open_spiel Documentation

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GETTING STARTED

CHAPTER

ONE

WHAT IS OPENSPIEL?

OpenSpiel is a collection of environments and algorithms for research in general reinforcement learning and search/planning in games. OpenSpiel also includes tools to analyze learning dynamics and other common evaluation metrics. Games are represented as procedural extensive-form games, with some natural extensions.

Open Spiel supports

- Single and multi-player games
- Fully observable (via observations) and imperfect information games (via information states and observations)
- Stochasticity (via explicit chance nodes mostly, even though implicit stochasticity is partially supported)
- n-player normal-form "one-shot" games and (2-player) matrix games
- Sequential and simultaneous move games
- Zero-sum, general-sum, and cooperative (identical payoff) games

Multi-language support

- C++17
- Python 3

The games and utility functions (e.g. exploitability computation) are written in C++. These are also available using pybind11 Python bindings.

The methods names are in `CamelCase` in C++ and `snake_case` in Python (e.g. `state.ApplyAction` in C++ will be `state.apply_action` in Python). See the pybind11 definition in open_spiel/python/pybind11/pyspiel.cc for the full mapping between names.

For algorithms, many are written in both languages, even if some are only available from Python.

Platforms

OpenSpiel has been tested on Linux (Debian 10 and Ubuntu 19.04), MacOS, and Windows 10 (through Windows Subsystem for Linux).

Visualization of games

There is a basic visualizer based on graphviz, see open_spiel/python/examples/treeviz_example.py.

There is an interactive viewer for OpenSpiel games called SpielViz.

CHAPTER

TWO

INSTALLATION

2.1 Python-only installation via pip

If you plan to only use the Python API, then the easiest way to install OpenSpiel is to use pip. On MacOS or Linux, simply run:

```
python3 -m pip install open_spiel
```

The binary distribution is new as of OpenSpiel 1.0.0, and is only supported on x86_64 architectures. If you encounter any problems, you can still install OpenSpiel via pip from source (see below), but please open an issue to let us know about the problem.

2.1.1 Python-only installation via pip (from source).

If the binary distribution is not an option, you can also build OpenSpiel via pip from source. CMake, Clang and Python 3 development files are required to build the Python extension. Note that we recommend Clang but g++ >= 9.2 should also work.

E.g. on Ubuntu or Debian:

```
# Check to see if you have the necessary tools for building OpenSpiel:
cmake --version        # Must be >= 3.12
clang++ --version      # Must be >= 7.0.0
python3-config --help

# If not, run this line to install them.
# On older Linux distros, the package might be called clang-9 or clang-10
sudo apt-get install cmake clang python3-dev

# On older Linux distros, the versions may be too old.
# E.g. on Ubuntu 18.04, there are a few extra steps:
# sudo apt-get install clang-10
# pip3 install cmake  # You might need to relogin to get the new CMake version
# export CXX=clang++-10

# Recommended: Install pip dependencies and run under virtualenv.
sudo apt-get install virtualenv python3-virtualenv
virtualenv -p python3 venv
source venv/bin/activate
```

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```
# Finally, install OpenSpiel and its dependencies:
python3 -m pip install --upgrade setuptools pip
python3 -m pip install --no-binary open_spiel

# To exit the virtual env
deactivate

## **IMPORTANT NOTE**. If the build fails, please first make sure you have the
## required versions of the tools above and that you followed the recommended
## option. Then, open an issue: https://github.com/deepmind/open_spiel/issues
```

Note that the build could take several minutes.

On MacOS, you can install the dependencies via `brew install cmake python3`. For clang, you need to install or upgrade XCode and install the command-line developer tools.

2.2 Installation from Source

The instructions here are for Linux and MacOS. For installation on Windows, see these separate installation instructions. On Linux, we recommend Ubuntu 20.04 (or 19.10), Debian 10, or later versions. There are known issues with default compilers on Ubuntu on 18.04, and `clang-10` must be installed separately. On MacOS, we recommend XCode 11 or newer.

For the Python API: our tests run using Python 3.8 and 3.9 on Ubuntu 20.04 and MacOS 10.15. We also test using Ubuntu 18.04 LTS with Python 3.6. So, we recommend one of these setups. If you encounter any problems on other setups, please let us know by opening an issue.

Currently there are two installation methods:

1. building from the source code and editing `PYTHONPATH`.
2. using `pip install` to build and testing using nox. A pip package to install directly does not exist yet.
3. installing via Docker.

2.3 Summary

In a nutshell:

```
./install.sh  # Needed to run once and when major changes are released.
./open_spiel/scripts/build_and_run_tests.sh # Run this every-time you need to rebuild.
```

1. Install system packages (e.g. cmake) and download some dependencies. Only needs to be run once or if you enable some new conditional dependencies (see specific section below).

   ```
   ./install.sh
   ```

2. Install your Python dependencies, e.g. in Python 3 using `virtualenv`:

   ```
   virtualenv -p python3 venv
   source venv/bin/activate
   ```

Use `deactivate` to quit the virtual environment.

`pip` should be installed once and upgraded:

```
curl https://bootstrap.pypa.io/get-pip.py -o get-pip.py
# Install pip deps as your user. Do not use the system's pip.
python3 get-pip.py
pip3 install --upgrade pip
pip3 install --upgrade setuptools testresources
```

3. This sections differs depending on the installation procedure:

   Building and testing from source

   ```
   pip3 install -r requirements.txt
   ./open_spiel/scripts/build_and_run_tests.sh
   ```

   Building and testing using PIP

   ```
   python3 -m pip install .
   pip install nox
   nox -s tests
   ```

   Optionally, use `pip install -e` to install in editable mode, which will allow you to skip this `pip install` step if you edit any Python source files. If you edit any C++ files, you will have to rerun the install command.

4. Only when building from source:

   ```
   # For the python modules in open_spiel.
   export PYTHONPATH=$PYTHONPATH:/<path_to_open_spiel>
   # For the Python bindings of Pyspiel
   export PYTHONPATH=$PYTHONPATH:/<path_to_open_spiel>/build/python
   ```

   to `./venv/bin/activate` or your `~/.bashrc` to be able to import OpenSpiel from anywhere.

To make sure OpenSpiel works on the default configurations, we do use the `python3` command and not `python` (which still defaults to Python 2 on modern Linux versions).

2.4 Installing via Docker

Please note that we don't regularly test the Docker installation. As such, it may not work at any given time. We are investigating enabling tests and proper longer-term support, but it may take some time. Until then, if you encounter a problem, please open an issue.

Option 1 (Basic, 3.13GB):

```
docker build --target base -t openspiel -f Dockerfile.base .
```

Option 2 (Slim, 2.26GB):

```
docker build --target python-slim -t openspiel -f Dockerfile.base .
```

If you are only interested in developing in Python, use the second image. You can navigate through the runtime of the container (after the build step) with:

```
docker run -it --entrypoint /bin/bash openspiel
```

Finally you can run examples using:

```
docker run openspiel python3 python/examples/matrix_game_example.py
docker run openspiel python3 python/examples/example.py
```

Option 3 (Jupyter Notebook):

Installs OpenSpiel with an additional Jupyter Notebook environment.

```
docker build -t openspiel-notebook -f Dockerfile.jupyter --rm .
docker run -it --rm -p 8888:8888 openspiel-notebook
```

More info: https://jupyter-docker-stacks.readthedocs.io/en/latest/

2.5 Running the first examples

In the `build` directory, running `examples/example` will prints out a list of registered games and the usage. Now, let's play game of Tic-Tac-Toe with uniform random players:

```
examples/example --game=tic_tac_toe
```

Once the proper Python paths are set, from the main directory (one above `build`), try these out:

```
# Similar to the C++ example:
python3 open_spiel/python/examples/example.py --game=breakthrough

# Play a game against a random or MCTS bot:
python3 open_spiel/python/examples/mcts.py --game=tic_tac_toe --player1=human --
↪player2=random
python3 open_spiel/python/examples/mcts.py --game=tic_tac_toe --player1=human --
↪player2=mcts
```

2.6 Detailed steps

2.6.1 Configuration conditional dependencies

See open_spiel/scripts/global_variables.sh to configure the conditional dependencies. See also the *Developer Guide*.

2.6.2 Installing system-wide dependencies

See open_spiel/scripts/install.sh for the required packages and cloned repositories.

2.6.3 Installing Python dependencies

Using a `virtualenv` to install python dependencies is highly recommended. For more information see: https://packaging.python.org/guides/installing-using-pip-and-virtual-environments/

Install dependencies (Python 3):

```
virtualenv -p python3 venv
source venv/bin/activate
pip3 install -r requirements.txt
```

Alternatively, although not recommended, you can install the Python dependencies system-wide with:

```
pip3 install --upgrade -r requirements.txt
```

2.6.4 Building and running tests

Make sure that the virtual environment is still activated.

By default, Clang C++ compiler is used (and potentially installed by open_spiel/scripts/install.sh).

Build and run tests (Python 3):

```
mkdir build
cd build
CXX=clang++ cmake -DPython3_EXECUTABLE=$(which python3) -DCMAKE_CXX_COMPILER=${CXX} ../
↪open_spiel
make -j$(nproc)
ctest -j$(nproc)
```

The CMake variable `Python3_EXECUTABLE` is used to specify the Python interpreter. If the variable is not set, CMake's FindPython3 module will prefer the latest version installed. Note, Python >= 3.6.0 is required.

One can run an example of a game running (in the `build/` folder):

```
./examples/example --game=tic_tac_toe
```

2.6.5 Setting Your PYTHONPATH environment variable

To be able to import the Python code (both the C++ binding `pyspiel` and the rest) from any location, you will need to add to your PYTHONPATH the root directory and the `open_spiel` directory.

When using a virtualenv, the following should be added to `<virtualenv>/bin/activate`. For a system-wide install, ddd it in your `.bashrc` or `.profile`.

```
# For the python modules in open_spiel.
export PYTHONPATH=$PYTHONPATH:/<path_to_open_spiel>
# For the Python bindings of Pyspiel
export PYTHONPATH=$PYTHONPATH:/<path_to_open_spiel>/build/python
```

CHAPTER

THREE

FIRST EXAMPLES

One can run an example of a game running (in the `build/` folder):

```
./examples/example --game=tic_tac_toe
```

Similar examples using the Python API (run from one above `build`):

```
# Similar to the C++ example:
python3 open_spiel/python/examples/example.py --game=breakthrough

# Play a game against a random or MCTS bot:
python3 open_spiel/python/examples/mcts.py --game=tic_tac_toe --player1=human --
↪player2=random
python3 open_spiel/python/examples/mcts.py --game=tic_tac_toe --player1=human --
↪player2=mcts
```

CHAPTER

FOUR

CONCEPTS

The following documentation describes the high-level concepts. Refer to the code comments for specific API descriptions.

Note that, in English, the word "game" is used for both the description of the rules (e.g. the game of chess) and for a specific instance of a playthrough (e.g. "we played a game of chess yesterday"). We will be using "playthrough" or "trajectory" to refer to the second concept.

The methods names are in `CamelCase` in C++ and `snake_case` in Python without any other difference (e.g. `state.ApplyAction` in C++ will be `state.apply_action` in Python).

4.1 The tree representation

There are mainly 2 concepts to know about (defined in open_spiel/spiel.h):

- A `Game` object contains the high level description for a game (e.g. whether it is simultaneous or sequential, the number of players, the maximum and minimum scores).
- A `State`, which describe a specifics point (e.g. a specific board position in chess, a specific set of player cards, public cards and past bets in Poker) within a trajectory.

All possible trajectories in a game are represented as a tree. In this tree, a node is a `State` and is associated to a specific history of moves for all players. Transitions are actions taken by players (in case of a simultaneous node, the transition is composed of the actions for all players).

Note that in most games, we deal with chance (i.e. any source of randomness) using a an explicit player (the "chance" player, which has id `kChancePlayerId`). For example, in Poker, the root state would just be the players without any cards, and the first transitions will be chance nodes to deal the cards to the players (in practice once card is dealt per transition).

See `spiel.h` for the full API description. For example, `game.NewInitialState()` will return the root `State`. Then, `state.LegalActions()` can be used to get the possible legal actions and `state.ApplyAction(action)` can be used to update `state` in place to play the given `action` (use `state.Child(action)` to create a new state and apply the action to it).

CHAPTER

FIVE

LOADING A GAME

The games are all implemented in C++ in open_spiel/games. Available games names can be listed using `RegisteredNames()`.

A game can be created from its name and its arguments (which usually have defaults). There are 2 ways to create a game:

- Using the game name and a structured `GameParameters` object (which, in Python, is a dictionary from argument name to compatible types (int, bool, str or a further dict). e.g. `{"players": 3}` with `LoadGame`.
- Using a string representation such as `kuhn_poker(players=3)`, giving `LoadGame(kuhn_poker(players=3))`. See `open_spiel/game_parameters.cc` for the exact syntax.

5.1 Creating sequential games from simultaneous games

It is possible to apply generic game transformations (see open_spiel/game_transforms/) such as loading an `n`-players simultaneous games into an equivalent turn-based game where simultaneous moves are encoded as `n` turns.

One can use `LoadGameAsTurnBased(game)`, or use the string representation, such as `turn_based_simultaneous_game(game=goofspiel(imp_info=True,num_cards=4,points_order=descending))`.

CHAPTER

SIX

PLAYING A TRAJECTORY

Here are for example the Python code to play one trajectory:

```
import random
import pyspiel
import numpy as np

game = pyspiel.load_game("kuhn_poker")
state = game.new_initial_state()
while not state.is_terminal():
  legal_actions = state.legal_actions()
  if state.is_chance_node():
    # Sample a chance event outcome.
    outcomes_with_probs = state.chance_outcomes()
    action_list, prob_list = zip(*outcomes_with_probs)
    action = np.random.choice(action_list, p=prob_list)
    state.apply_action(action)
  else:
    # The algorithm can pick an action based on an observation (fully observable
    # games) or an information state (information available for that player)
    # We arbitrarily select the first available action as an example.
    action = legal_actions[0]
    state.apply_action(action)
```

See open_spiel/python/examples/example.py for a more thorough example that covers more use of the core API.

See open_spiel/python/examples/playthrough.py (and open_spiel/python/algorithms/generate_playthrough.py) for an richer example generating a playthrough and printing all available information.

In C++, see open_spiel/examples/example.cc which generates random trajectories.

CHAPTER

SEVEN

AVAILABLE GAMES

.: thoroughly-tested. In many cases, we verified against known values and/or reproduced results from papers.

~: implemented but lightly tested.

X: known issues (see code for details).

7.1 Details

7.1.1 Backgammon

- Players move their pieces through the board based on the rolls of dice.
- Idiosyncratic format.
- Traditional game.
- Non-deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.2 Battleship

- Players place ships and shoot at each other in turns.
- Pieces on a board.
- Traditional game.
- Deterministic.
- Imperfect information.
- 2 players.
- Good for correlated equilibria.
- Farina et al. '19, Correlation in Extensive-Form Games: Saddle-Point Formulation and Benchmarks. Based on the original game (wikipedia)

7.1.3 Blackjack

- Simplified version of blackjack, with only HIT/STAND moves.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 1 player.
- Wikipedia

7.1.4 Breakthrough

- Simplified chess using only pawns.
- Pieces on a grid.
- Modern game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.5 Bridge

- A card game where players compete in pairs.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 4 players.
- Wikipedia

7.1.6 (Uncontested) Bridge bidding

- Players score points by forming specific sets with the cards in their hands.
- Card game.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Wikipedia

7.1.7 Catch

- Agent must move horizontally to 'catch' a descending ball. Designed to test basic learning.
- Agent on a grid.
- Research game.
- Non-deterministic.
- Perfect information.
- 1 players.
- Mnih et al. 2014, Recurrent Models of Visual Attention,Osband et al '19, Behaviour Suite for Reinforcement Learning, Appendix A

7.1.8 Cliff Walking

- Agent must find goal without falling off a cliff. Designed to demonstrate exploration-with-danger.
- Agent on a grid.
- Research game.
- Deterministic.
- Perfect information.
- 1 players.
- Sutton et al. '18, page 132

7.1.9 Clobber

- Simplified checkers, where tokens can capture neighbouring tokens. Designed to be amenable to combinatorial analysis.
- Pieces on a grid.
- Research game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.10 Coin Game

- Agents must collect their and their collaborator's tokens while avoiding a third kind of token. Designed to test divining of collaborator's intentions
- Agents on a grid.
- Research game.
- Non-deterministic.
- Perfect, incomplete information.

- 2 players.
- Raileanu et al. '18, Modeling Others using Oneself in Multi-Agent Reinforcement Learning

7.1.11 Connect Four

- Players drop tokens into columns to try and form a pattern.
- Tokens on a grid.
- Traditional game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.12 Cooperative Box-Pushing

- Agents must collaborate to push a box into the goal. Designed to test collaboration.
- Agents on a grid.
- Research game.
- Deterministic.
- Perfect information.
- 2 players.
- Seuken & Zilberstein '12, Improved Memory-Bounded Dynamic Programming for Decentralized POMDPs

7.1.13 Chess

- Players move pieces around the board with the goal of eliminating the opposing pieces.
- Pieces on a grid.
- Traditional game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.14 Dark Hex

- Hex, except the opponent's tokens are hidden. (Imperfect-information version)
- Uses tokens on a hex grid.
- Research game.
- Deterministic.
- Imperfect information.
- 2 players.

7.1.15 Deep Sea

- Agent must explore to find reward (first version) or penalty (second version). Designed to test exploration.
- Agent on a grid.
- Research game.
- Deterministic.
- Perfect information.
- 1 players.
- Osband et al. '17, Deep Exploration via Randomized Value Functions

7.1.16 First-price Sealed-Bid Auction

- Agents submit bids simultaneously; highest bid wins, and that's the price paid.
- Idiosyncratic format.
- Research game.
- Non-deterministic.
- Imperfect, incomplete information.
- 2-10 players.
- Wikipedia

7.1.17 Gin Rummy

- Players score points by forming specific sets with the cards in their hands.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Wikipedia

7.1.18 Go

- Players place tokens on the board with the goal of encircling territory.
- Tokens on a grid.
- Traditional game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.19 Goofspiel

- Players bid with their cards to win other cards.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 2-10 players.
- Wikipedia

7.1.20 Hanabi

- Players can see only other player's pieces, and everyone must cooperate to win.
- Idiosyncratic format.
- Modern game.
- Non-deterministic.
- Imperfect information.
- 2-5 players.
- Wikipedia and Bard et al. '19, The Hanabi Challenge: A New Frontier for AI Research
- Implemented via Hanabi Learning Environment

7.1.21 Havannah

- Players add tokens to a hex grid to try and form a winning structure.
- Tokens on a hex grid.
- Modern game.
- Deterministic.
- Perfect information.
- 2 players.

- Wikipedia

7.1.22 Hearts

- A card game where players try to avoid playing the highest card in each round.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 3-6 players.
- Wikipedia

7.1.23 Hex

- Players add tokens to a hex grid to try and link opposite sides of the board.
- Uses tokens on a hex grid.
- Modern game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia
- Hex, the full story by Ryan Hayward and Bjarne Toft

7.1.24 Kriegspiel

- Chess with opponent's pieces unknown. Illegal moves have no effect - it remains the same player's turn until they make a legal move.
- Traditional chess variant, invented by Henry Michael Temple in 1899.
- Deterministic.
- Imperfect information.
- 2 players.
- Wikipedia
- Monte Carlo tree search in Kriegspiel
- Game-Tree Search with Combinatorially Large Belief States, Parker 2005

7.1.25 Kuhn poker

- Simplified poker amenable to game-theoretic analysis.
- Cards with bidding.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Wikipedia

7.1.26 Laser Tag

- Agents see a local part of the grid, and attempt to tag each other with beams.
- Agents on a grid.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Leibo et al. '17, Lanctot et al. '17

7.1.27 Leduc poker

- Simplified poker amenable to game-theoretic analysis.
- Cards with bidding.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Southey et al. '05, Bayes' bluff: Opponent modelling in poker

7.1.28 Lewis Signaling

- Receiver must choose an action dependent on the sender's hidden state. Designed to demonstrate the use of conventions.
- Idiosyncratic format.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.

- Wikipedia

7.1.29 Liar's Dice

- Players bid and bluff on the state of all the dice together, given only the state of their dice.
- Dice with bidding.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Wikipedia

7.1.30 Markov Soccer

- Agents must take the ball to their goal, and can 'tackle' the opponent by predicting their next move.
- Agents on a grid.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Littman '94, Markov games as a framework for multi-agent reinforcement learning,He et al. '16, Opponent Modeling in Deep Reinforcement Learning

7.1.31 Matching Pennies (Three-player)

- Players must predict and match/oppose another player. Designed to have an unstable Nash equilibrium.
- Idiosyncratic format.
- Research game.
- Deterministic.
- Imperfect information.
- 3 players.
- "Three problems in learning mixed-strategy Nash equilibria"

7.1.32 Mean Field Game : routing

- Representative player chooses at each nodes where they go. They has an origin, a destination and a departure time and choose their route to minimize their travel time. Time spent on each link is a function of the distribution of players on the link when the player reaches the link.
- Network with choice of route.
- Research game.
- Mean-field (with a unique player).
- Explicit stochastic game (only for initial node).
- Perfect information.
- Cabannes et. al. '21, Solving N-player dynamic routing games with congestion: a mean field approach.

7.1.33 Negotiation

- Agents with different utilities must negotiate an allocation of resources.
- Idiosyncratic format.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- Lewis et al. '17, Cao et al. '18

7.1.34 Oh Hell

- A card game where players try to win exactly a declared number of tricks.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 3-7 players.
- Wikipedia

7.1.35 Oshi-Zumo

- Players must repeatedly bid to push a token off the other side of the board.
- Idiosyncratic format.
- Traditional game.
- Deterministic.
- Imperfect information.
- 2 players.

- Buro, 2004. Solving the oshi-zumo game Bosansky et al. '16, Algorithms for Computing Strategies in Two-Player Simultaneous Move Games

7.1.36 Oware

- Players redistribute tokens from their half of the board to capture tokens in the opponent's part of the board.
- Idiosyncratic format.
- Traditional game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.37 Pentago

- Players place tokens on the board, then rotate part of the board to a new orientation.
- Uses tokens on a grid.
- Modern game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.38 Phantom Tic-Tac-Toe

- Tic-tac-toe, except the opponent's tokens are hidden. Designed as a simple, imperfect-information game.
- Uses tokens on a grid.
- Research game.
- Deterministic.
- Imperfect information.
- 2 players.
- Auger '11, Multiple Tree for Partially Observable Monte-Carlo Tree Search,Lisy '14, Alternative Selection Functions for Information Set Monte Carlo Tree Search, Lanctot '13

7.1.39 Pig

- Each player rolls a dice until they get a 1 or they 'hold'; the rolled total is added to their score.
- Dice game.
- Traditional game.
- Non-deterministic.
- Perfect information.
- 2-10 players.
- Wikipedia

7.1.40 Poker (Hold 'em)

- Players bet on whether their hand of cards plus some communal cards will form a special set.
- Cards with bidding.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 2-10 players.
- Wikipedia
- Implemented via ACPC.

7.1.41 Quoridor

- Each turn, players can either move their agent or add a small wall to the board.
- Idiosyncratic format.
- Modern game.
- Deterministic.
- Perfect information.
- 2-4 players.
- Wikipedia

7.1.42 Reconnaissance Blind Chess

- Chess with opponent's pieces unknown, with sensing moves.
- Chess variant, invented by John Hopkins University Applied Physics Lab. Used in NeurIPS competition and Hidden Information Game Competition.
- Deterministic.
- Imperfect information.
- 2 players.

- JHU APL Main site
- Markowitz et al. '18, On the Complexity of Reconnaissance Blind Chess
- Newman et al. '16, Reconnaissance blind multi-chess: an experimentation platform for ISR sensor fusion and resource management

7.1.43 Routing game

- Players choose at each nodes where they go. They have an origin, a destination and a departure time and choose their route to minimize their travel time. Time spent on each link is a function of the number of players on the link when the player reaches the link.
- Network with choice of route.
- Research game.
- Simultaneous.
- Deterministic.
- Perfect information.
- Any number of players.
- Cabannes et. al. '21, Solving N-player dynamic routing games with congestion: a mean field approach.

7.1.44 Sheriff

- Bargaining game.
- Deterministic.
- Imperfect information.
- 2 players.
- Good for correlated equilibria.
- Farina et al. '19, Correlation in Extensive-Form Games: Saddle-Point Formulation and Benchmarks.
- Based on the board game "Sheriff of Nottingham" (bbg)

7.1.45 Slovenian Tarok

- Trick-based card game with bidding.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 3-4 players.
- Wikipedia
- Luštrek et al. 2003, A program for playing Tarok

7.1.46 Skat (simplified bidding)

- Each turn, players bid to compete against the other two players.
- Cards with bidding.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 3 players.
- Wikipedia

7.1.47 Solitaire (K+)

- A single-player card game.
- Card game.
- Traditional game.
- Non-deterministic.
- Imperfect information.
- 1 players.
- Wikipedia and Bjarnason et al. '07, Searching solitaire in real time

7.1.48 Tic-Tac-Toe

- Players place tokens to try and form a pattern.
- Uses tokens on a grid.
- Traditional game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

7.1.49 Tiny Bridge

- Simplified Bridge with fewer cards and tricks.
- Cards with bidding.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2, 4 players.
- See implementation for details.

7.1.50 Tiny Hanabi

- Simplified Hanabi with just two turns.
- Idiosyncratic format.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2-10 players.
- Foerster et al 2018, Bayesian Action Decoder for Deep Multi-Agent Reinforcement Learning

7.1.51 Trade Comm

- Players with different utilities and items communicate and then trade.
- Idiosyncratic format.
- Research game.
- Non-deterministic.
- Imperfect information.
- 2 players.
- A simple emergent communication game based on trading.

7.1.52 Y

- Players place tokens to try and connect sides of a triangular board.
- Tokens on hex grid.
- Modern game.
- Deterministic.
- Perfect information.
- 2 players.
- Wikipedia

CHAPTER

EIGHT

-RANK

OpenSpiel now supports using Alpha-Rank ("-Rank: Multi-Agent Evaluation by Evolution", 2019) for both single-population (symmetric) and multi-population games. Specifically, games can be specified via payoff tables (or tensors for the >2 players case) as well as Heuristic Payoff Tables (HPTs).

The following presents several typical use cases for Alpha-Rank. For an example complete python script, refer to open_spiel/python/egt/examples/alpharank_example.py.

8.1 Importing the Alpha-Rank module

```
from open_spiel.python.egt import alpharank
from open_spiel.python.egt import alpharank_visualizer
```

8.2 Running Alpha-Rank on various games

8.2.1 Example: symmetric 2-player game rankings

In this example, we run Alpha-Rank on a symmetric 2-player game (Rock-Paper-Scissors), computing and outputting the rankings in a tabular format. We demonstrate also the conversion of standard payoff tables to Heuristic Payoff Tables (HPTs), as both are supported by the ranking code.

```
# Load the game
game = pyspiel.load_matrix_game("matrix_rps")
payoff_tables = utils.game_payoffs_array(game)

# Convert to heuristic payoff tables
payoff_tables= [heuristic_payoff_table.from_matrix_game(payoff_tables[0]),
                heuristic_payoff_table.from_matrix_game(payoff_tables[1].T)]

# Check if the game is symmetric (i.e., players have identical strategy sets
# and payoff tables) and return only a single-player's payoff table if so.
# This ensures Alpha-Rank automatically computes rankings based on the
# single-population dynamics.
_, payoff_tables = utils.is_symmetric_matrix_game(payoff_tables)

# Compute Alpha-Rank
(rhos, rho_m, pi, num_profiles, num_strats_per_population) = alpharank.compute(
    payoff_tables, alpha=1e2)
```

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```
# Report results
alpharank.print_results(payoff_tables, payoffs_are_hpt_format, pi=pi)
```

Output

```
Agent        Rank         Score
-----        ----         -----
0            1            0.33
1            1            0.33
2            1            0.33
```

8.2.2 Example: multi-population game rankings

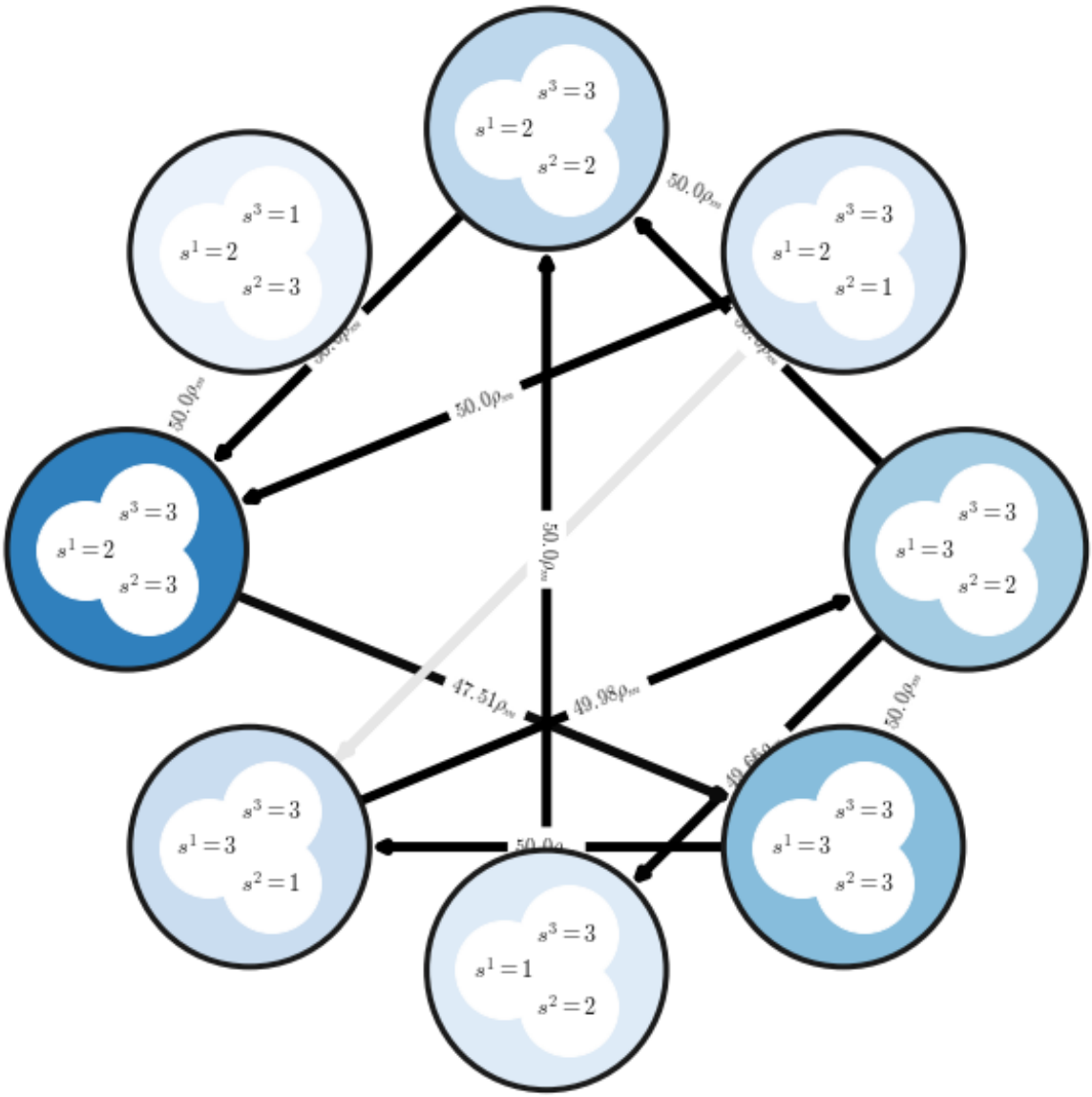
The next example demonstrates computing Alpha-Rank on an asymmetric 3-player meta-game, constructed by computing payoffs for Kuhn poker agents trained via extensive-form fictitious play (XFP). Here we use a helper function, `compute_and_report_alpharank`, which internally conducts the pre-processing and visualization shown in the previous example.

```
# Load the game
payoff_tables = alpharank_example.get_kuhn_poker_data(num_players=3)

# Helper function for computing & reporting Alpha-Rank outputs
alpharank.compute_and_report_alpharank(payoff_tables, alpha=1e2)
```

Output

```
Agent        Rank         Score
-----        ----         -----
(2,3,3)      1            0.22
(3,3,3)      2            0.14
(3,2,3)      3            0.12
(2,2,3)      4            0.09
(3,1,3)      5            0.08
(2,1,3)      6            0.05
(1,2,3)      7            0.04
(2,3,1)      8            0.02
...          ...          ...
```



8.3 Visualizing and reporting results

This section provides details on various methods used for reporting the final Alpha-Rank results.

8.3.1 Basic Ranking Outputs

The final rankings computed can be printed in a tabular manner using the following interface:

```
alpharank.print_results(payoff_tables, payoffs_are_hpt_format, pi=pi)
```

Output

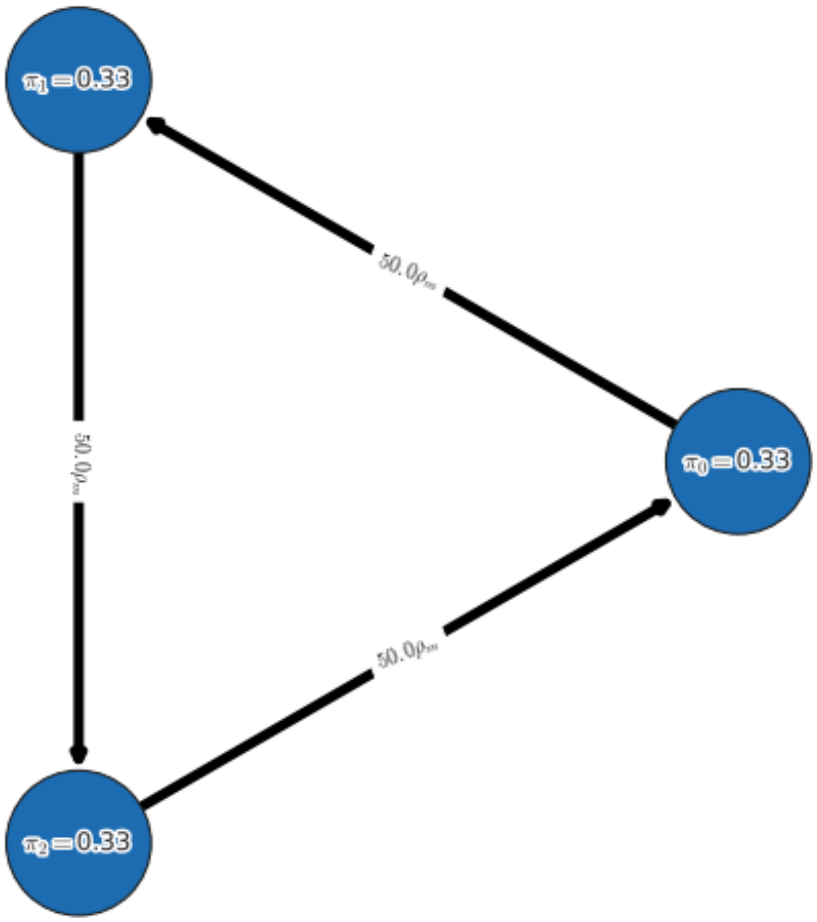
```
Agent        Rank         Score
-----        ----         -----
0            1            0.33
1            1            0.33
2            1            0.33
```

8.3.2 Markov Chain Visualization

One may visualize the Alpha-Rank Markov transition matrix as follows:

```
m_network_plotter = alpharank_visualizer.NetworkPlot(payoff_tables, rhos,
                                                     rho_m, pi,strat_labels,
                                                     num_top_profiles=8)
m_network_plotter.compute_and_draw_network()
```

Output

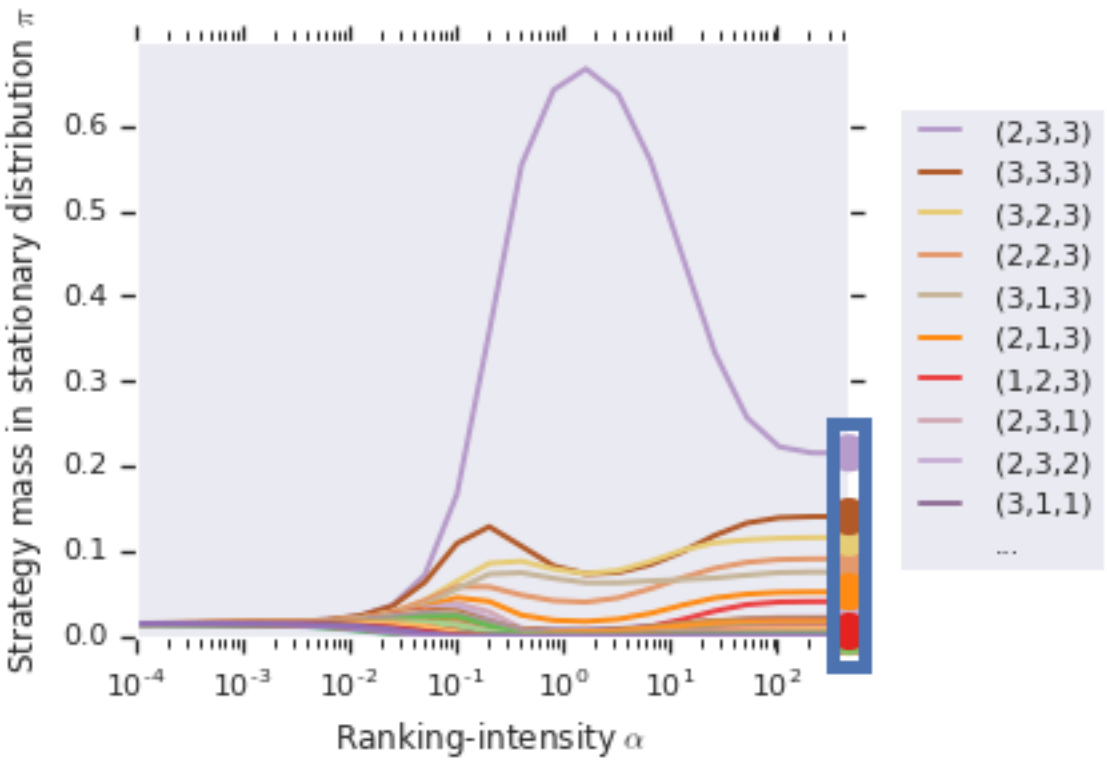


8.3.3 Alpha-sweep plots

One may choose to conduct a sweep over the ranking-intensity parameter, alpha (as opposed to choosing a fixed alpha). This is, in general, useful for general games where bounds on payoffs may be unknown, and where the ranking computed by Alpha-Rank should use a sufficiently high value of alpha (to ensure correspondence to the underlying Markov-Conley chain solution concept). In such cases, the following interface can be used to both visualize the sweep and obtain the final rankings computed:

```
alpharank.sweep_pi_vs_alpha(payoff_tables, visualize=True)
```

Output


Strategy mass in stationary distribution π
0.0
0.1
0.2
0.3
0.4
0.5
0.6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Ranking-intensity α
(2,3,3)
(3,3,3)
(3,2,3)
(2,2,3)
(3,1,3)
(2,1,3)
(1,2,3)
(2,3,1)
(2,3,2)
(3,1,1)
...

CHAPTER

NINE

JULIA OPENSPIEL

We also provide a Julia wrapper for the OpenSpiel project. Most APIs are aligned with those in Python (some are extended to accept `AbstractArray` and/or keyword arguments for convenience). See `spiel.h` for the full API description.

9.1 Install

For general usage, you can install this package in the Julia REPL with `] add OpenSpiel`. Note that this method only supports the Linux platform and ACPC is not included. For developers, you need to follow the instructions bellow to install this package:

1. Install Julia and dependencies. Edit `open_spiel/scripts/global_variables.sh` and set `OPEN_SPIELOPEN_SPIEL_BUILD_WITH_JULIA=ON` (you may also turn on other options as you wish). Then run `./install.sh`. If you already have Julia installed on your system, make sure that it is visible in your terminal and its version is v1.3 or later. Otherwise, Julia v1.3.1 will be automatically installed in your home dir and a soft link will be created at `/usr/local/bin/julia`.
2. Build and run tests

```
./open_spiel/scripts/build_and_run_tests.sh
```

3. Install `] dev ./open_spiel/julia` (run in Julia REPL).

9.2 Known Problems

1. There's a problem when building this package on Mac with XCode v11.4 or above (see discussions here). To fix it, you need to install the latest `libcxxwrap` by following the instructions here after running `./install.sh`. Then make sure that the result of `julia --project=./open_spiel/julia -e 'using CxxWrap; print(CxxWrap.prefix_path())'` points to the newly built `libcxxwrap`. After that, build and install this package as stated above.

9.3 Example

Here we demonstrate how to use the Julia API to play one game:

```
using OpenSpiel

# Here we need the StatsBase package for weighted sampling
using Pkg
Pkg.add("StatsBase")
using StatsBase

function run_once(name)
    game = load_game(name)
    state = new_initial_state(game)
    println("Initial state of game[$(name)] is:\n$(state)")

    while !is_terminal(state)
        if is_chance_node(state)
            outcomes_with_probs = chance_outcomes(state)
            println("Chance node, got $(length(outcomes_with_probs)) outcomes")
            actions, probs = zip(outcomes_with_probs...)
            action = actions[sample(weights(collect(probs)))]
            println("Sampled outcome: $(action_to_string(state, action))")
            apply_action(state, action)
        elseif is_simultaneous_node(state)
            chosen_actions = [rand(legal_actions(state, pid-1)) for pid in 1:num_
↪players(game)]  # in Julia, indices start at 1
            println("Chosen actions: $([action_to_string(state, pid-1, action) for (pid,␣
↪action) in enumerate(chosen_actions)])")
            apply_action(state, chosen_actions)
        else
            action = rand(legal_actions(state))
            println("Player $(current_player(state)) randomly sampled action: $(action_
↪to_string(state, action))")
            apply_action(state, action)
        end
        println(state)
    end
    rts = returns(state)
    for pid in 1:num_players(game)
        println("Utility for player $(pid-1) is $(rts[pid])")
    end
end

run_once("tic_tac_toe")
run_once("kuhn_poker")
run_once("goofspiel(imp_info=True,num_cards=4,points_order=descending)")
```

9.4 Q&A

1. What is `StdVector`?

   `StdVector` is introduced in CxxWrap.jl recently. It is a wrapper of `std::vector` in the C++ side. Since that it is a subtype of `AbstractVector`, most functions should just work out of the box.

2. `0-based` or `1-based`?

   As this package is a low-level wrapper of OpenSpiel C++, most APIs are zero-based: for instance, the `Player` id starts from zero. But note that some bridge types, like `StdVector`, implicitly convert between indexing conventions, so APIs that use `StdVector` are one-based.

3. I can't find the `xxx` function/type in the Julia wrapper/The program exits unexpectedly.

   Although most of the functions and types should be exported, there is still a chance that some APIs are not well tested. So if you encounter any error, please do not hesitate to create an issue.

CHAPTER

TEN

THE CODE STRUCTURE

Generally speaking, the directories directly under `open_spiel` are C++ (except for `integration_tests` and `python`). A similar structure is available in `open_spiel/python`, containing the Python equivalent code.

Some top level directories are special:

- `open_spiel/integration_tests`: Generic (python) tests for all the games.
- `open_spiel/tests`: The C++ common test utilities.
- `open_spiel/scripts`: The scripts useful for development (building, running tests, etc).

For example, we have for C++:

- `open_spiel/`: Contains the game abstract C++ API.
- `open_spiel/games`: Contains the games C++ implementations.
- `open_spiel/algorithms`: The C++ algorithms implemented in OpenSpiel.
- `open_spiel/examples`: The C++ examples.
- `open_spiel/tests`: The C++ common test utilities.

For Python you have:

- `open_spiel/python/examples`: The Python examples.
- `open_spiel/python/algorithms/`: The Python algorithms.

CHAPTER

ELEVEN

C++ AND PYTHON IMPLEMENTATIONS.

Some objects (e.g. `Policy`, `CFRSolver`, `BestResponse`) are available both in C++ and Python. The goal is to be able to use C++ objects in place of Python objects for most of the cases. In particular, for the objects that are well supported, expect to have in the test for the Python object, a test checking that both the C++ and the Python implementation behave the same.

CHAPTER

TWELVE

ADDING A GAME

We describe here only the simplest and fastest way to add a new game. It is ideal to first be aware of the general API (see `spiel.h`).

1. Choose a game to copy from in `games/` (or `python/games/`). Suggested games: Tic-Tac-Toe and Breakthrough for perfect information without chance events, Backgammon or Pig for perfect information games with chance events, Goofspiel and Oshi-Zumo for simultaneous move games, and Leduc poker and Liar's dice for imperfect information games. For the rest of these steps, we assume Tic-Tac-Toe.
2. Copy the header and source: `tic_tac_toe.h`, `tic_tac_toe.cc`, and `tic_tac_toe_test.cc` to `new_game.h`, `new_game.cc`, and `new_game_test.cc` (or `tic_tac_toe.py` and `tic_tac_toe_test.py`).
3. Configure CMake:
   - If you are working with C++: add the new game's source files to `games/CMakeLists.txt`.
   - If you are working with C++: add the new game's test target to `games/CMakeLists.txt`.
   - If you are working with Python: add the test to `python/CMakeLists.txt` and import it in `python/games/__init__.py`
4. Update boilerplate C++/Python code:
   - In `new_game.h`, rename the header guard at the the top and bottom of the file.
   - In the new files, rename the inner-most namespace from `tic_tac_toe` to `new_game`.
   - In the new files, rename `TicTacToeGame` and `TicTacToeState` to `NewGameGame` and `NewGameState`.
   - At the top of `new_game.cc`, change the short name to `new_game` and include the new game's header.
5. Update Python integration tests:
   - Add the short name to the list of expected games in `python/tests/pyspiel_test.py`.
6. You should now have a duplicate game of Tic-Tac-Toe under a different name. It should build and the test should run, and can be verified by rebuilding and running the example `examples/example --game=new_game`.
7. Now, change the implementations of the functions in `NewGameGame` and `NewGameState` to reflect your new game's logic. Most API functions should be clear from the game you copied from. If not, each API function that is overridden will be fully documented in superclasses in `spiel.h`.
8. Once done, rebuild and rerun the tests to ensure everything passes (including your new game's test!).
9. Add a playthrough file to catch regressions:
   - Run `./open_spiel/scripts/generate_new_playthrough.sh new_game` to generate a random game, to be used by integration tests to prevent any regression. `open_spiel/integration_tests/playthrough_test.py` will automatically load the playthroughs and compare them to newly generated playthroughs.

- If you have made a change that affects playthroughs, run `./scripts/regenerate_playthroughs.sh` to update them.

CHAPTER

THIRTEEN

CONDITIONAL DEPENDENCIES

The goal is to make it possible to optionally include external dependencies and build against them. The setup was designed to met the following needs:

- **Single source of truth**: We want a single action to be sufficient to manage the conditional install and build. Thus, we use bash environment variables, that are read both by the install script (`install.sh`) to know whether we should clone the dependency, and by CMake to know whether we should include the files in the target. Tests can also access the bash environment variable.
- **Light and safe defaults**: By default, we exclude the dependencies to diminish install time and compilation time. If the bash variable is unset, we download the dependency and we do not build against it.
- **Respect the user-defined values**: The `global_variables.sh` script, which is included in all the scripts that needs to access the constant values, do not override the constants but set them if and only if they are undefined. This respects the user-defined values, e.g. on their `.bashrc` or on the command line.

When you add a new conditional dependency, you need to touch:

- the root CMakeLists.txt to add the option, with an OFF default
- add the option to `scripts/global_variables.sh`
- change `install.sh` to make sure the dependency is installed
- use constructs like `if (${OPEN_SPIEL_OPEN_SPIEL_BUILD_WITH_HANABI})` in CMake to optionally add the targets to build.

CHAPTER

FOURTEEN

DEBUGGING TOOLS

For complex games it may be tricky to get all the details right. Reading through the playthrough You can visualize small game trees using open_spiel/python/examples/treeviz_example.py or for large games there is an interactive viewer for OpenSpiel games called SpielViz.

CHAPTER

FIFTEEN

GUIDELINES

Above all, OpenSpiel is designed to be easy to install and use, easy to understand, easy to extend ("hackable"), and general/broad. OpenSpiel is built around two major important design criteria:

- **Keep it simple.** Simple choices are preferred to more complex ones. The code should be readable, usable, extendable by non-experts in the programming language(s), and especially to researchers from potentially different fields. OpenSpiel provides reference implementations that are used to learn from and prototype with, rather than fully-optimized / high-performance code that would require additional assumptions (narrowing the scope / breadth) or advanced (or lower-level) language features.
- **Keep it light.** Dependencies can be problematic for long-term compatibility, maintenance, and ease-of- use. Unless there is strong justification, we tend to avoid introducing dependencies to keep things easy to install and more portable.

CHAPTER

SIXTEEN

SUPPORT EXPECTATIONS

We, the OpenSpiel authors, definitely engage in supporting the community. As it can be time-consuming, we try to find a good balance between ensuring we are responsive and being able to continue to do our day-to-day work and research.

Generally speaking, if you are willing to get a specific feature implemented, the most effective way is to implement it and send a Pull Request. For large changes, or ones involving design decisions, open a bug to check the idea is ok first.

The higher the quality, the easier it will be to be accepted. For instance, following the C++ Google style guide and Python Google style guide will help with the integration.

As examples, MacOS support, Window support, example improvements, various bug-fixes or new games has been straightforward to be included and we are very thankful to everyone who helped.

16.1 Bugs

We aim to answer bugs at a reasonable pace, several times a week. However, for bugs involving large changes (e.g. adding new games, adding public state supports) we cannot commit to implementing it and encourage everyone to contribute directly.

16.2 Pull requests

You can expect us to answer/comment back and you will know from the comment if it will be merged as is or if it will need additional work.

For pull requests, they are merged as batches to be more efficient, at least every two weeks (for bug fixes, it will likely be faster to be integrated). So you may need to wait a little after it has been approved to actually see it merged.

CHAPTER

SEVENTEEN

ROADMAP AND CALL FOR CONTRIBUTIONS

Contributions to this project must be accompanied by a Contributor License Agreement (CLA). See CONTRIBUTING.md for the details.

Here, we outline our intentions for the future, giving an overview of what we hope to add over the coming years. We also suggest a number of contributions that we would like to see, but have not had the time to add ourselves.

Before making a contribution to OpenSpiel, please read the guidelines. We also kindly request that you contact us before writing any large piece of code, in case (a) we are already working on it and/or (b) it's something we have already considered and may have some design advice on its implementation. Please also note that some games may have copyrights which might require legal approval. Otherwise, happy hacking!

The following list is both a Call for Contributions and an idealized road map. We certainly are planning to add some of these ourselves (and, in some cases already have implementations that were just not tested well enough to make the release!). Contributions are certainly not limited to these suggestions!

- **AlphaZero**. An implementation of AlphaZero. Preferably, an implementation that closely matches the pseudocode provided in the paper.
- **Checkers / Draughts**. This is a classic game and an important one in the history of game AI ("Checkers is solved").
- **Chinese Checkers / Halma**. Chinese Checkers is the canonical multiplayer (more than two player) perfect information game. Currently, OpenSpiel does not contain any games in this category.
- **Correlated Equilibrium**. There is a simple linear program that can be solved to find a correlated equilibrium in a normal-form game (see Section 4.6 of Shoham & Leyton-Brown '09). This would be a nice complement to the existing solving of zero-sum games in `python/algorithms/lp_solver.py`.
- **Deep TreeStrap**. An implementation of TreeStrap (see Bootstrapping from Game Tree Search), except with a DQN-like replay buffer, storing value targets obtained from minimax searches. We have an initial implementation, but it is not yet ready for release. We also hope to support PyTorch for this algorithm as well.
- **Double Neural Counterfactual Regret Minimization**. This is a technique similar to Regression CFR that uses a robust sampling technique and a new network architecture that predicts both the cumulative regret *and* the average strategy. (Ref)
- **Differentiable Games and Algorithms**. For example, Symplectic Gradient Adjustment (Ref).
- **Emergent Communication Algorithms**. For example, RIAL and/or DIAL and CommNet.
- **Emergent Communication Games**. Referential games such as the ones in Ref1, Ref2, Ref3.
- **Extensive-form Evolutionary Dynamics**. There have been a number of different evolutionary dynamics suggested for the sequential games, such as state-coupled replicator dynamics (Ref), sequence-form replicator dynamics (Ref1, Ref2), sequence-form Q-learning (Ref), and the logit dynamics (Ref).
- **Game Query/Customization API**. There is no easy way to retrieve game-specific information since all the algorithms interact with the general API only. But sometimes this is necessary, such as when a technique is

being tested or specialized on one game. There is also no way to change the representation of observations without changing the implementation of the game. This module would expose game-specific information via queries and customization without having to hack the game implementations directly.

- **General Games Wrapper**. There are several general game engine languages and databases of general games that currently exist, for example within the general game-playing project and the Ludii General Game System. A very nice addition to OpenSpiel would be a game that interprets games represented in these languages and presents them as OpenSpiel games. This could lead to the potential of evaluating learning agents on hundreds to thousands of games.
- **Go API**. We currently have a prototype Go API similar to the Python API. It is exposed using cgo via a C API much like the CFFI Python bindings from the Hanabi Learning Environment. It is not currently ready for release, but should be possible in a future update.
- **Grid Worlds**. There are currently four grid world games in OpenSpiel: Markov soccer, the coin game, cooperative box-pushing, and laser tag. There could be more, especially ones that have been commonly used in multiagent RL. Also, the current grid worlds can be improved (they all are fully-observable).
- **Heuristic Payoff Tables and Empirical Game-Theoretic Analysis**. Methods found in Analyzing Complex Strategic Interactions in Multi-Agent Systems, Methods for Empirical Game-Theoretic Analysis, An evolutionary game-theoretic analysis of poker strategies, Ref4.
- **Monte Carlo Tree Search Solver**. General enhancement to Monte Carlo tree search, backpropagate proven wins and loses as far up as possible. See Winands el al. '08.
- **Minimax-Q and other classic MARL algorithms**. Minimax-Q is a classic multiagent reinforcement learning algorithm (Markov games as a framework for multi-agent reinforcement learning. Other classic algorithms, such as Correlated Q-learning, NashQ, and Friend-or-Foe Q-learning (Friend-or-foe q-learning in general-sum games would be welcome as well.
- **Nash Averaging**. An evaluation tool first described in Re-evaluating Evaluation.
- **Negotiation Games**. A game similar to the negotiation game presented in Ref1, Ref2. Also, Colored Trails (Modeling how Humans Reason about Others with Partial Information, Metastrategies in the coloredtrails game.
- **Opponent Modeling / Shaping Algorithms**. For example, DRON, LOLA, and Stable Opponent Shaping.
- **PyTorch**. While we officially support Tensorflow, the API is agnostic to the library that is used for learning. We would like to have some examples and support for PyTorch as well in the future.
- **Repeated Games**. There is currently no explicit support for repeated games. Supporting repeated games as one sequential game could be useful for application of RL algorithms. This could take the form of another game transform, where intermediate rewards are given for game instances. It could also support random termination, found in the literature and tournaments.
- **Sequential Social Dilemmas**. Sequential social dilemmas, such as the ones found in Ref1, Ref2 . Wolfpack could be a nice one, since pursuit-evasion games have been common in the literature (Ref). Also the coin games from Ref1 and Ref2, and Clamity, Cleanup and/or Harvest from Ref3 Ref4.
- **Single-Agent Games and Environments**. There are only a few single-player games or traditional RL environments (Klondike solitaire, catch, Deep Sea), despite the API supporting the use case. Games that fit into the category, such as Morpion, Blackjack, and traditional RL environments such as grid worlds and others used to learn RL would be welcome contributions.
- **Structured Action Spaces**. Currently, actions are integers between 0 and some value. There is no easy way to interpret what each action means in a game-specific way. Nor is there any way to easily represent a composite action in terms of its parts. A structured action space could represent actions as a sequence of values (like information states and observations– and can also include shapes) which can be learned instead of mappings to flat numbers. Then, each game could have a mapping from the structured action to the action taken.

- **TF_Trajectories**. The source code currently includes a batch inference for running a batch of episodes using Tensorflow directly from C++ (in `contrib/`). It has not yet been tested with CMake and public Tensorflow. We would like to officially support this and move it into the core library.
- **Visualizations of games**. There exists an interactive viewer for OpenSpiel games called SpielViz. Contributions to this project are welcome.

CHAPTER

EIGHTEEN

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Names are ordered lexicographically. Typo or similar contributors are omitted.

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18.3 External contributors

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