solution to the indifference equations.

**Return type** array

`nashpy.algorithms.support_enumeration.support_enumeration(A, B, non_degenerate=False, tol=1e-16)`  
 Obtain the Nash equilibria using support enumeration.

Algorithm implemented here is Algorithm 3.4 of [Nisan2007]

1. For each  $k$  in  $1 \dots \min(\text{size of strategy sets})$
2. For each  $I, J$  supports of size  $k$
3. Solve indifference conditions
4. Check that have Nash Equilibrium.

#### Parameters

- **A** (*array*) – The row player utility matrix.
- **B** (*array*) – The column player utility matrix
- **non\_degenerate** (*bool*) – Whether or not to consider supports of equal size. By default (False) only considers supports of equal size.
- **tol** (*float*) – A tolerance parameter for equality.

**Yields** *tuple* – The equilibria.

### nashpy.algorithms.vertex\_enumeration module

A class for the vertex enumeration algorithm

`nashpy.algorithms.vertex_enumeration.vertex_enumeration(A, B)`  
 Obtain the Nash equilibria using enumeration of the vertices of the best response polytopes.

Algorithm implemented here is Algorithm 3.5 of [Nisan2007]

1. Build best responses polytopes of both players
2. For each vertex pair of both polytopes
3. Check if pair is fully labelled
4. Return the normalised pair

#### Parameters

- **A** (*array*) – The row player utility matrix.
- **B** (*array*) – The column player utility matrix

**Yields** *tuple* – The equilibria.

### nashpy.algorithms.lemke\_howson module

A class for the Lemke Howson algorithm

`nashpy.algorithms.lemke_howson.lemke_howson(A, B, initial_dropped_label=0)`  
 Obtain the Nash equilibria using the Lemke Howson algorithm implemented using integer pivoting.

Algorithm implemented here is Algorithm 3.6 of [Nisan2007].

1. Start at the artificial equilibrium (which is fully labeled)

2. Choose an initial label to drop and move in the polytope for which the vertex has that label to the edge that does not share that label. (This is implemented using integer pivoting)
3. A label will now be duplicated in the other polytope, drop it in a similar way.
4. Repeat steps 2 and 3 until have Nash Equilibrium.

**Parameters**

- **A** (*array*) – The row player payoff matrix
- **B** (*array*) – The column player payoff matrix
- **initial\_dropped\_label** (*int*) – The initial dropped label.

**Returns** An equilibria

**Return type** Tuple

`nashpy.algorithms.lemke_howson.shift_tableau(tableau, shape)`

Shift a tableau to ensure labels of pairs of tableaux coincide

**Parameters**

- **tableau** (*array*) – a tableau corresponding to a vertex of a polytope.
- **shape** (*tuple*) – the required shape of the tableau

**Returns** The shifted tableau

**Return type** array

`nashpy.algorithms.lemke_howson.tableau_to_strategy(tableau, basic_labels, strategy_labels)`

Return a strategy vector from a tableau

**Parameters**

- **tableau** (*array*) – a tableau corresponding to a vertex of a polytope.
- **basic\_labels** (*set*) – the set of basic labels.
- **strategy\_labels** (*set*) – the set of labels that correspond to strategies.

**Returns** A strategy.

**Return type** array

## nash.learning package

### Submodules

#### nashpy.learning.fictitious\_play module

Code to carry out fictitious learning

`nashpy.learning.fictitious_play.fictitious_play(A, B, iterations, play_counts=None)`

Implement fictitious play

**Parameters**

- **A** (*array*) – The row player payoff matrix.
- **B** (*array*) – The column player payoff matrix.
- **iterations** (*int*) – The number of iterations of the algorithm.

- **play\_counts** (*array*) – The play counts.

**Yields** *array* – The play counts.

`nashpy.learning.fictitious_play.get_best_response_to_play_count(A, play_count)`

Returns the best response to a belief based on the playing distribution of the opponent

**Parameters**

- **A** (*array*) – The utility matrix.
- **play\_count** (*array*) – The play counts.

**Returns** The action that corresponds to the best response.

**Return type** `int`

`nashpy.learning.fictitious_play.update_play_count(play_count, play)`

Update a belief vector with a given play

**Parameters**

- **play\_count** (*array*) – The play counts.
- **play** (*int*) – The given play.

**Returns** The updated play counts.

**Return type** `array`

## 4.5.2 Submodules

### 4.5.3 `nashpy.game` module

A class for a normal form game

**class** `nashpy.game.Game(*args)`

Bases: `object`

A class for a normal form game.

**Parameters**

- **A** (-) – non zero sum games.
- **B** (*2 dimensional list/arrays representing the payoff matrices for*) – non zero sum games.
- **A** – zero sum game.

**asymmetric\_replicator\_dynamics** (*x0=None, y0=None, timepoints=None*)

Returns two arrays, corresponding to the two players, showing the probability of each strategy being played over time using the asymmetric replicator dynamics algorithm.

**Parameters**

- **x0** (*array*) – The initial population distribution of the row player.
- **y0** (*array*) – The initial population distribution of the column player.
- **timepoints** (*array*) – The iterable of timepoints.

**Returns** The 2 population distributions over time.

**Return type** `Tuple`

**fictitious\_play**(*iterations*, *play\_counts=None*)

Return a given sequence of actions through fictitious play. The implementation corresponds to the description of chapter 2 of [Fudenberg1998].

1. Players have a belief of the strategy of the other player: a vector representing the number of times the player has chosen a given strategy. 2. Players choose a best response to the belief. 3. Players update their belief based on the latest choice of the opponent.

**Parameters**

- **iterations** (*int*) – The number of iterations of the algorithm.
- **play\_counts** (*array*) – The play counts.

**Returns** The play counts

**Return type** Generator

**is\_best\_response**(*sigma\_r*, *sigma\_c*)

Checks if *sigma\_r* is a best response to *sigma\_c* and vice versa.

**Parameters**

- **sigma\_r** (*array*) – The row player strategy
- **sigma\_c** (*array*) – The column player strategy

**Returns** A pair of booleans, the first indicates if *sigma\_r* is a best response to *sigma\_c*. The second indicates if *sigma\_c* is a best response to *sigma\_r*.

**Return type** tuple

**lemke\_howson**(*initial\_dropped\_label*)

Obtain the Nash equilibria using the Lemke Howson algorithm implemented using integer pivoting.

Algorithm implemented here is Algorithm 3.6 of [Nisan2007].

1. Start at the artificial equilibrium (which is fully labeled)
2. Choose an initial label to drop and move in the polytope for which the vertex has that label to the edge that does not share that label. (This is implemented using integer pivoting)
3. A label will now be duplicated in the other polytope, drop it in a similar way.
4. Repeat steps 2 and 3 until have Nash Equilibrium.

**Parameters** **initial\_dropped\_label** (*int*) – The initial dropped label.

**Returns** An equilibria

**Return type** Tuple

**lemke\_howson\_enumeration**()

Obtain Nash equilibria for all possible starting dropped labels using the lemke howson algorithm. See *Game.lemke\_howson* for more information.

Note: this is not guaranteed to find all equilibria.

**Yields** *tuple* – An equilibria

**replicator\_dynamics**(*y0=None*, *timepoints=None*)

Implement replicator dynamics Return an array showing probability of each strategy being played over time. The total population is constant. Strategies can either stay constant if equilibria is achieved, replicate or die.

**Parameters**

- **y0** (*array*) – The initial population distribution.
- **timepoints** (*array*) – The iterable of timepoints.

**Returns** The population distributions over time.

**Return type** *array*

**stochastic\_fictitious\_play**(*iterations*, *play\_counts=None*, *etha=0.1*, *epsilon\_bar=0.01*)

Return a given sequence of actions and mixed strategies through stochastic fictitious play. The implementation corresponds to the description given in [Hofbauer2002].

**Parameters**

- **iterations** (*int*) – The number of iterations of the algorithm.
- **play\_counts** (*array*) – The play counts.
- **etha** (*float*) – The noise parameter for the logit choice function.
- **epsilon\_bar** (*float*) – The maximum stochastic perturbation.

**Returns** The play counts

**Return type** *Generator*

**support\_enumeration**(*non\_degenerate=False*, *tol=1e-16*)

Obtain the Nash equilibria using support enumeration.

Algorithm implemented here is Algorithm 3.4 of [Nisan2007].

1. For each  $k$  in  $1 \dots \min(\text{size of strategy sets})$
2. For each  $I, J$  supports of size  $k$
3. Solve indifference conditions
4. Check that have Nash Equilibrium.

**Parameters**

- **non\_degenerate** (*bool*) – Whether or not to consider supports of equal size. By default (False) only considers supports of equal size.
- **tol** (*float*) – A tolerance parameter for equality.

**Returns** The equilibria.

**Return type** *generator*

**vertex\_enumeration**()

Obtain the Nash equilibria using enumeration of the vertices of the best response polytopes.

Algorithm implemented here is Algorithm 3.5 of [Nisan2007].

1. Build best responses polytopes of both players
2. For each vertex pair of both polytopes
3. Check if pair is fully labelled
4. Return the normalised pair

**Returns** The equilibria.

**Return type** *generator*

#### 4.5.4 Module contents

A library to compute equilibria of 2 player normal form games



## CONTRIBUTOR DOCUMENTATION

This guide explains the various tools and steps used to contribute code to Nashpy.

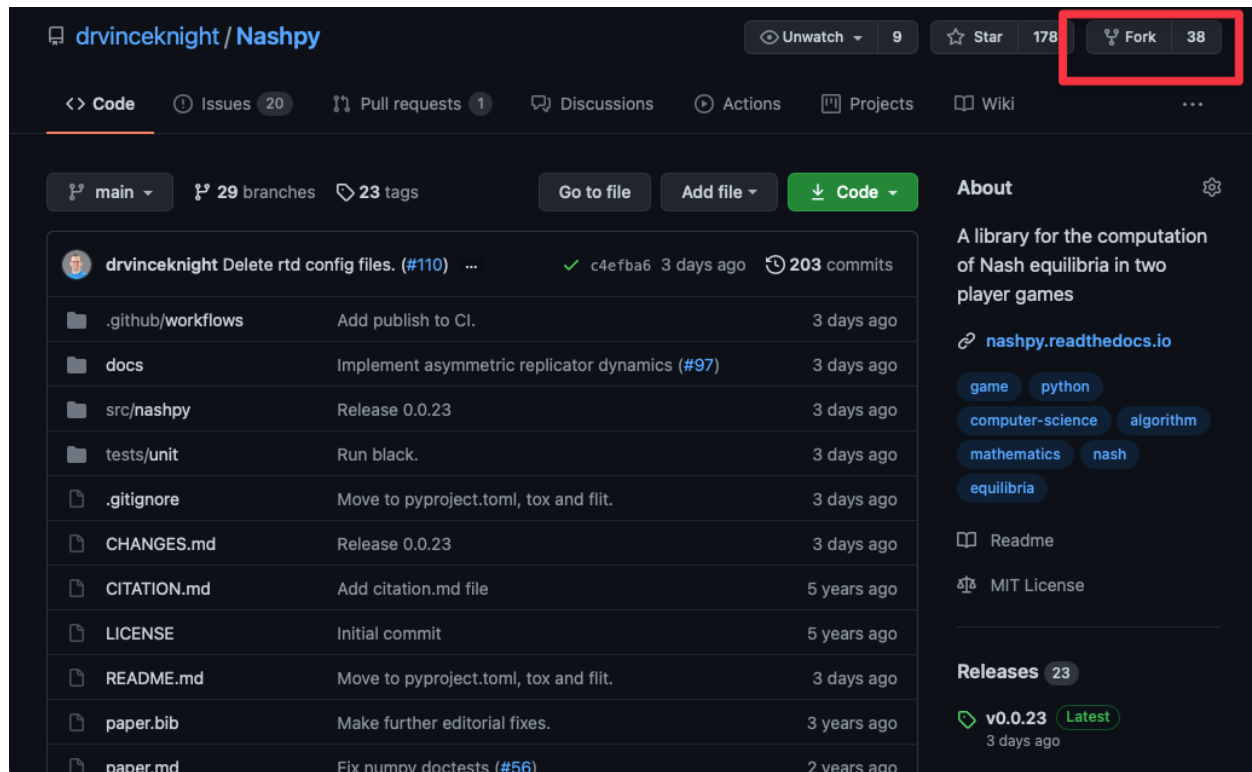
### 5.1 Tutorial: make a contribution to the documentation

In this tutorial we will make a contribution to the documentation of Nashpy.

#### 5.1.1 Forking the repository

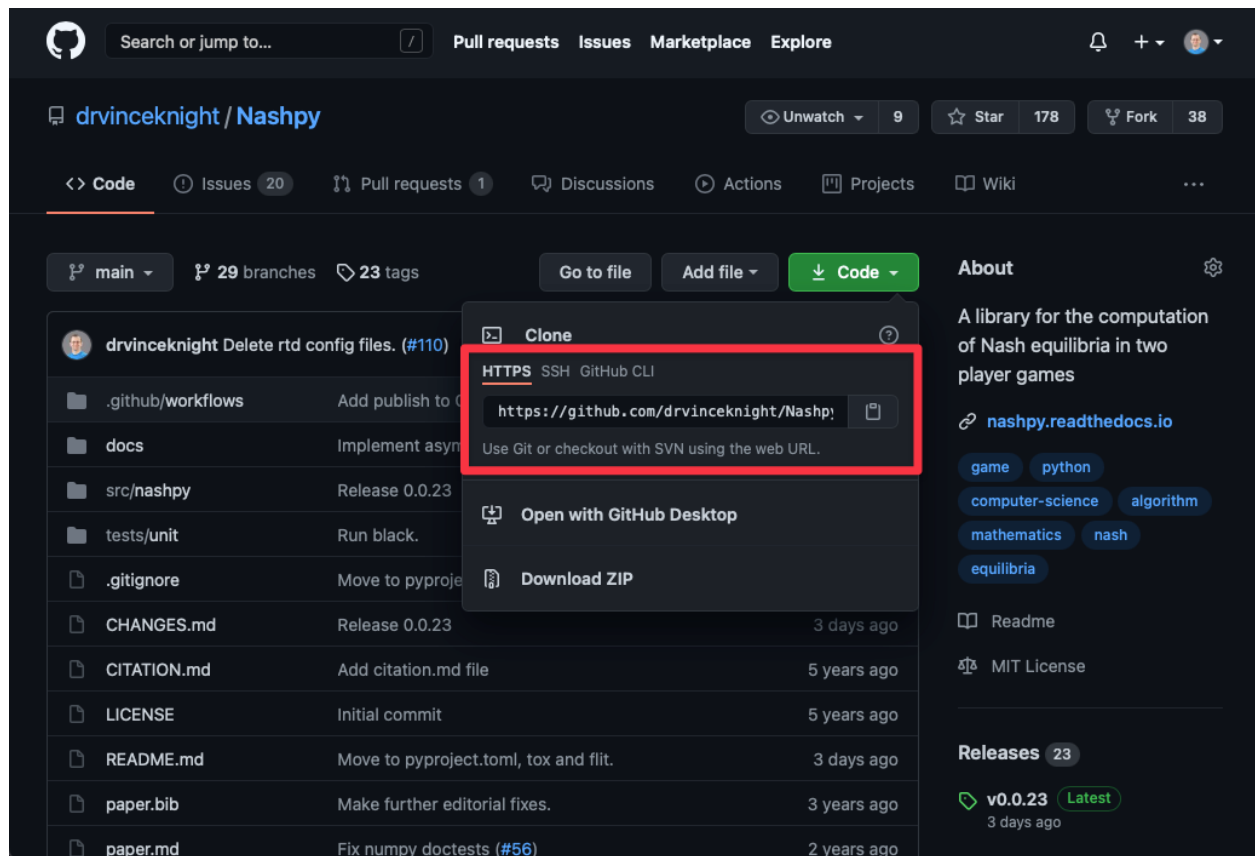
Navigate to <http://github.com> and create an account. If you are in education you can apply for a specific education account here: <https://education.github.com>.

Navigate to the Github repository for Nashpy: <https://github.com/drvinceknight/Nashpy>. This is the hub for development of the source code. You cannot make modification to this copy of the source code so you need to create your own copy under your Github account. You do this by creating a **fork**. Do this by clicking the Fork button and following the instructions:



### 5.1.2 Cloning the repository

Once we have a fork of the repository on **your** Github account, create a copy of it to your computer. This is called cloning. Do this by clicking the *Code* button and copying the address of the repository to your clipboard:



If you have not installed `git` go to <https://git-scm.com> and install.

Now to create a clone of the source code open your command line tool and type the following (**replace** <your username> with your Github username):

```
$ git clone https://github.com/<your username>/Nashpy.git
```

This will download the source code to your computer:

```
$ git clone https://github.com/<your username>/Nashpy.git
Cloning into 'Nashpy'...
remote: Enumerating objects: 1813, done.
remote: Counting objects: 100% (362/362), done.
remote: Compressing objects: 100% (225/225), done.
remote: Total 1813 (delta 160), reused 233 (delta 79), pack-reused 1451
Receiving objects: 100% (1813/1813), 439.94 KiB | 2.67 MiB/s, done.
Resolving deltas: 100% (905/905), done.
```

### 5.1.3 Creating a branch

In order to modify the source code you must create a new branch. After cloning, first change directory in to the Nashpy source code:

```
$ cd Nashpy
```

Now, to keep the changes you are about to make separate from the `main` source code, create a **branch**:

```
$ git branch add-name-to-contributors-list
```

Now checkout to that branch:

```
$ git checkout add-name-to-contributors-list
```

### 5.1.4 Modifying the documentation

Using your preferred editor, open the file `Nashpy/docs/contributing/reference/contributors/index.rst`. If you do not have a preferred editor [Visual Studio Code](#) is recommended.

Now add you name to the file (**replace** `<your username>` with your Github username):

```
List of contributors
-----
- `@drvinceknight <https://github.com/drvinceknight>`_
- `@<your username> <https://github.com/<your username>`_
```

### 5.1.5 Checking the modification

To build the documentation, first create a virtual environment specifically for purposes to work on Nashpy:

```
$ python -m venv env
```

This creates a directory `env` which holds a separate version of python. To tell your command line tool to now use this version:

On Linux or macOS type:

```
$ source env/bin/activate
```

On Windows type:

```
$ env\Scripts\activate
```

Now install the Nashpy software in to this environment:

```
$ python -m pip install flit
$ python -m flit install --symlink
```

To build the documentation:

```
$ cd docs
$ sphinx-build -b html . _build/html
Running Sphinx v3.1.2
loading pickled environment... done
building [mo]: targets for 0 po files that are out of date
building [html]: targets for 2 source files that are out of date
updating environment: 1 added, 2 changed, 1 removed
reading sources... [100%] contributing/tutorial/index
looking for now-outdated files... none found
pickling environment... done
checking consistency... done
preparing documents... done
writing output... [100%] index
generating indices... genindex py-modindexdone
highlighting module code... [100%] nashpy.learning.fictitious_play
writing additional pages... searchdone
copying images... [100%] _static/contributing/tutorial/cloning/main.png
copying static files... .. done
copying extra files... done
dumping search index in English (code: en)... done
dumping object inventory... done
build succeeded.

The HTML pages are in _build/html.
```

You can open `_build/html/index.html` in a browser to see the documentation locally which should include the changes you made.

### 5.1.6 Running the test suite

You can run the entire test suite which will check that this modification has not caused any problems:

```
$ python -m pip install tox
$ python -m tox
```

### 5.1.7 Committing the change

Now you need to **stage** this file:

```
$ git add docs/contributing/reference/contributors/index.rst
```

Now commit this file:

```
$ git commit
```

This will open a text editor where you can write your commit title and message:

```
Add <your username> to list of contributors

I am doing the contribution tutorial.
```

Closing the editor will commit the changes you made.

### 5.1.8 Pushing the change to Github

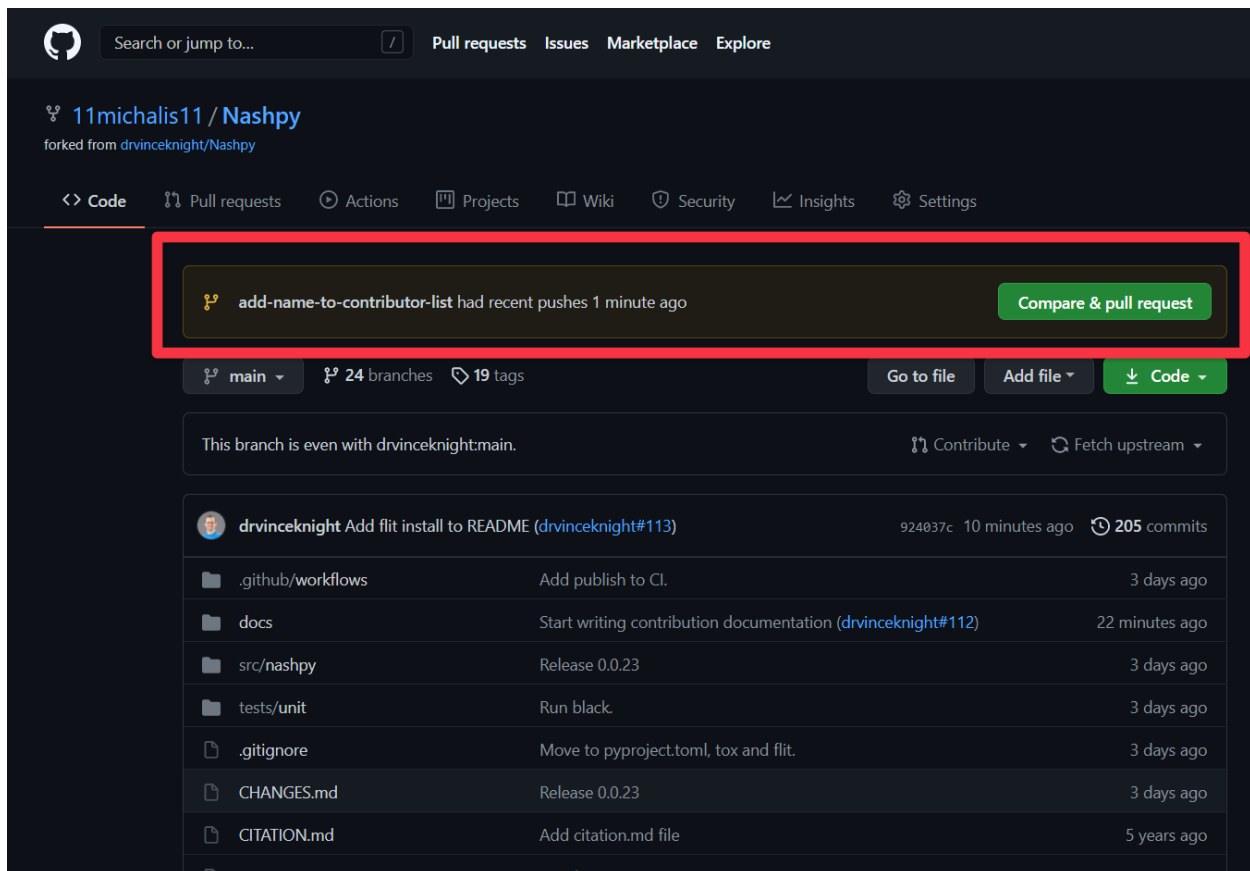
Now that all that is done, you are going to send the changes back to your copy of the source code on Github:

```
$ git push origin add-name-to-contributors-list
```

### 5.1.9 Opening a Pull Request

You now have 2 copies of the modified source code of Nashpy. One locally on your computer, the other under your Github account. In order to include those changes in to the main source code of Nashpy you will open a Pull request.

To do this, go to your fork of the Nashpy repository: [https://github.com/<your\\_username>/Nashpy](https://github.com/<your_username>/Nashpy). You should see a Compare and Pull Request button:

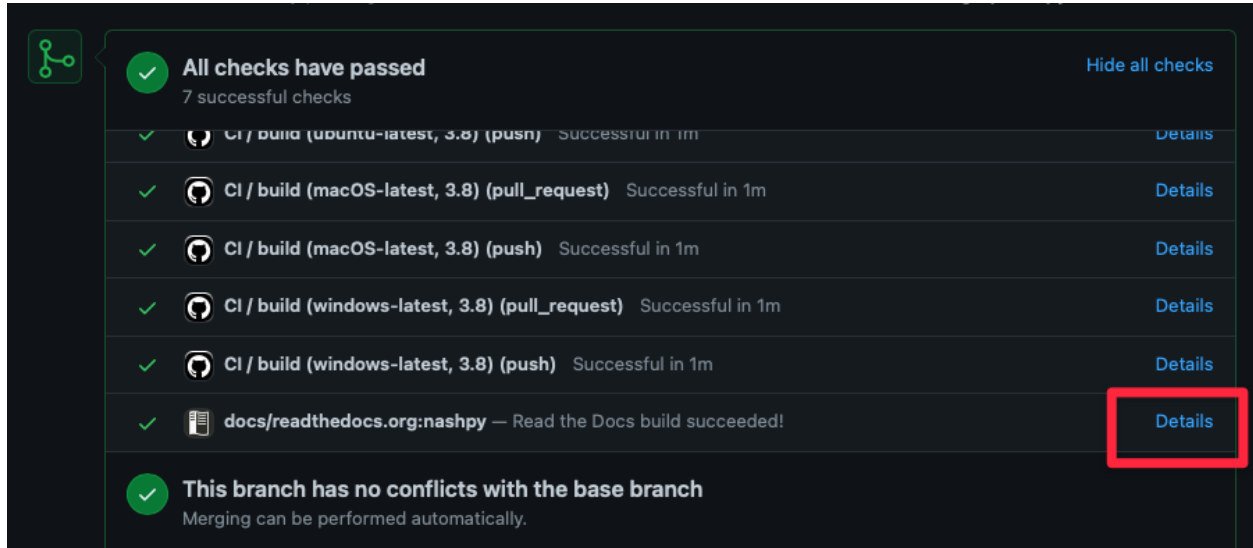


Once you have clicked on that, you can review your changes and then eventually click on Create pull request to create the Pull Request.

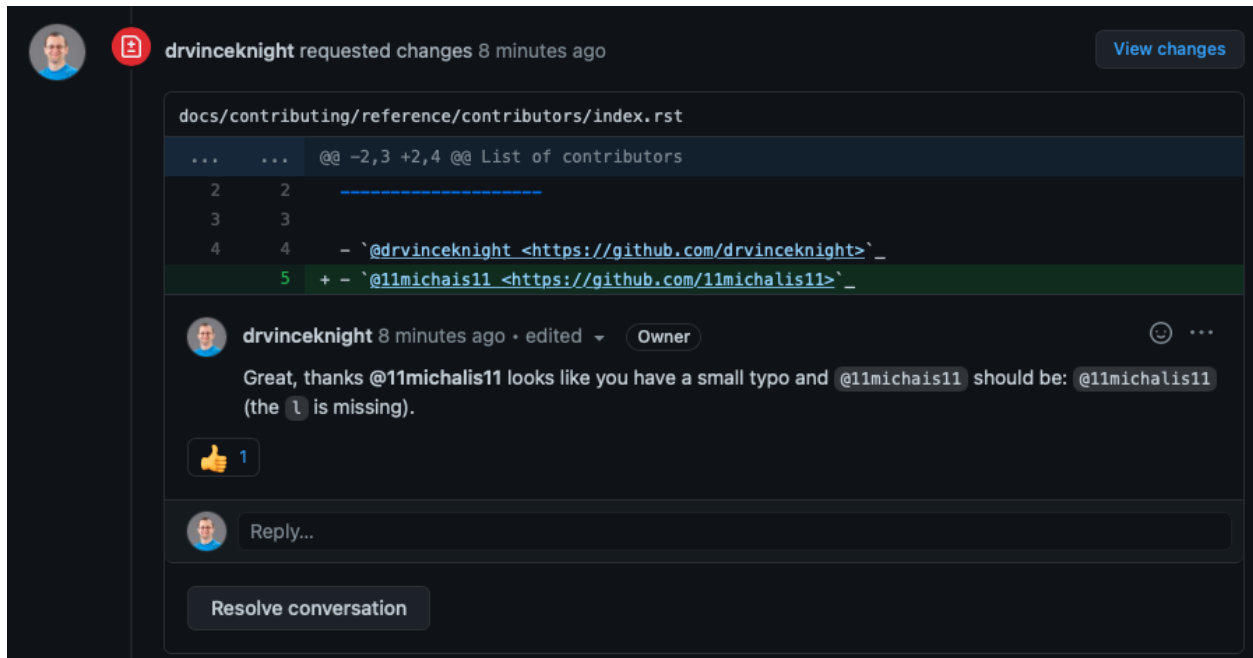
### 5.1.10 Making further modifications

Once a Pull Request is opened, a number of automated checks will start. This will check the various software tests but also build a viewable version of the documentation.

You can click on the corresponding details button to see any of these:



Your modification will also be reviewed:



To make any required changes, **modify the files**.

Then stage and commit the files:

```
$ git add docs/contributing/reference/contributors/index.rst
$ git commit
```

This will open a text editor where you can write your commit title and message (similarly to before).

Once this is done, push the code to Github which will automatically update the pull request:

```
$ git push origin add-name-to-contributors-list
```

This final process of making further modifications might repeat itself and eventually the Pull Request will be **merged** and your changes included in the main version of the Nashpy source code.

## 5.2 How to

How to:

### 5.2.1 How to fork the repository

1. Navigate to <https://github.com/drvinecknight/Nashpy>
2. Click on *Fork*
3. Follow any remaining instructions, for example if you have an organisation account on Github you will be prompted to say which account you would like to fork with.

### 5.2.2 How to clone the repository

In order to obtain a copy of *your fork of the repository on github* to your local machine run the following at your command line:

```
$ git clone https://github.com/<username>/Nashpy.git
```

### 5.2.3 How to update from upstream

In order to bring your local repository up to date with any upstream changes:

```
$ git remote add upstream https://github.com/drvinecknight/Nashpy.git  
$ git pull upstream main
```

The above:

1. Creates a new remote with alias `upstream` that points at the main source repository for Nashpy. You can list all your remote repositories by running:

```
$ git remote -v
```

2. Pulls the latest changes from the main branch of the upstream repository.

### 5.2.4 How to create a branch

To create a branch with name `<name-of-branch>` run:

```
$ git branch <name-of-branch>
```

To go to that branch:

```
$ git checkout <name-of-branch>
```

#### How to branch from a specific branch, tag or commit

To create a branch with name `<name-of-branch>` from a specific branch, tag or commit with name `<location>` run:

```
$ git branch <name-of-branch> <location>
```

#### How to create a branch and checkout to it at the same time

You can create a branch with name `<name-of-branch>` and checkout in a single command:

```
$ git checkout -b <name-of-branch>
```

### 5.2.5 How to create a virtual environment

To create a virtual environment with name `<name>` run:

```
$ python -m venv <name>
```

#### How to activate `<name>`

On Linux or macOS type:

```
$ source env/bin/activate
```

On Windows type:

```
$ env\Scripts\activate
```

### 5.2.6 How to install the library from source

To install the library from the source files:

```
$ python -m pip install flit
$ python -m flit install
```

### How to install an editable version of the library from source

If you want to install a version of the library from the source files so that modifications of the source files are directly usable:

```
$ python -m flit install --symlink
```

### 5.2.7 How to run tests

To install tox:

```
$ python -m pip install tox
```

To run all tests:

```
$ python -m tox
```

If you want to run the tests across a single version of Python:

```
$ python -m tox -e <version>
```

where `version` is either `py38` or `py39`.

### 5.2.8 How to check for insensitive language

The documentation is checked for insensitive or inconsiderate language using `alex`.

#### How to install alex

To install alex run:

```
$ npm install alex --global
```

Note that this required node, information on install node is available here: <https://www.npmjs.com/get-npm>

#### How to run alex

To run alex on the documentation:

```
$ alex docs**/*.rst
```

To run alex on the `README.md` file:

```
$ alex README.md
```

## How to ignore some checks

To ignore some specific checks annotations can be used. For example *John Nash* is annotated to ignore insensitive related to gendered pronouns:

```
.. <!--alex disable he-she-->
.. <!--alex disable her-him-->
```

This library is named after the mathematician John Nash. He is most famous for his work in Game Theory that culminated in him winning a Noble prize in Economics. The book [Nasar2011]\_ (popularized in a 2001 movie) gives a good overview of his life.

The work he received a Noble prize for was a proof that a game **\*\*always\*\*** has an equilibrium [Nash1950]\_. His proof is an exceptional piece of mathematics where he uses a fixed point theorem by showing that an equilibrium is equivalent to a fixed point of a function.

```
.. <!--alex enable he-she-->
.. <!--alex enable her-him-->
```

Another example is the README.md file where an annotation is added to ignore a specific use of the word “bi”:

### ## Usage

Create bi-matrix games by passing two 2 dimensional arrays/lists:

## 5.2.9 How to write a docstring

All functionality needs have a documentation string (docstrings). The convention used in Nashpy is to follow Numpy’s docstring convention:

```
def <function>(<signature>):
    """
    <short summary>

    Parameters
    -----
    <paramter> : <type>
        <description>
    <paramter> : <type>
        <description>
    ...
    <paramter> : <type>
        <description>

    Returns
    -----
    <type>
        <description>
    """
```

If the function/method does not return anything but is instead a **generator** then Returns should be replaced with Yields.

### How to check docstrings in a module

Running tests with *tox* will automatically check formatting of docstrings.

If you want to check a specific file, use *darglint*:

```
$ python -m pip install darglint
$ darglint -s numpy <path_to_file>
```

## 5.2.10 How to write tests

The *pytest* framework is used for writing and running tests for Nashpy.

Tests should be written in one of the following locations:

- In a preexisting file in the `test/` directory.
- In a new file in the `test/` directory.

Thanks to *pytest* the format for a test is:

```
def test_<functionality>():
    """
    <short summary if necessary>
    """
    <code logic>
    assert <boolean>
```

For guidance on how to run tests see: *How to run tests*.

When writing a new test it is good practice to ensure the test fails (either by modifying the test or by modifying the source code): this ensures that *pytest* is running the test in question.

Note that when adding new functionality the coverage of the test suite will be checked using *coverage*. Thus, in practice multiple tests will need to be written to test new functionality completely.

### Hypothesis

Property based tests are tests that use random sampling in an efficient manner to test given properties as opposed to specific values. Nashpy uses *hypothesis* for this.

For example the following tests that for any given `M`, which is a 3 by 3 numpy integer array, the length of the output of `get_derivative_of_fitness` is as expected:

```
from hypothesis import given, settings
from hypothesis.strategies import integers
from hypothesis.extra.numpy import arrays

@given(M=arrays(np.int8, (3, 3)))
def test_property_get_derivative_of_fitness(M):
    t = 0
    x = np.zeros(M.shape[1])
```

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```
derivative_of_fitness = get_derivative_of_fitness(x, t, M)

assert len(derivative_of_fitness) == len(x)
```

### 5.2.11 How to make a commit

To commit changes to a given code <file.py>.

First, stage it:

```
$ git add <file.py>
```

Now that the file is staged, create a commit:

```
$ git commit
```

This will open a text editor (a default text editor of your choice can be set). In there write a commit message in the following format:

```
<commit title>

<commit message>
```

Save and exit from the text editor and your commit should be applied.

#### Commit message style

The <commit title> should be short and follow the style: “If this commit is applied it will <commit title> will happen.”

The <commit message> should include further details and can go over many lines.

Here is some good guidance on writing commit messages: <https://chris.beams.io/posts/git-commit/>

#### Do not use `git commit -m "<commit message>"`

It is possible to write a commit message directly as you make the commit by typing:

```
$ git commit -m <commit title>
```

This is not recommended as it encourages unclear commit messages.

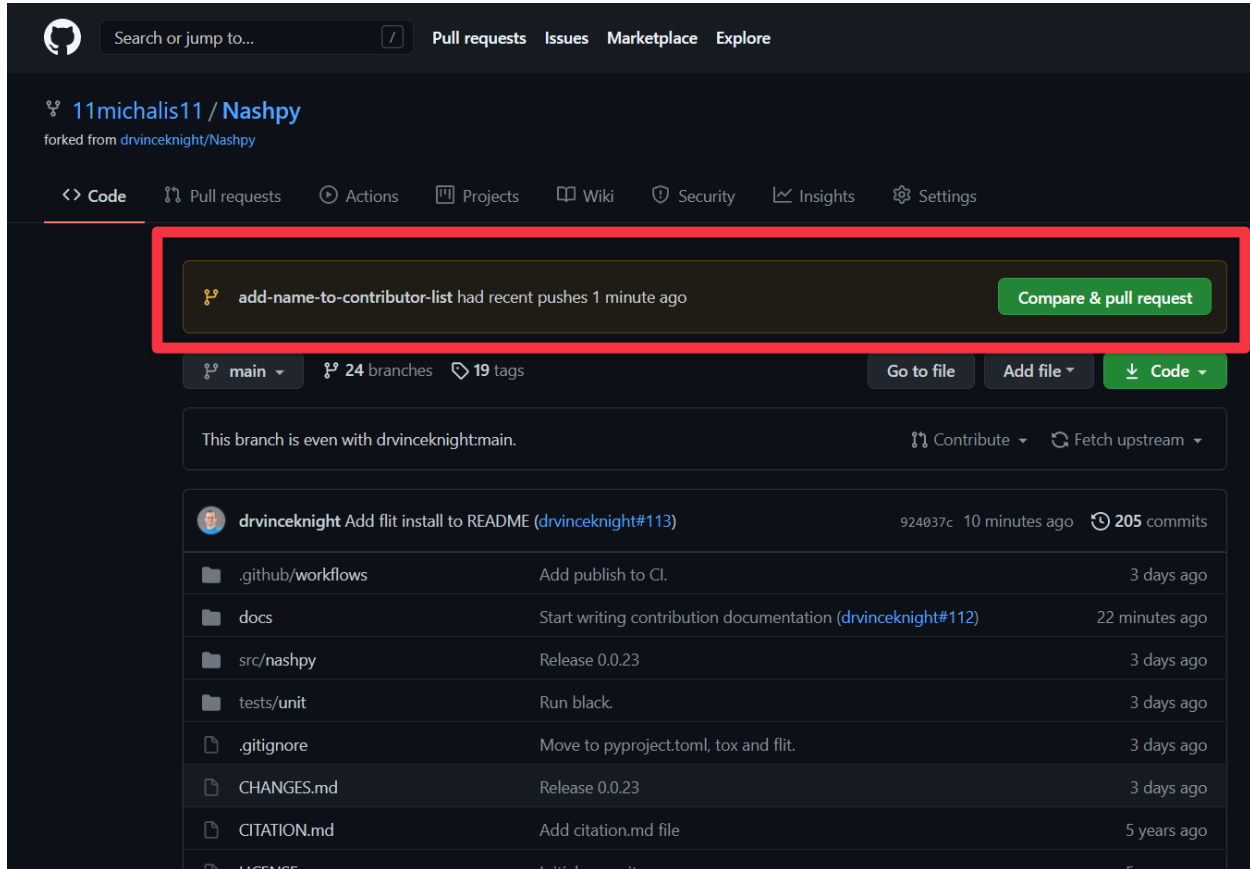
### 5.2.12 How to push changes

In order to push a copy of your committed changes on the <branch-name> branch to *your fork of the repository on github* run the following at your command line:

```
$ git push origin <branch-name>
```

### 5.2.13 How to open a pull request

Once you have *pushed your changes to github* you can open a request for these changes to be incorporated in to the main repository by going to your fork of the Nashpy repository: [https://github.com/<your\\_username>/Nashpy](https://github.com/<your_username>/Nashpy). You should see a Compare and Pull Request button:



Once you have clicked on that, you can review your changes and then eventually click on Create pull request to create the Pull Request.

## 5.3 Discussion

### 5.3.1 The code structure of Nashpy

#### The directory structure

The directory structure for Nashpy is:

```

|— src/
|— tests/
|— docs/
|— CHANGES.md
|— CITATION.md
|— LICENSE
|— README.md

```

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```
├── paper.bib
├── paper.md
├── pyproject.toml
├── .readthedocs.yml
├── setup.cfg
└── tox.ini
```

Here is a brief description of each of these:

### The `src/` directory

The `src/` directory contains the source code. It's structure is as follows:

```
src/
├── nashpy
│   ├── __init__.py
│   ├── game.py
│   ├── algorithms/
│   ├── integer_pivoting/
│   ├── learning/
│   └── polytope/
```

- The `__init__.py` file contains the various commands to import all the functionality of the library.
- The `game.py` file contains the main `nashpy.Game` class.
- The `algorithms/` directory contains further modules with algorithms for computation of Nash equilibria.
- The `integer_pivoting/` directory contains further modules with algorithms for integer pivoting.
- The `learning/` directory contains further modules for various learning algorithms.
- The `polytope` directory contains further modules with code for *best response polytopes*.

### The `tests/` directory

This contains all the test files.

### The `docs/` directory

The documentation is written using the Diataxis framework [Procida2021]. As well as various configuration files for *sphinx* there are 5 main subdirectories:

```
docs/
├── contributing
│   ├── discussion/
│   ├── how-to/
│   ├── index.rst
│   ├── reference/
│   └── tutorial/
├── discussion/
└── how-to/
```

(continues on next page)

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```
├─ index.rst
├─ reference/
└─ tutorial/
```

- The `contributing/` directory contains the specific contributing documentation. Which itself is written using Diataxis [Procida2021].
- The `discussion/` directory contains source files for the discussion described at [Procida2021] as: “explanation is discussion that clarifies and illuminates a particular topic.”
- The `reference/` directory contains source files for the reference described at [Procida2021] as: “reference guides are technical descriptions of the machinery and how to operate it.”
- The `how-to/` directory contains source files for the how to guides described at [Procida2021] as: “how-to guides are directions that take the reader through the steps required to solve a real-world problem”
- The `tutorial/` directory contains source files for the tutorial described at [Procida2021] as: “tutorials are lessons that take the reader by the hand through a series of steps to complete a project of some kind.”

### The `CHANGES.md` file

Makes a note of different changes in versions of Nashpy.

### The `CITATION.md` file

Contains information for citing Nashpy.

### The `LICENSE` file

Contains the license.

### The `README.md` file

Contains the first entry point documentation to the Nashpy project.

### The `paper.bib` and `paper.md` files

These are the source files for the [Journal of Open Source Software](#) paper written about Nashpy: [Knight2018].

### The `pyproject.toml` file

Contains all the build instructions for packaging Nashpy and is used by *flit*.

### The `.readthedocs.yml` file

This includes configuration settings for the online service that hosts the documentation *read the docs*.

### The `setup.cfg` file

Contains some configuration instructions for testing.

### The `tox.ini` file

Contains the instructions for the test runner `tox`.

### The `Game` class

The `nashpy.Game` class is an umbrella class that creates an object oriented interface to all functionality of Nashpy as methods on a game.

## 5.3.2 Writing clean tests with `pytest`

The `pytest` framework allows for cleaner tests to be written but also for efficient running of tests with multiple plugins.

### Plugins

#### Coverage: `pytest-cov`

The `pytest-cov` plugin allows you to run coverage checks with `pytest`.

#### Flake8: `pytest-flake8`

The `pytest-flake8` plugin allows you to run `flake8` checks with `pytest`.

#### Stochastic effects: `pytest-randomly`

The `pytest-randomly` plugin does two things (for Nashpy):

1. It randomly shuffles the order of tests: this ensures that tests passing is not dependent on the order in which they run.
2. It seeds stochastic tests to ensure that any exceptions are reproducible. In practice this has little effect here as ideally stochastic tests are seeded or written with *hypothesis*.

### Nicer look: `pytest-sugar`

The `pytest-sugar` plugin changes the look of `pytest`.

### Further plugins

The *Talk Python to Me* podcast episode 267 featured a discussion of a number of `pytest` plugins: <https://talkpython.fm/episodes/show/267/15-amazing-pytest-plugins>

## 5.3.3 Testing across environments with `tox`

The `tox` project allows for the automation of many tasks related to Python packaging and testing.

For Nashpy it is used to:

1. Configure all tests.
2. Test across multiple python versions.

### Configure all tests

All test commands are written in `tox.ini`. This include things like checking style with `black` and presence of docstrings with `interrogate`. Running all the checks is done with a single standard command: `python -m tox`.

Note that *checking for insensitive language in documentation* is not configured or run by `tox`.

### Test across multiple python versions

This is done thanks to configurations written in `tox.ini`:

```
[tox]
isolated_build = True
envlist = py38, py39
```

## 5.3.4 Installing and packaging with `flit`

TODO

## 5.3.5 Virtual environments

TODO

### 5.3.6 Checking code is tested with coverage

TODO

### 5.3.7 Testing with properties with hypothesis

TODO

### 5.3.8 Ensuring consistent code style with Black

TODO

### 5.3.9 Static code analysis with flake8

TODO

### 5.3.10 Checking the presence of docstrings with interrogate

TODO

### 5.3.11 Checking the format of docstrings with darglint

Documentation strings, more commonly referred to as `docstrings` in python are strings that directly document a function. Their presence is checked using *Checking the presence of docstrings with interrogate* but the particular format they are written in is checked using `darglint`.

Once installed darlint can be used to check one of three docstring styles:

1. Google style guide
2. Sphinx style guide
3. Numpy style guide

For example, consider the file `main.py`:

```
def get_mean(collection):
    """
    Obtain the average of a collection of objects.

    Parameters
    -----
    collection : list
        A list of numbers

    Returns
    -----
    float
        The mean of the numbers.
    """
    return sum(collection) / len(collection)
```

After installing darglint:

```
$ python -m pip install darglint
```

If we check the format of this file against the Google style guide:

```
$ darglint -s google main.py
main.py:get_mean:1: DAR101: - collection
main.py:get_mean:1: DAR201: - return
```

we get two errors, we can cross reference the error codes DAR101 and DAR201 at <https://github.com/terrencepreilly/darglint#error-codes>.

- DAR101: “The docstring is missing a parameter in the definition.”
- DAR201: “The docstring is missing a return from definition.”

Note that our file does have both those things but here darglint is telling us that they do not match with the google style guide.

If we check the format of this file against the Sphinx style guide:

```
$ darglint -s sphinx main.py
main.py:get_mean:1: DAR101: - collection
main.py:get_mean:1: DAR201: - return
```

we get the same two errors.

Running, the file against the Numpy style guide gives:

```
$ darglint -s numpy main.py
$
```

No errors are raised as this is indeed written using the Numpy style guide which is also the convention chosen for the entire Nashpy source code.

### Running darglint as part of the test suite

If darglint is installed it will automatically run as part of the flake8 check. For Nashpy this is done as part of the pytest run which is all configured using tox.

## 5.3.12 Using sphinx for documentation

TODO

### Using sphinx-togglebutton for the questions

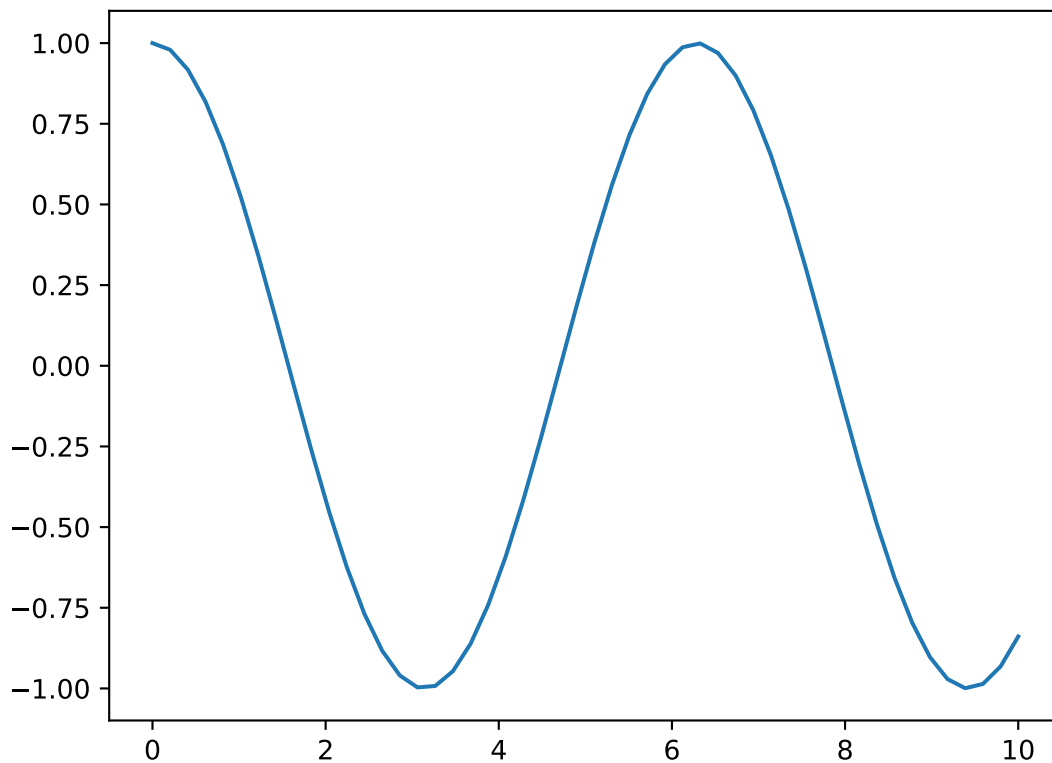
TODO

### Using matplotlib for plotting directives

The matplotlib library includes a sphinx plugin that allows for plot directives. To enable it, ensure that "matplotlib.sphinxext.plot\_directive" is included in extensions in conf.py.

For example the following will create a plot:

```
.. plot::  
  
    import matplotlib.pyplot as plt  
    import numpy as np  
  
    xs = np.linspace(0, 10)  
    plt.plot(xs, np.cos(xs))
```



### 5.3.13 Ensuring the code in the documentation is correct with doctests

TODO

### 5.3.14 Checking for insensitive language with alex

`alex` is a tool that allows you to identify insensitive and/or inconsiderate language in written prose. The following description is taken from the project page:

“Whether your own or someone else’s writing, alex helps you find gender favoring, polarizing, race related, religion inconsiderate, or other unequal phrasing in text.”

As an example consider the following markdown file:

```
# A typical user of Nashpy

He will use it to study games.
```

If we run alex on it:

```
$ alex main.md
```

We get:

```
$ alex main.md
main.md
3:1-3:3  warning  `He` may be insensitive, use `They`, `It` instead he-she retext-
↪equality

1 warning
```

Correcting the markdown file to:

```
# A typical user of Nashpy

They will use it to study games.
```

Running alex now gives:

```
$ alex main.md
main.md: no issues found
```

The above example is quite a clear one, alex assists by identifying errors like this but also more subtle ones.

It is possible to ignore certain checks [using a configuration file](#) but as described in [the how to guide](#) it is also possible to annotate the file itself. This is preferred as it makes exceptions explicit.

## FAQ

The Frequently asked questions about alex can be found here: <https://github.com/get-alex/alex#faq> This includes:

Q: This is stupid!

A: Not a question. And yeah, alex isn't very smart. People are much better at this. But people make mistakes, and alex is there to help

The Nashpy library uses alex for exactly this reason, it is one of many efforts made to ensure the project is inclusive.

### 5.3.15 Using Github Actions to check automatically run all checks and publish new releases

TODO

### 5.3.16 Hosting documentation on Read The Docs

Read the docs is a web service that builds and hosts documentation. You can read more about the service here: <https://readthedocs.org>

The documentation contained in docs/ is automatically built and can be viewed at <https://nashpy.readthedocs.io/en/stable/>.

## Settings

Read the docs allows you to configure your build using a `readthedocs.yml` file. This is not currently used by Nashpy.

The default version (ie when going to <https://nashpy.readthedocs.io/>) is the `stable` version which means the last release.

You can view the version of the documentation currently on the `main` branch by going to: <https://nashpy.readthedocs.io/latest>.

## Configuration file

Read the docs can have specific settings set in a `.readthedocs.yml` file. Details on this can be found here: <https://docs.readthedocs.io/en/stable/config-file/v2.html#packages>

One specific setting used by Nashpy is:

```
python:
  version: 3.8
  install:
    - method: pip
      path: .
```

This ensures Read the docs does not look for a `requirements.txt` file to install the library. Instead it runs `pip install .` which uses *The pyproject.toml file*.

A powerful feature offered by Read the docs is that it can build documentation in pull requests.

## Building documentation in pull requests

To set this up you need to ensure the following things are done:

1. The repository settings on Read the docs instruct pull requests to be built.
2. The correct web hook is in place on Github.
3. The correct settings of the web hook are done on the Github repository.

To instruct pull requests to be built ensure the following box is ticked in the Advanced settings for your project on Read the docs:

**Settings**

- Advanced Settings •
- Edit Versions
- Domains
- Maintainers
- Redirects
- Translations
- Subprojects
- Integrations
- Environment Variables
- Automation Rules
- Notifications
- Traffic Analytics
- Search Analytics
- Advertising

### Advanced Settings

**Global settings**

**Default version\***  
stable

The version of your project that / redirects to

**Default branch**  
main

What branch "latest" points to. Leave empty to use the default value for your VCS (eg. trunk or master).

**Analytics code**

Google Analytics Tracking ID (ex. UA-22345342-1). This may slow down your page loads.

☐ **Disable Analytics**  
Disable Google Analytics completely for this project (requires rebuilding documentation)

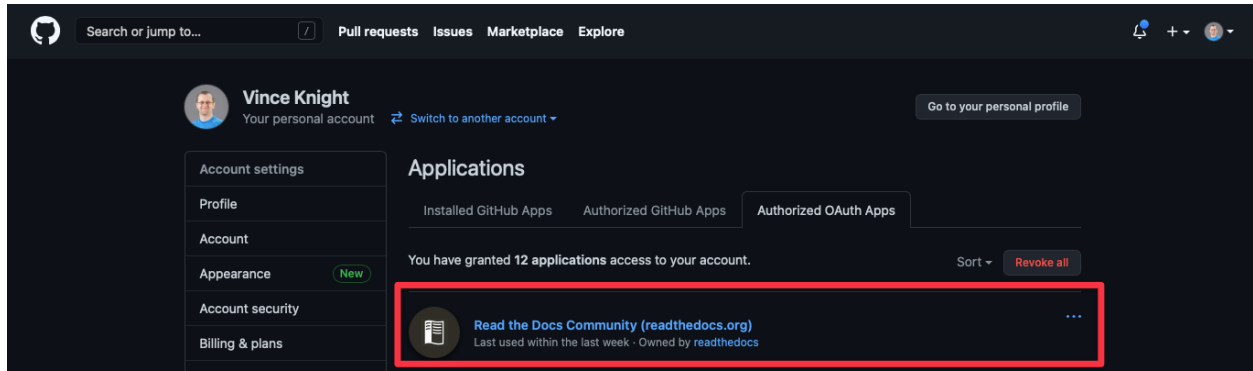
☒ **Show version warning**  
Show warning banner in non-stable nor latest versions.

☐ **Single version**  
A single version site has no translations and only your "latest" version, served at the root of the domain. Use this with caution, only turn it on if you will **never** have multiple versions of your docs.

☒ **Build pull requests for this project**  
More information in [our docs](#)

Setting up the web hooks correctly is described here: <https://docs.readthedocs.io/en/latest/pull-requests.html>

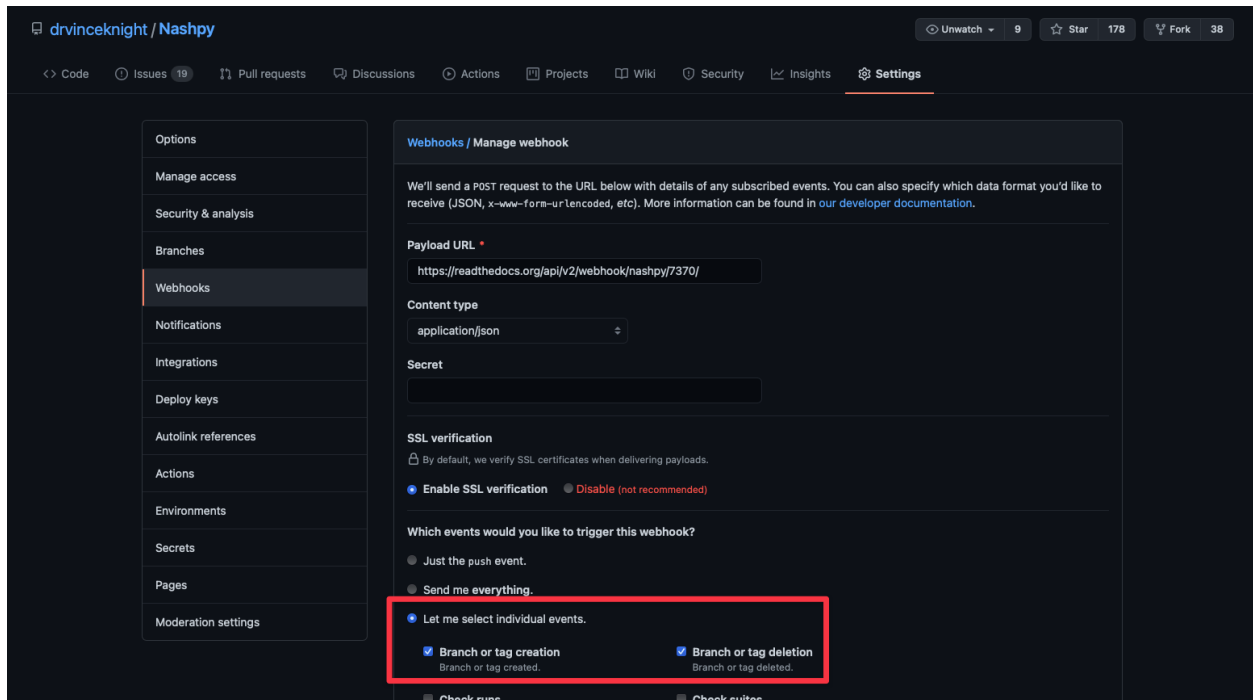
When done correctly this is what [Applications settings](#) should look like:

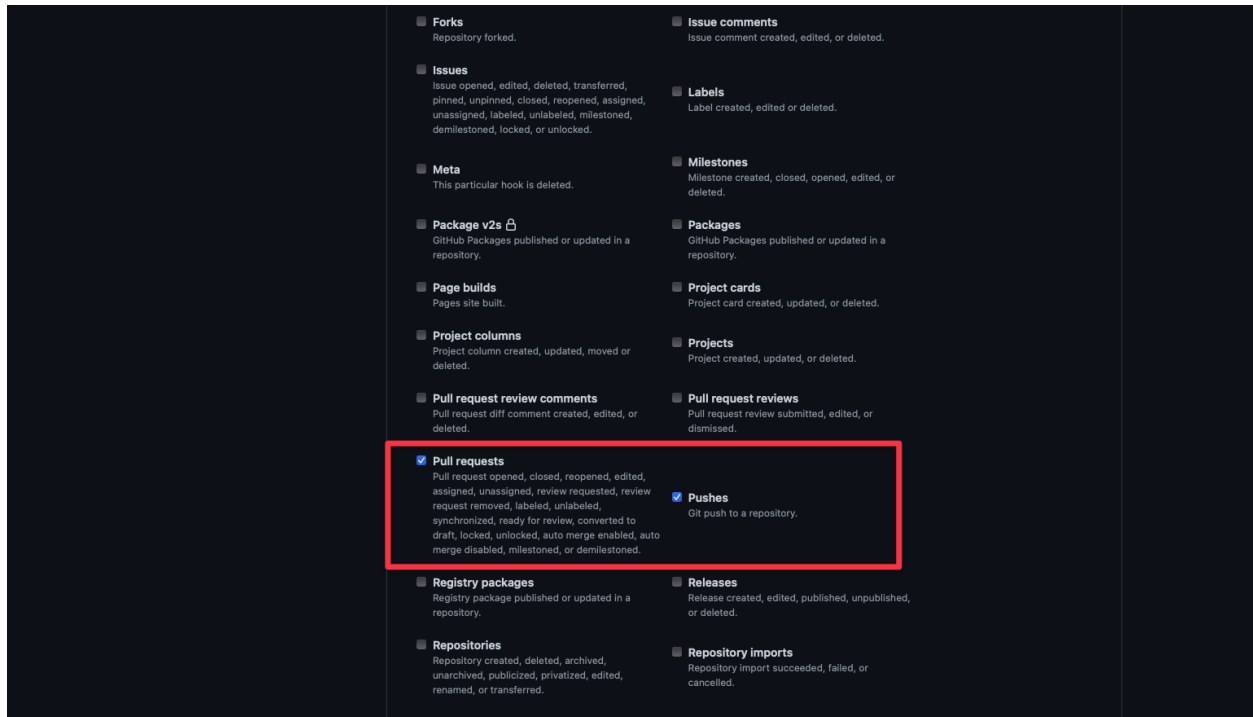


The final thing to check is the setting on the specific Github repository (under Settings/Webhooks) which should have the following 4 boxes ticked:

- Branch or tag creation
- Branch or tag deletion
- Pull requests
- Pushes

When done correctly this should look like:

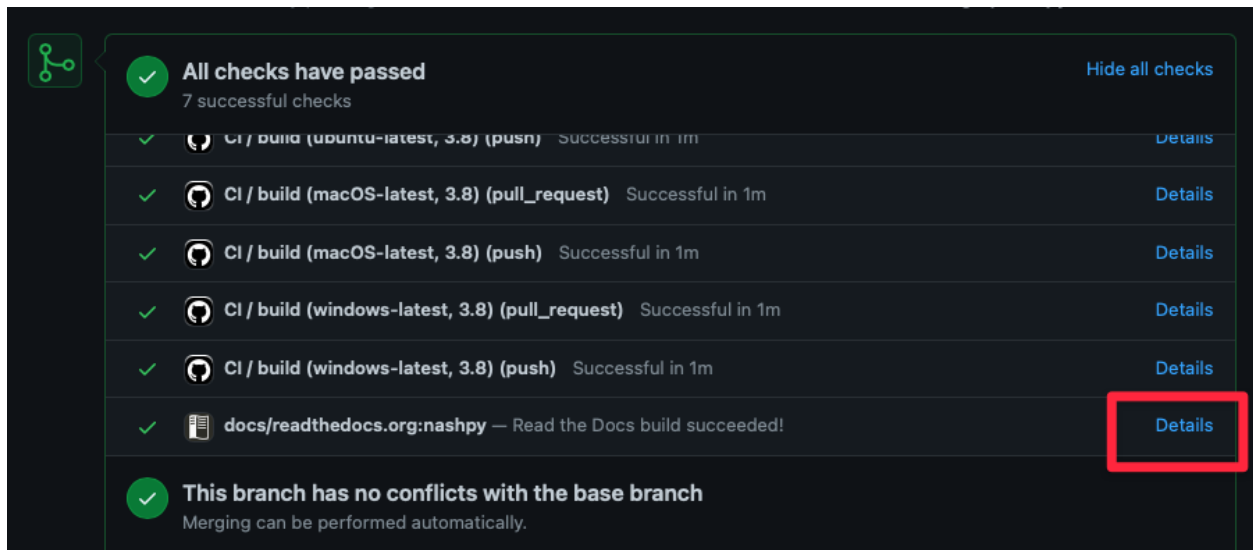




This is described here: <https://docs.readthedocs.io/en/latest/webhooks.html#github> (although note that ticking the Pull Requests box is not indicated there).

## Reviewing documentation on Pull Requests

If this is all done correctly you will be able to view your documentation during pull requests:



For example here is how the documentation looked for pull request that added this specific page of the documentation:


118

Search docs

Tutorial: building and finding the equilibrium for a simple game
How to
Reference
Discussion

Contributor documentation

Tutorial: making a contribution to the documentation
How to

Discussion

The code structure of Nashpy
Writing clean tests with pytest
Testing across environments with tox
Installing and packaging with flit
Checking code is tested with coverage
Testing with properties with hypothesis
Ensuring consistent code style with Black
Static code analysis with flake8
Checking the presence of docstrings with interrogate
Using sphinx for documentation
Ensuring the code in the documentation is correct with doctests
Using Github Actions to check automatically run all checks and

Read the Docs v: 118

Docs » Contributor documentation » Discussion » Hosting documentation on Read The Docs

Edit on GitHub

Warning

This page was created from a pull request (#118).

## Hosting documentation on Read The Docs

Read the docs is a web service that builds and hosts documentation. You can read more about the service here: <https://readthedocs.org>

The documentation contained in `docs/` is automatically built and can be viewed at <https://nashpy.readthedocs.io/en/stable/>.

## Settings

Read the docs allows you to configure your build using a `readthedocs.yml` file. This is not currently used by Nashpy.

The default version (ie when going to <https://nashpy.readthedocs.io/>) is the `stable` version which means the last release.

You can view the version of the documentation currently on the `main` branch by going to: <https://nashpy.readthedocs.io/latest>.

A powerful feature offered by Read the docs is that it can build documentation in pull requests.

## Building documentation in pull requests

To set this up you need to ensure the following things are done:

1. The repository settings on Read the docs instruct pull requests to be built.
2. The correct web hook is in place on Github.
3. The correct settings of the web hook are done on the Github repository.

## 5.4 Reference

### 5.4.1 Contributing Bibliography

This is a collection of various bibliographic items referenced in the contributor documentation.

### 5.4.2 List of contributors

- @drvinceknight
- @11michalis11
- @asinghgaba
- @katiemcgoldrick



## INDICES AND TABLES

- `genindex`
- `modindex`
- `search`



## INDICES AND TABLES

- `genindex`
- `modindex`
- `search`



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