# Introduction to Google OR-Tools for ENGRI 1101 [*]

## 1 Installation

The quickest way to get OR-Tools working for Python is to install the binary version. This can be done by running the following in terminal:

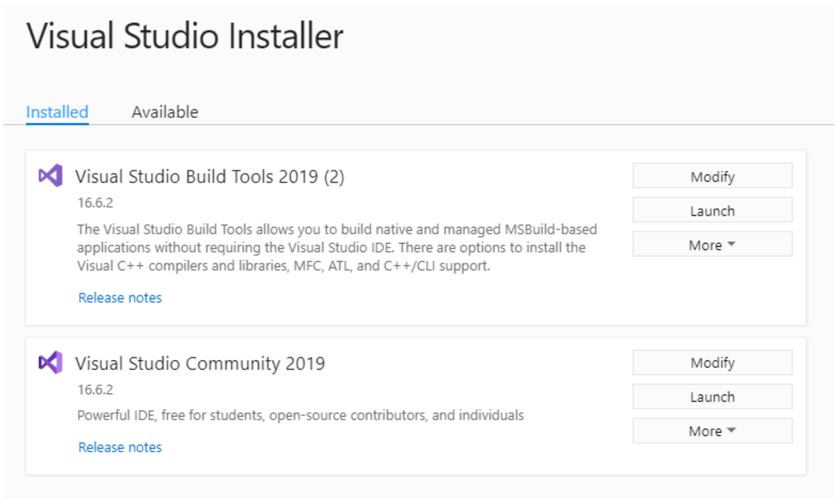
```
python -m pip install --upgrade --user ortools
```

However, to use OR-Tools with a third-party solver (such as Gurobi), it must be compiled from source. Google offers reasonably detailed instructions on doing so for Linux, MacOS, and Windows. However, some additional steps may be necessary. Here, we give a full set of instructions to successfully use Gurobi through OR-Tools on both MacOS and Windows.

### 1.1 Windows

These instructions are adapted from those presented by David Williamson and Jody Zhu.

1. Install Visual Studio 2019 Community and Build Tools for Visual Studio 2019. Your Visual Studio Installer should look like this:



Visual Studio Installer

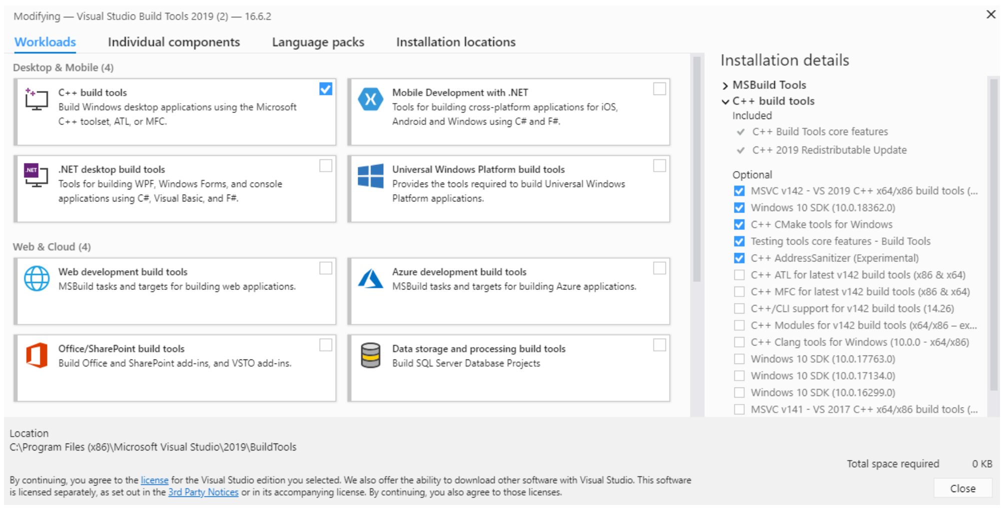
Installed Available

Visual Studio Build Tools 2019 (2)
16.6.2
The Visual Studio Build Tools allows you to build native and managed MSBuild-based applications without requiring the Visual Studio IDE. There are options to install the Visual C++ compilers and libraries, MFC, ATL, and C++/CLI support.
Release notes

Visual Studio Community 2019
16.6.2
Powerful IDE, free for students, open-source contributors, and individuals
Release notes

2. Click "Modify" for Build Tools. Then check "C++ build tools."

[*]Currently set up for use by course developers. Should be updated and reworked for 1101 students.



Modifying — Visual Studio Build Tools 2019 (2) — 16.6.2

Workloads | Individual components | Language packs | Installation locations

Desktop & Mobile (4)

- [✓] C++ build tools — Build Windows desktop applications using the Microsoft C++ toolset, ATL, or MFC.
- [ ] Mobile Development with .NET — Tools for building cross-platform applications for iOS, Android and Windows using C# and F#.
- [ ] .NET desktop build tools — Tools for building WPF, Windows Forms, and console applications using C#, Visual Basic, and F#.
- [ ] Universal Windows Platform build tools — Provides the tools required to build Universal Windows Platform applications.

Web & Cloud (4)

- [ ] Web development build tools — MSBuild tasks and targets for building web applications.
- [ ] Azure development build tools — MSBuild tasks and targets for building Azure applications.
- [ ] Office/SharePoint build tools — Build Office and SharePoint add-ins, and VSTO add-ins.
- [ ] Data storage and processing build tools — Build SQL Server Database Projects

Installation details

> MSBuild Tools

∨ C++ build tools

Included
- ✓ C++ Build Tools core features
- ✓ C++ 2019 Redistributable Update

Optional
- [✓] MSVC v142 - VS 2019 C++ x64/x86 build tools (...
- [✓] Windows 10 SDK (10.0.18362.0)
- [✓] C++ CMake tools for Windows
- [✓] Testing tools core features - Build Tools
- [✓] C++ AddressSanitizer (Experimental)
- [ ] C++ ATL for latest v142 build tools (x86 & x64)
- [ ] C++ MFC for latest v142 build tools (x86 & x64)
- [ ] C++/CLI support for v142 build tools (14.26)
- [ ] C++ Modules for v142 build tools (x64/x86 – ex...
- [ ] C++ Clang tools for Windows (10.0.0 - x64/x86)
- [ ] Windows 10 SDK (10.0.17763.0)
- [ ] Windows 10 SDK (10.0.17134.0)
- [ ] Windows 10 SDK (10.0.16299.0)
- [ ] MSVC v141 - VS 2017 C++ x64/x86 build tools (...

Location
C:\Program Files (x86)\Microsoft Visual Studio\2019\BuildTools

By continuing, you agree to the license for the Visual Studio edition you selected. We also offer the ability to download other software with Visual Studio. This software is licensed separately, as set out in the 3rd Party Notices or in its accompanying license. By continuing, you also agree to those licenses.

Total space required 0 KB

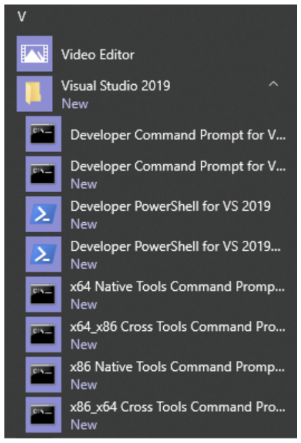
Close

3. Install cmake using "Windows win64-x64 Installer" under Binary distributions.

4. Make sure you have the correct Python and Git.

5. Run `git clone -b master https://github.com/google/or-tools` to get the master branch of the source code (Any command prompt can be used here which is **not** the case for the next step).

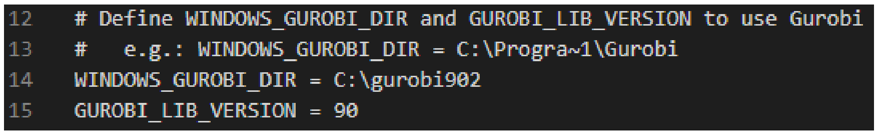
6. Open x64 Native Tools Command Prompt that is in the Visual Studio 2019 folder


V
Video Editor
Visual Studio 2019
New
Developer Command Prompt for V...
Developer Command Prompt for V...
New
Developer PowerShell for VS 2019
New
Developer PowerShell for VS 2019...
New
x64 Native Tools Command Promp...
New
x64_x86 Cross Tools Command Pro...
New
x86 Native Tools Command Promp...
New
x86_x64 Cross Tools Command Pro...
New

7. Navigate to your "or-tools" folder (cd .. to go up and cd "name" to go down)

8. Run `tools\make third_party`

9. *(Assumes Gurobi has been installed correctly with a license)* Edit the `Makefile.local` file. Note that `WINDOWS_GUROBI_DIR` might be different depending where "gurobi902" is located.



```
# Define WINDOWS_GUROBI_DIR and GUROBI_LIB_VERSION to use Gurobi
#    e.g.: WINDOWS_GUROBI_DIR = C:\Progra~1\Gurobi
WINDOWS_GUROBI_DIR = C:\gurobi902
GUROBI_LIB_VERSION = 90
```

10. Run `tools\make python`

11. This stopped with an error for me, so I edited `Makefile.win.mk` on the line for `STATIC_SCIP_LNK` to change `scip.lib` to `libscip.lib`. Then I reran `tools\make python`, and this worked.

12. I need to install a package wheel, so ran `pip install wheel`

13. Run `tools\make install_python`

14. If you previously installed ortools from binary, run `pip uninstall ortools`

## 1.2 MacOS

These instructions are adapted from those presented by David Williamson

1. Run `xcode-select --install`

2. Verify `xcode-select -p` returns `/Applications/Xcode.app/Contents/Developer`

3. Install Homebrew:
   ```
   /usr/bin/ruby -e "$(curl -fsSL https://raw.githubusercontent.com/Homebrew/install/master/install)"
   ```

4. Update Homebrew: `brew update`

5. Verify `brew --version` returns
   ```
   Homebrew 1.6.9-8-g25542d7
   Homebrew/homebrew-core (git revision 0e0c84; last commit 2018-06-20)
   ```

6. Install the remaining prerequisites:

   (a) Run `brew install cmake wget pkg-config`

   (b) Run `brew install swig`

   (c) Run `brew install python`

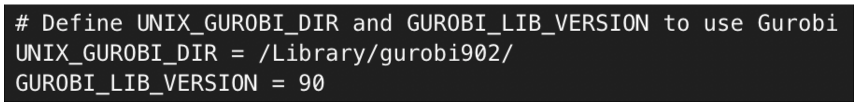
   (d) Run `python3 -m pip install -U --user wheel six`

7. Run `git clone -b master https://github.com/google/or-tools` to get the source master branch

8. Navigate to installation location

9. Run `make third_party`

10. *(Assumes Gurobi has been installed correctly with a license)* Edit the `Makefile.local` file. Note that `UNIX_GUROBI_DIR` might be different depending where "gurobi902" is located.



```
# Define UNIX_GUROBI_DIR and GUROBI_LIB_VERSION to use Gurobi
UNIX_GUROBI_DIR = /Library/gurobi902/
GUROBI_LIB_VERSION = 90
```

11. Run `make python`

12. Run `make install_python`

13. You may have to edit a line in in `makefiles\Makefile.python.mx` by adding `--prefix=` at the end

```
install_python: pypi_archive
    cd "$(PYPI_ARCHIVE_TEMP_DIR)$Sortools" && "$(PYTHON_EXECUTABLE)" setup.\
py install --user --prefix=
```

14. If you previously installed ortools from binary, run `pip uninstall ortools`

## 2 Documentation

Google offers decent documentation. Here, we introduce the subset of functionality that 1101 students will use. Furthermore, some standard style guidelines are established[1].

### 2.1 Imports

All Jupyter Notebooks should begin with the following imports named accordingly. Both `numpy` and `math` are standard imports. `pandas` is used for manipulating CSV files which act as AMPL dat files. `itertools` is used for taking the cartesian product of two or more sets. Lastly, `pywraplp` is the package used for creating and solving LPs.

```python
#imports
import numpy as np
import math as math
import pandas as pd
import itertools as it
from ortools.linear_solver import pywraplp as OR
```

### 2.2 Model

To solve an LP or MIP, we first create a `Solver` similar to an AMPL model.

```
m = OR.Solver(<name>, <problem_type>)
```

instantiates a solver where `problem_type` declares which solver is used to solve the model. Assuming OR-Tools was complied from source for use with Gurobi, the available options for `problem_type` are

- `GLOP_LINEAR_PROGRAMMING`: An open-source LP solver (by Google)
- `CBC_MIXED_INTEGER_PROGRAMMING`: An open-sorce MIP solver
- `GUROBI_MIXED_INTEGER_PROGRAMMING`: A leading commercial MIP solver

For example, we can define a model named "ex" that uses Gurobi to solve mixed integer programs:

```python
m = OR.Solver('ex', OR.Solver.GUROBI_MIXED_INTEGER_PROGRAMMING)
```

Use `m.EnableOutput()` to see solver output. (This goes to terminal right now. Looking into a better way)

[1]Style guidelines are adapted from those written by Jody Zhu

### 2.3 Sets and Parameters

Similar to AMPL, sets should be named in uppercase. In Python, they are represented by a list. Some helpful commands are `SET.append(x)` which adds x to the SET and `SET1.extend(SET2)` which adds elements of SET2 to SET1. Furthermore, `list(it.product(SET1,SET2))` returns the cartesian product of SET1 and SET2. Parameters should be named in lowercase. It is good practice to keep both set and parameter names no more than 6 characters. Parameters that have values for every element of a set should be stored as a Python dictionary. Here is an example for a max flow formulation (which will serve as a running example).

```
NODES = ['S',2,3,4,5,6,'T']
EDGES = [('S',2), ('S',3), (2,3), (2,4), (2,5), (3,5),
         (3,6), (4,'T'), (5,4), (5,6), (5,'T'),(6,'T')]
s = 'S'
t = 'T'
cap = {('S',2):1, ('S',3):7, (2,3):5, (2,4):6, (2,5):2, (3,5):2,
            (3,6):4, (4,'T'):5, (5,4):1, (5,6):4, (5,'T'):4, (6,'T'):3}
```

### 2.4 Variables

To add an additional variable to a model, we use the method `m.NumVar(<lb>, <ub>, <name>)` for continuous variables and `m.IntVar(<lb>, <ub>, <name>)` for integer variables. In both cases, `lb` and `ub` refer to the lower and upper bound for that variables respectively. Note that `m.infinity()` and `-m.infinity()` can be used when there is no upper or lower bound. The decision variables for the max flow formulation are instantiated as follows.

```
f = {}
for i,j in EDGES:
    f[i,j] = m.NumVar(0, m.infinity(), ('(%s, %s)' % (i,j)))
```

### 2.5 Objective Function

The objective function is specified by passing an expression in the variables to `m.Maximize(<expression>)` or `Minimize(<expression>)` depending on the direction of optimization. Often, expressions consist of a summation. In Python, `sum(x[i] for i in SET if <boolean expression>)` is useful for summing over elements. The objective of max flow is

```
m.Maximize(sum(f[i,j] for i,j in EDGES if j == sink))
```

### 2.6 Constraints

To add a constraint to the model, we use `m.Add(<boolean expression>)` where the constraint is represented by some boolean expression in the variables. The only comparison operators that should be used are <=, >=, or ==. It is best practice to have some comment describing what each constraint does as seen below.

```python
# subject to: edge capacity
for i,j in EDGES:
    m.Add(f[i,j] <= capacity[i,j])

# subject to: flow conservation
for k in VERTICES:
    if k != sink and k != source:
        flowIn = sum(f[i,j] for i,j in EDGES if j == k)
        flowOut = sum(f[i,j] for i,j in EDGES if i == k)
        m.Add(flowIn == flowOut)
```

## 2.7 Solve

To solve the model, we use `m.Solve()`. The optimal value is then retrieved using `m.Objective().Value()`. By iterating through `m.variables()`, one can examine the value of each variable using method `.solution_value()`. An example solution output is:

```python
m.Solve()
print('Solution:')
print('Objective value =', m.Objective().Value())
for i,j in EDGES:
    print(f[i,j].name(),':', f[i,j].solution_value())
```

```
Solution:
Objective value = 6.0
(S, 2) : 1.0
(S, 3) : 5.0
(2, 3) : 0.0
(2, 4) : 1.0
(2, 5) : 0.0
(3, 5) : 2.0
(3, 6) : 3.0
(4, T) : 1.0
(5, 4) : 0.0
(5, 6) : 0.0
(5, T) : 2.0
(6, T) : 3.0
```

## 2.8 Early Termination

One way to terminate early is by setting a time limit. This can be done using `m.SetTimeLimit(<time>)` where `<time>` is the time limit in milliseconds. For MIPs, one can terminate by the relative MIP gap defined as

$$\frac{|\texttt{best\_bound} - \texttt{incumbent}|}{|\texttt{incumbent}|}.$$

This is done as follows:

```python
param = OR.MPSolverParameters()
param.SetDoubleParam(param.RELATIVE_MIP_GAP, <gap>)
```

where <gap> is the gap to terminate at (say 0.05 for a solution within 5% of optimal). Note, when running `m.Solve()` , you must pass these parameters using `m.Solve(param)` . If one terminates by time limit, the MIP gap can be ascertained through

```
incumbent = m.Objective().Value()
best_bound = m.Objective().BestBound()
if not incumbent == 0:
    gap = abs(best_bound - incumbent) / abs(incumbent)
else:
    gap = -1
```

If the time limit is set too small, the solver may not reach a feasible solution. In this case, every variable is set to zero. This often results in an objective value of zero. Hence, to prevent a divide by zero error when dividing by the incumbent, the gap is set to -1 (may be better ways to handle this...)

## 2.9 Solver-Specific Parameters

Gurobi offers an extensive set of parameters that "control the operation of the Gurobi solver." All of these parameters can be set through the OR-Tools interface using `m.SetSolverSpecificParametersAsString(<param_file>)` where `param_file` is a PRM file. Below is an example of some possible termination parameters that could be set.

```
m = OR.Solver('ex', OR.Solver.GUROBI_MIXED_INTEGER_PROGRAMMING)
m.SetSolverSpecificParametersAsString('''TimeLimit 3000 \n
                                         NodeLimit 100 \n
                                         MIPGap 0.05''')
```

(To my knowledge, one can not set general parameters for CBC yet)