

Davos: a Python package “smuggler” for constructing lightweight reproducible notebooks

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Abstract

Reproducibility is a core requirement of modern scientific research. For computational research, reproducibility means that code should produce the same results, even when run on different systems. A standard approach to ensuring reproducibility entails packaging a project’s dependencies along with its primary code base. Existing solutions vary in how deeply these dependencies are specified, ranging from virtual environments, to containers, to virtual machines. Each of these existing solutions requires installing or setting up a system for running the desired code, increasing the complexity and time cost of sharing or engaging with reproducible science. Here, we propose a lighter-weight solution: the Davos package. When used in combination with a notebook-based Python project, Davos provides a mechanism for specifying the correct versions of the project’s dependencies directly within the code that requires them, and automatically installing them in an isolated environment when the code is run. The Davos package further ensures that these packages and specific versions are used every time the notebook’s code is executed. This enables researchers to share a complete reproducible copy of their code within a single Jupyter notebook file.

Keywords: Reproducibility, Open science, Python, Jupyter Notebook, Google Colaboratory, Package management

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Metadata

Current code version

Nr.	Code metadata description	Metadata value
C1	Current code version	v0.2.4
C2	Permanent link to code/repository used for this code version	https://github.com/ContextLab/davos/tree/v0.2.4
C3	Code Ocean compute capsule	
C4	Legal Code License	MIT
C5	Code versioning system used	git
C6	Software code languages, tools, and services used	Python, JavaScript, PyPI/pip, IPython, Jupyter, ipykernel, PyZMQ. Additional tools used for tests: pytest, Selenium, Requests, mypy, GitHub Actions
C7	Compilation requirements, operating environments, and dependencies	Dependencies: Python ≥ 3.6 , packaging, setuptools. Supported OSes: MacOS, Linux, Unix-like. Supported IPython environments: Jupyter Notebooks, JupyterLab, Google Colaboratory, Binder, IDE-based notebook editors, IPython shell.
C8	Link to developer documentation/manual	https://github.com/ContextLab/davos#readme
C9	Support email for questions	contextualdynamics@gmail.com

Table 1: Code metadata

1. Motivation and significance

The same computer code may not behave identically under different circumstances. For example, when code depends on external packages, different versions of those packages may function differently. Or when CPU or GPU instruction sets differ across machines, the same high-level code may be compiled into different machine instructions. Because executing identical code does not guarantee identical outcomes, code sharing alone is often insufficient for enabling researchers to reproduce each other’s work, or to collaborate on projects involving data collection or analysis.

Within the Python [1] community, external packages that are published in the most popular repositories [2, 3] are associated with version numbers and tags that allow users to guarantee they are installing exactly the same code across different computing environments [4]. While it is *possible* to manually install the intended version of every dependency of a Python script or package, manually tracking down those dependencies can impose a substantial burden on the user and create room for mistakes and inconsistencies. Further, when dependency versions are left unspecified, replicating the original computing environment becomes difficult or impossible [5].



Figure 1: **Systems for sharing code within the Python ecosystem.** From left to right: plain-text **Python scripts** (.py files) provide the most basic “system” for sharing raw code. Scripts may reference external packages, but those packages must be manually installed on other users’ systems. Further, any checking needed to verify that the correct versions of those packages were installed must also be performed manually. **Jupyter notebooks** (.ipynb files) comprise embedded text, executable code, and media (including rendered figures, code output, etc.). When the **Davos package** is imported into a Jupyter notebook, the notebook’s functionality is extended to automatically install any required external packages (at their correct versions, when specified). **Virtual environments** allow users to install an isolated copy of Python and all required dependencies. This typically entails distributing a configuration file (e.g., a `pyproject.toml` [6] or `environment.yml` file) that specifies all project dependencies (including version numbers of external packages) alongside the primary code base. Users can then install a third-party tool [e.g., 7, 8] to read the file and build the environment. **Containers** provide a means of defining an isolated environment that includes a complete operating system (independent of the user’s operating system), in addition to (optionally) specifying a virtual environment or other configurations needed to provide the necessary computing environment. Containers are typically defined using specification files (e.g., a plain-text `Dockerfile`) that instruct the virtualization engine regarding how to build the containerized environment. **Virtual machines** provide a complete hardware-level simulation of the computing environment. In addition to simulating specific hardware, virtual machines (typically specified using binary image files) must also define operating system-level properties of the computing environment. Systems to the left of the blue vertical line entail sharing individual files, with no additional installation or configuration needed to run the target code. Systems to the right of the red vertical line support precise control over dependencies and versioning. Notebooks enhanced using the Davos package are easily shareable and require minimal setup costs, while also facilitating high reproducibility by enabling precise control over project dependencies.

Computational researchers and other programmers have developed a broad set of approaches and tools to facilitate code sharing and reproducible outcomes (Fig. 1). At one extreme, simply distributing a set of Python scripts (`.py` files) may enable others to use or gain insights into the relevant work. Because Python is installed by default on most modern operating systems, for some projects, this may be sufficient. Another popular approach entails creating Jupyter notebooks [9] that comprise a mix of text, executable code, and embedded media. Notebooks may call or import external scripts or packages—or even intersperse snippets of other programming or markup languages—in order to provide a more compact and readable experience for users. Both of these systems (Python scripts and notebooks) provide a convenient means of sharing code, with the caveat that they do not specify the computing environment in which the code is executed. Therefore the functionality of code shared using these systems cannot be guaranteed across different users or setups.

At another extreme, virtual machines [10, 11, 12] provide a hardware-level simulation of the desired system. Virtual machines are typically isolated, such that installing or running software on a virtual machine does not impact the user’s primary operating system or computing environment. Containers [e.g., 13, 14] provide a similar “isolated” experience. Although containerized environments do not specify hardware-level operations, they are typically packaged with a complete operating system, in addition to a complete copy of Python and any relevant package dependencies. Virtual environments [e.g., 7, 8] also provide a computing environment that is largely separated from the user’s main environment. They incorporate a copy of Python and the target software’s dependencies, but virtual environments do not specify or reproduce an operating system for the runtime environment. Each of these systems (virtual machines, containers, and virtual environments) guarantees (to differing degrees—at the hardware level, operating system level, and Python environment level, respectively) that the relevant code will run similarly for different users. However, each of these systems also relies on additional software that can be complex or resource-intensive to install and use, creating potential barriers to both contributing to and taking advantage of open science resources.

We designed Davos to occupy a “sweet spot” between these extremes. Davos is a notebook-installable package that adds functionality to the default notebook experience. Like standard Jupyter notebooks, Davos-enhanced notebooks allow researchers to include text, executable code, and media within a single file. No further setup or installation is required from the user, beyond what is needed to run standard Jupyter notebooks. And like virtual environments, Davos provides a convenient mechanism for fully specifying (and installing, as needed) a complete set of Python dependencies, including specific package versions, which are contained and isolated from the rest of the user’s system.

2. Software description

The Davos package is named after Davos Seaworth, a smuggler referred to as “the Onion Knight” from the series *A Song of Ice and Fire* by George R. R. Martin [15]. The `smuggle` keyword provided by Davos is a play on Python’s `import` keyword: whereas importing can load a package into the Python workspace within the existing rules and frameworks provided by the Python language, “smuggling” provides an alternative that expands the scope and reach of “importing.” Like the character Davos Seaworth (who became famous for smuggling onions through a blockade on his homeland), we use “onion” comments to precisely control how packages are smuggled into the Python workspace.



Figure 2: **Package structure.** The Davos package comprises two interdependent subpackages. The `davos.core` subpackage includes modules for parsing `smuggle` statements and onion comments, installing and validating packages, isolating and managing installed packages, and configuring Davos’s behavior. The `davos.implementations` subpackage includes environment-specific modifications and features that are needed to support the core functionality across different notebook-based environments. Individual modules (i.e., `.py` files) are represented by lime rounded rectangles, and arrows denote dependencies (each arrow points to a module that imports objects defined in the module at the arrow’s source).

2.1. Software architecture

The Davos package consists of two interdependent subpackages (see Fig. 2). The first, `davos.core`, comprises a set of modules that implement the bulk of the package’s core functionality, including pipelines for installing and validating packages, custom parsers for the `smuggle` statement (see Sec. 2.2.1) and onion comment (see Sec. 2.2.2), a system for isolating dependencies of different projects (see Sec. 2.2.3), and a runtime interface for configuring Davos’s behavior (see Sec. 2.2.4). However, certain critical aspects of this functionality require (often substantially) different implementations depending on properties of the notebook environment in which Davos is used (e.g., whether the frontend is provided by Jupyter or Google Colaboratory, or which version of IPython [16] is used by the notebook kernel). To deal with this, environment-dependent components of core features and behaviors are isolated and abstracted to “helper functions” in the `davos.implementations` subpackage. This second subpackage defines multiple, interchangeable versions of each helper function, organized into modules by the conditions that trigger their use. At runtime, Davos detects various features in the notebook environment and selectively imports a single version of each helper function into the top-level `davos.implementations` namespace, allowing `davos.core` modules to access the proper implementations for the current notebook environment in a single, consistent location. An additional benefit of this design is that it allows both maintainers and users to easily extend Davos to support new, updated, or custom notebook variants by adding new `davos.implementations` modules that define their own versions of each helper function, modified from existing implementations as needed.

2.2. Software functionalities

2.2.1. The `smuggle` statement

Functionally, importing Davos in an IPython notebook enables an additional Python keyword: “`smuggle`” (see Sec. 2.3 for details on how this works). The `smuggle` keyword

can be used as a drop-in replacement for Python’s built-in `import` keyword to load packages, modules, and other objects into the notebook’s namespace. However, whereas `import` will fail if the requested package is not installed locally, `smuggle` statements can handle missing packages on the fly. If a smuggled package does not exist in the user’s Python environment, Davos will download and install it automatically, expose its contents to Python’s `import` machinery, and load it into the notebook for immediate use.

Importantly, packages installed by Davos are made available for use in the notebook without affecting the user’s Python environment or existing packages. By default, `smuggle` statements will install missing packages (and any missing dependencies of those packages) into a notebook-specific, virtual environment-like directory called a “project” (see Sec. 2.2.3). In turn, `smuggle` statements executed in a particular notebook will preferentially load packages from that notebook’s project directory whenever they are available, rather than searching for them in the user’s main Python environment. In this way, `smuggle` statements can be substituted for `import` statements to automatically ensure that all packages needed to run a notebook are installed and available at runtime each time the notebook is run, without risking interfering with dependencies of the user’s other Python programs, or other Davos-enhanced notebooks.

2.2.2. The onion comment

For greater control over the behavior of `smuggle` statements, Davos defines an additional construct called the “onion comment.” An onion comment is a special type of inline comment that may be placed on a line containing a `smuggle` statement to customize how Davos searches for the smuggled package locally and, if necessary, downloads and installs it. Onion comments follow a simple format based on the “type comment” syntax introduced in PEP 484 [17], and are designed to make managing packages with Davos intuitive and familiar. To construct an onion comment, users provide the name of the installer program (e.g., `pip`) and the same arguments one would use to manually install the package as desired via the command line:

```
# enable smuggle statements
import davos

# if numpy is not installed locally, pip-install it and display verbose output
smuggle numpy as np          # pip: numpy --verbose

# pip-install pandas (if necessary) without using or writing to the package cache
smuggle pandas as pd        # pip: pandas --no-cache-dir

# pip-install scipy from a relative local path, in editable mode
from scipy.stats smuggle ttest_ind  # pip: -e ../../pkgs/scipy
```

Occasionally, a package’s distribution name (i.e., the name used when installing it) may differ from its top-level module name (i.e., the name used when importing it). In such cases, an onion comment may be used to ensure that Davos installs the proper package if it cannot be found locally:

```
# package is named "python-dateutil" on PyPI, but imported as "dateutil"
smuggle dateutil          # pip: python-dateutil

# package is named "scikit-learn" on PyPI, but imported as "sklearn"
from sklearn.decomposition smuggle PCA  # pip: scikit-learn
```

Because onion comments may be constructed to specify any aspect of the installer program’s behavior, they provide a mechanism for precisely controlling how, where, and when smuggled packages are installed. Critically, if an onion comment includes a version specifier [4], Davos will ensure that the version of the package loaded into the notebook matches the specific version requested (or satisfies the given version constraints). If the smuggled package exists locally, Davos will extract its version information from its metadata and compare it to the specifier provided. If the two are incompatible (or no local installation is found), Davos will download, install, and load a suitable version of the package instead:

```
# specifically use matplotlib v3.4.2, pip-installing it if needed
smuggle matplotlib.pyplot as plt      # pip: matplotlib==3.4.2

# use a version of seaborn no older than v0.9.1, but prior to v0.11
smuggle seaborn as sns                # pip: seaborn>=0.9.1,<0.11
```

Onion comments can also be used to `smuggle` specific VCS references (e.g., Git [18] branches, commits, tags, etc.):

```
# use quail as the package existed on GitHub at commit 6c847a4
smuggle quail      # pip: git+https://github.com/ContextLab/quail.git@6c847a4
```

Davos processes onion comments internally before forwarding arguments to the installer program. In addition to preventing shared notebooks from executing arbitrary code in a user’s shell, this enables Davos to adjust its behavior based on how particular flags will affect the behavior of the installer program. For example, including pip’s `--no-input` flag will also temporarily enable Davos’s non-interactive mode (see Sec. 2.2.4). Similarly, if an onion comment contains either `-I/--ignore-installed`, `-U/--upgrade`, or `--force-reinstall`, Davos will install and load a new copy of the smuggled package without first checking for it locally:

```
# install and load hypertools v0.7 even if it already exists locally
smuggle hypertools as hyp      # pip: hypertools==0.7 --ignore-installed

# always install and load the latest version of requests, including pre-releases
from requests smuggle Session # pip: requests --upgrade --pre
```

Since the purpose of an onion comment is to describe how a smuggled package should be installed (if necessary) so that it can be loaded and used immediately, options that would normally cause the package not to be installed (such as `-h/--help` or `--dry-run`) are disallowed. Additionally, when using a Davos “project” to isolate smuggled packages (the default behavior; see Sec. 2.2.3), onion comments may not contain options that would change the package’s installation location (such as `-t/--target`, `--root`, or `--prefix`). However, if the user disables project-based isolation and specifies `--target <dir>`, Davos will ensure that `<dir>` is included in the module search path (i.e., `sys.path`), prepending it if necessary, so the package can be loaded.

2.2.3. Projects

Standard approaches to installing packages from within a notebook can alter the local Python environment in potentially unexpected and undesired ways. For example, running

a notebook that installs its dependencies via system shell commands (prefixed with “!”) or IPython magic commands (prefixed with “%”) may cause other existing packages in the user’s environment to be uninstalled and replaced with alternate versions. This can lead to incompatibilities between installed packages, affect the behavior of the user’s other scripts or notebooks, or even interfere with system applications.

To prevent Davos-enhanced notebooks from having unwanted side-effects on the user’s environment, packages installed via `smuggle` statements are automatically isolated using a custom, virtual environment-like system called “projects.” Davos projects are similar to standard Python virtual environments (e.g., created with the standard library’s `venv` module or a third-party tool like `virtualenv` [19]), but with a few noteworthy differences that make them generally lighter-weight and simpler to use. Like a standard virtual environment, a Davos project consists of a directory (within a hidden `.davos` folder in the user’s home directory) that houses third-party packages needed for a particular Python project, workflow, or task. However, unlike standard virtual environments, Davos projects do not need to be manually created, activated, or deactivated, and serve to *supplement* the user’s existing Python environment rather than replace it.

When Davos is imported into a notebook, a project directory for that notebook is automatically created (if it does not exist already). When `smuggle` statements within that notebook are then executed, any packages (or specific versions of packages) that are not already available in the user’s Python environment will be installed into the notebook’s project directory (along with any missing dependencies of those packages). During each `smuggle` statement’s execution, Davos also temporarily prepends the notebook’s project directory to the module search path so that these project-installed packages are visible when searching for smuggled packages locally, and prioritized for use over packages in the user’s main environment.

Thus, rather than constructing fully separate Python environments from scratch, Davos projects work by providing any additions or modifications to the user’s existing package environment needed to satisfy the dependencies of their corresponding notebooks. In some cases, this might include every package smuggled into a notebook (e.g., if the notebook is run inside a freshly created, empty virtual environment). In other cases, the existing environment may already provide all required packages, and the notebook’s project directory will be unused (in which case it will be deleted automatically when the notebook kernel is shut down). But in all cases, dependencies installed by Davos are confined to the project directory and the user’s existing environment will be unaffected.

By default, Davos projects are named based on the absolute path to their corresponding notebooks, and are therefore notebook-specific.

Because `smuggle` statements are evaluated each time the notebook is run, this system ensures that all required packages and specified package versions are always available and used, even if the notebook’s main runtime environment is changed. For example, if a user

===== **TODO: finish editing from here to end** =====

We implemented a “project” system in Davos to protect against the above scenario. By default, importing Davos creates a new project folder in the user’s home directory (contained within a hidden `.davos` folder). The default project name is computed to uniquely identify each notebook according to its filename and path. Any packages that were not originally available in the notebook’s runtime environment are installed to the

notebook's project directory. When external libraries are `smuggled`, Davos temporally appends the current project directory to the search path. Because the user's system path remains unchanged, and because none of the runtime environment's packages are altered, the user's system and runtime environment remain unaffected (aside from installing the Davos package itself to the runtime environment).

Each notebook's project may be customized by setting `davos.project` to any string that can be used as a valid folder name in the user's operating system. By customizing the project name, users can build multi-notebook projects that share the same core set of dependencies without needing to duplicate each package for each notebook in the project.

Finally, if the user *does* wish to modify their runtime environment, this may be done by setting `davos.project` to `None`. Doing so will cause any packages installed by Davos to affect the user's runtime environment. This is generally not recommended, as it can lead to unintended consequences for other code that shares the runtime environment.

2.2.4. Configuring and querying Davos

Davos's behavior may be customized by modifying a set of attributes attached to the `davos` module object that is added to the workspace when Davos is imported. These attributes may be modified, displayed, or checked programmatically at runtime (see Sec. 3 for an illustrative example or Sec. 2.3 for implementation details and additional information). These include:

- `.active`: This attribute controls whether support for `smuggle` statements and onion comments is enabled (`True`) or disabled (`False`). When Davos is first imported, the `.active` attribute is set to `True`.
- `.auto_rerun`: This attribute controls how Davos behaves when attempting to `smuggle` a new version of a package that was previously imported and cannot be reloaded. This can happen if the package includes extension modules that dynamically link C or C++ objects to the Python interpreter, and the code that generates those objects was changed between the previously imported and to-be-smuggled versions. If this attribute is set to `True`, Davos will automatically restart the notebook kernel and rerun all code up to (and including) the current `smuggle` statement. If set to `False` (the default), Davos will instead issue a warning, pause execution, and prompt the user to either restart and rerun the notebook, or continue running with the previously imported package version until the next time the kernel is restarted manually. Note that, as of this writing, the `.auto_rerun` attribute is not supported in Google Colaboratory notebooks.
- `.confirm_install`: If set to `True` (default: `False`), Davos will require user confirmation before installing a smuggled package that does not yet exist in the user's environment.
- `.noninteractive`: Setting this attribute to `True` (default: `False`) enables non-interactive mode, in which all user interactions (prompts and dialogues) are disabled. Note that in non-interactive mode, the `confirm_install` option is set to `False`. If `auto_rerun` is set to `False` while in non-interactive mode, Davos will raise an exception if a smuggled package cannot be reloaded, rather than prompting the user.

- `.pip_executable`: This attribute’s value specifies the path to the `pip` executable used to install smuggled packages. The default is programmatically determined from the Python environment and falls back to `sys.executable -m pip` if no executable can be found.
- `.suppress_stdout`: If this attribute is set to `True` (default: `False`), Davos suppresses printed (console) outputs from both itself and the installer program. This can be useful when smuggling packages that need to install many dependencies and/or generate extensive output. However, if the installer program throws an error, both its stdout and stderr streams will be displayed alongside the Python traceback to allow for debugging.
- `.project`: **TODO: fix this** This attribute is a string that specifies the name of the “project” associated with the current notebook. As described in Section 2.2.3, a notebook’s project determines where and how any `smuggled` dependencies are installed if they are not available in the current runtime environment. By default, this attribute is named according to the current notebook’s absolute file path. However, the project name may be customized to enable shared dependency installations across notebooks (see Sec. 2.2.3).

Davos namespace also defines the `davos.configure()` function, which allows setting multiple configuration options simultaneously. In addition to the above configurable attributes, the `davos` object also includes several read-only attributes that contain potentially useful information about the current environment or Davos’s behavior:

- `.environment`: This attribute’s value is a string describing the notebook environment Davos was imported into. As of the current version (0.2.0), this attribute will be set to either `\IPython<7.0"`, `\IPython>=7.0"`, or `\Colaboratory"`.
- `.ipython_shell`: This attribute contains the global `IPython InteractiveShell` instance underlying the notebook kernel session.
- `.smuggled`: This attribute is set to a Python dictionary that functions as a cache of any `smuggle` commands run during the current session. The dictionary’s keys are package names and the values are arguments passed via the corresponding `smuggle` statement’s onion comment.
- `.all_projects`: This attribute contains a list of all local projects (i.e., projects with virtual environment directories located in `$HOME/.davos/projects`). See Section 2.2.3 for additional information about Davos projects.

2.3. Implementation details

Although Davos is designed to *appear* to add a new keyword to Python’s vocabulary, this illusion is actually created through several “hacks” that make use of the notebook’s IPython backend for processing and executing users’ code. Specifically, when Davos is first imported, or when it is activated after having been set to an inactive state, two actions are triggered. First, the `smuggle()` function is injected into the IPython user namespace. Second, the Davos parser is registered as a custom IPython input transformer.

IPython preprocesses all executed code as plain text before it is sent to the Python compiler, in order to handle special constructs like `%magic` and `!shell` commands. Davos

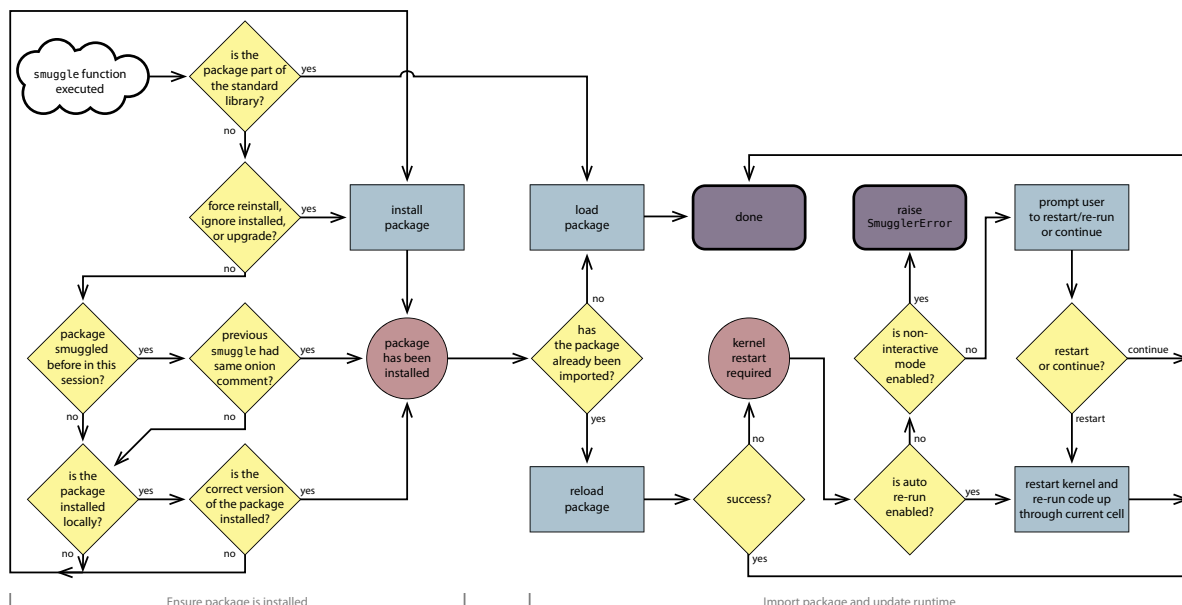


Figure 3: **smuggle() function algorithm.** At a high level, the **smuggle()** function may be conceptualized as following two basic steps. First (left), Davos ensures that the correct version of the desired package has been installed, carrying out the installation automatically if needed. Second (right), Davos imports the package and updates the current runtime environment.

uses this process to transform **smuggle** statements into syntactically valid Python code. The Davos parser uses a regular expression to match lines of code containing **smuggle** statements (and, optionally, onion comments), extract relevant information from their text, and replace them with equivalent calls to the **smuggle()** function. For example, if a user runs a notebook cell containing

```
smuggle numpy as np      # pip: numpy>1.16,<=1.20 -vv
```

the code that is actually executed by the Python interpreter would be

```
smuggle(name="numpy", as_="np", installer="pip",
        args_str="\"numpy>1.16,<=1.20 -vv\"",
        installer_kwargs={'editable': False,
                          'spec': 'numpy>1.16,<=1.20',
                          'verbosity': 2})
```

The call to the **smuggle()** function carries out Davos’s central logic by determining whether the smuggled package must be installed, carrying out the installation if necessary, and subsequently loading it into the namespace. This process is outlined in Figure 3. Because the **smuggle()** function is defined in the notebook namespace, it is also possible (though never necessary) to call it directly. Deactivating Davos will delete the name “**smuggle**” from the namespace, unless its value has been overwritten and no longer refers to the **smuggle()** function. It will also deregister the Davos parser from the set of input transformers run when each notebook cell is executed. While the overhead added by the Davos parser is minimal, this may be useful, for example, when optimizing or precisely profiling code.

3. Illustrative Example

Across different versions of a given package, particular modules, functions, and other objects may be updated, removed, renamed, or otherwise altered. In addition to changing the behaviors of active computations, these changes can render saved objects created using one version of a package incompatible with other versions of the same package. For example, the popular `pandas` [20] library used to include the `Panel` data structure for storing 3-dimensional arrays. Since version 0.20.0, however, the `Panel` class has been deprecated, and in version 0.25.0, it was removed entirely. Suppose a user had a dataset stored in a `Panel` object (created using an older version of `pandas`) and had saved it to their disk (e.g., for later reuse or to share with other users) by serializing the `Panel` with Python’s `pickle` protocol. The `pickle` protocol is a popular built-in method of persisting data in Python that allows users to save, share, and load arbitrary objects. However, in order to successfully “unpickle” (i.e., load and restore) a “pickled” (i.e., previously saved) object, the object’s class must be defined in and importable from the same module as when it was saved. Thus, because of the `Panel` class’s removal, the user’s dataset could not be read by any version of `pandas` from 0.25.0 or beyond. These incompatibilities are also not limited solely to traditional forms of data. For example, saved model states and other objects may reference modules, functions, attributes, classes, or other objects that may not be identical (or even present) across all versions of their associated package.

The example provided in Figure 4 demonstrates how the Davos package can be used to circumvent these incompatibilities by carefully controlling which versions of each package are used in different parts of the notebook. The example shows how a dataset and model that require now-incompatible components of the `pandas` and `scikit-learn` [21] packages may be loaded in (using older versions of each package) and used alongside more recent versions of each package that provide new and improved functionality. When included at the top of a Jupyter notebook, the code in Figure 4 ensures that these objects will be loaded successfully and analyzed using the same set of package versions, no matter when or by whom the notebook is run.

After installing and importing Davos (lines 1–2), we first `smuggle` two utilities for interacting with local files in the code below. The `smuggle` statement in line 4 loads the `is_file()` function from the Python standard library’s `os.path` module. Standard library modules are included with all Python distributions, so this line is functionally equivalent to an `import` statement and does not need or benefit from an onion comment. Line 5 loads the `joblib` package [22], installing it first, if necessary. Since `joblib`’s I/O interface has historically remained stable and backwards-compatible across releases, requiring that users have a particular exact version installed would likely be unnecessarily restrictive. However, a *future* release might introduce some breaking change. The onion comment in line 5 helps ensure the analysis notebook continues to run properly in the future by limiting allowable versions to those already released when the code was written:

```
1 %pip install davos
2 import davos
3
4 extra_msg = "pandas<0.25.0 is needed to load the old data file and requires Python<3.8"
5 davos.require_python(">=3.6,<3.8", extra_msg=extra_msg)
```

Line 7 then uses the `davos.config` object to enable Davos’s `auto_rerun` option before smuggling the next two packages: `NumPy` [23] and `pandas`. Because these packages rely heavily on custom C data types, loading the particular versions from the onion comments

```

1  %pip install davos
2  import davos
3
4  extra_msg = "pandas<0.25.0 is needed to load the old data file and requires Python<3.8"
5  davos.require_python(">=3.6,<3.8", extra_msg=extra_msg)
6
7  from os.path smuggle is_file
8  smuggle joblib                                # pip: joblib<=1.2.0
9
10 davos.auto_rerun = True
11 smuggle numpy as np                            # pip: numpy==1.21.6
12
13 if not is_file("~/datasets/data-new.csv"):
14     smuggle pandas as pd                        # pip: pandas<0.25.0
15     tmp_data = pd.read_pickle("~/datasets/data-old.pkl")
16     tmp_data.to_frame().to_csv("~/datasets/data-new.csv")
17
18 smuggle pandas as pd                            # pip: pandas==1.3.5
19
20 davos.configure(auto_rerun=False, suppress_stdout=True, noninteractive=True)
21 smuggle tensorflow as tf                        # pip: tensorflow==2.9.2
22 from umap smuggle UMAP                        # pip: umap-learn[plot,parametric_umap]==0.5.3
23 davos.configure(suppress_stdout=False, noninteractive=False)
24
25 smuggle matplotlib.pyplot as plt               # pip: matplotlib==3.5.3
26 smuggle seaborn as sns                        # pip: seaborn==0.12.1
27 smuggle quail                                  # pip: git+https://github.com/myfork/quail@6c847a4
28
29 davos.project = None
30 smuggle widgetsnbextension as _
31 davos.use_default_project()
32 smuggle ipywidgets as _                        # pip: ipywidgets==7.6.5
33
34 from tqdm.notebook smuggle tqdm                # pip: tqdm==4.62.3
35
36 data = pd.read_csv("~/datasets/data-new.csv", index_col=[0, 1])
37 smuggle sklearn                                # pip: scikit-learn<0.22.0
38 transformer = joblib.load("~/models/text-transformer.joblib")
39 smuggle sklearn                                # pip: scikit-learn==1.1.3

```

Figure 4: **Example use case for Davos.** Snippets from this example are also excerpted in the main text of Section 3.

may require restarting the notebook kernel if different versions had been previously imported during the same interpreter session (see Sec. 2.2.4).

```
7 from os.path smuggle is_file
8 smuggle joblib # pip: joblib<=1.2.0
```

Setting the `auto_rerun` attribute to `True` is particularly useful for managing the installation of `pandas` in the next lines:

```
10 davos.auto_rerun = True
11 smuggle numpy as np # pip: numpy==1.21.6
```

If we suppose that the data contained in `data-old.pkl` is stored in a pickled `Panel` object, then we must use a version of `pandas` prior to 0.25.0 (i.e., the version in which the `Panel` class was removed) to be able to load it in. Line 11 ensures that an older version of `pandas` will be imported, enabling the data to be read in (and, in line 13, written to a CSV file, which is compatible with newer `pandas` versions).

Newer versions of `pandas` have brought substantial improvements including better performance, bug fixes, and additional functionality. Although the original dataset had to be read in using an older version of the package, we can take advantage of these more recent updates by smuggling `pandas` a second time on line 15 (whose onion comment specifies that version 1.3.5 should be installed and loaded). Since a different version of `pandas` had already been loaded by the Python interpreter (on line 11), the notebook kernel must be restarted in order to replace the old version’s custom C extensions with those from the new version. The `auto_rerun` flag set on line 7 enables Davos to trigger this process automatically so that the code can continue running without user intervention, and converting the dataset to a CSV file in lines 10–13 ensures that the older version of `pandas` does not need to be reinstalled.

Next, line 17 uses the `davos.configure()` function to disable the `auto_rerun` option and simultaneously enable two other options: `suppress_stdout` and `noninteractive`. With these options enabled, lines 18–19 smuggle TensorFlow [24], a powerful end-to-end platform for building and working with machine learning models, and UMAP [25], a package that implements a family of related manifold learning techniques. The onion comment in line 19 also specifies that UMAP should be installed with the optional requirements needed for its “plot” and “parametric_umap” features. Together, these two packages depend on 36 other unique packages, most of which have dependencies of their own. And if many of these are not already installed in the user’s environment, lines 18–19 could take several minutes to run. Enabling the `noninteractive` option ensures that the installation will continue automatically without user input during that time. Enabling `suppress_stdout` also suppresses console outputs while installing these packages and their many dependencies to prevent other potentially important outputs from being buried.

```
13 if not is_file("~/datasets/data-new.csv"):
14     smuggle pandas as pd # pip: pandas<0.25.0
15     tmp_data = pd.read_pickle("~/datasets/data-old.pkl")
16     tmp_data.to_frame().to_csv("~/datasets/data-new.csv")
17
18 smuggle pandas as pd # pip: pandas==1.3.5
```

After re-enabling these two options (line 20), we next smuggle specific versions of three plotting packages: `Matplotlib` [26], `seaborn` [27], and `Quail` [28] (lines 22–24).

385 Because the first two are requirements of UMAP’s optional “plot” feature, they will have
386 already been installed by line 19, though possibly as different versions than those specified
387 in the onion comments on lines 22 and 23. If the installed and specified versions are the
388 same, these `smuggle` statements will function like standard `import` statements to load the
389 packages into the notebook namespace. If they differ, Davos will download the requested
390 versions in place of the installed versions before doing so.

```
20  davos.configure(auto_rerun=False, suppress_stdout=True, noninteractive=True)
21  smuggle tensorflow as tf          # pip: tensorflow==2.9.2
22  from umap smuggle UMAP           # pip: umap-learn[plot,parametric_umap]==0.5.3
```

392 Line 24 uses an onion comment to specify that `Quail` should be installed directly from a
393 specific GitHub commit (6c847a4). This ability to load packages directly from GitHub
394 repositories can enable developers to more easily use forked or modified versions of other
395 packages in their notebooks, even if those versions have not been officially released.

396 In lines 26–29, we demonstrate another aspect of Davos’s functionality that supports
397 more advanced installation scenarios. The `ipywidgets` [29] package provides an API
398 for creating various JavaScript widgets with Python code, and the `widgetsnbextension`
399 package provides the machinery needed by the notebook frontend to display them.

```
23  davos.configure(suppress_stdout=False, noninteractive=False)
24
25  smuggle matplotlib.pyplot as plt  # pip: matplotlib==3.5.3
26  smuggle seaborn as sns           # pip: seaborn==0.12.1
27  smuggle quail                    # pip: git+https://github.com/myfork/quail@6c847a4
```

401 A complication is that `ipywidgets` must be installed in the same environment as the
402 IPython kernel, whereas `widgetsnbextension` must be installed in the environment that
403 houses the Jupyter notebook server. In many basic setups, these two environments are
404 the same. However, a common “advanced” approach entails running the notebook server
405 from a base environment, with additional environments each providing their own separate,
406 interchangeable IPython kernels. To accommodate this multi-environment scenario, on
407 lines 26 and 28, we use the `pip_executable` option to control which environments each
408 package should be installed to. Once these two packages are installed and imported, line
409 31 smuggles `tqdm` [30], which display progress bars to provide status updates for running
410 code. In Jupyter notebooks, the `tqdm.notebook` module can be imported to enable more
411 aesthetically pleasing progress bars that are displayed via `ipywidgets`, if that package is
412 installed and importable. Therefore, to take advantage of this feature, it was important
413 to `smuggle tqdm` after ensuring the `ipywidgets` package was available.

414 Next, we load in the reformatted dataset (line 33) and pre-trained model (line 35)
415 that we wish to use in our analysis. In our hypothetical example, we can suppose that the
416 model was provided as a `scikit-learn` `Pipeline` object that passes data through two
417 pretrained models in succession. First, a trained `CountVectorizer` instance converts text
418 data to an array of word counts. Second, the word counts are passed to a topic model [31]
419 using a pretrained `LatentDirichletAllocation` instance.

```
29  davos.project = None
30  smuggle widgetsnbextension as _
31  davos.use_default_project()
32  smuggle ipywidgets as _          # pip: ipywidgets==7.6.5
33
34  from tqdm.notebook smuggle tqdm  # pip: tqdm==4.62.3
```


Let us suppose that the `Pipeline` object had been saved by its original creator using the `joblib` package, as `scikit-learn`'s documentation recommends. Because `joblib` uses the `pickle` protocol internally, the ability to save and load pre-trained models is not guaranteed across different `scikit-learn` versions. For example, suppose that the `Pipeline` object was created using `scikit-learn` v0.21.3. In that version of `scikit-learn`, the `LatentDirichletAllocation` class was defined in `sklearn.decomposition.online_lda`. However, in version 0.22.0, that module was renamed to `_online_lda`, and in version 0.22.1, it was again renamed to `_lda`.

In order to correctly load the model that includes the pre-trained `LatentDirichletAllocation` instance, in line 34, we first `smuggle` a version of `scikit-learn` prior to v0.22.0 (i.e., before the first time the relevant module's name was changed). Once the model is loaded and reconstructed in memory from a compatible package version (line 35), we upgrade to a newer version of `scikit-learn` in line 36. Taken together, the code in Figure 4 shows how Davos can enable users to load in data and models that are incompatible with newer versions of `pandas` and `scikit-learn`, but still *analyze* and manipulate the data and model output using the latest approaches and implementations.

4. Impact

Like virtual environments, containers, and virtual machines, the Davos package (when used in conjunction with Jupyter notebooks) provides a lightweight mechanism for sharing code and ensuring reproducibility across users and computing environments (Fig. 1). Further, Davos enables users to fully specify (and install, as needed) any project dependencies within the same notebook. This provides a system whereby executable code (along with text and media) *and* code for setting up and configuring the project dependencies, may be combined within a single notebook file.

Although existing notebooks *can* incorporate system calls that install project requirements, handling project requirements in the general case is non-trivial (e.g., see Fig. 3). Further, Davos incorporates its own virtual environment system that isolates notebook-installed packages from the runtime environment (Sec. 2.2.3). In many setups this feature can eliminate the need to set up a separate virtual environment or container (e.g., in conjunction with a `requirements.txt`, `project.toml`, or `environment.yml` file specifying the project's dependencies).

We designed Davos for use in research applications. For example, in many settings, Davos may be used as a drop-in replacement for more-difficult-to-set-up virtual environments, containers, and/or virtual machines. For researchers, this lowers barriers to sharing code. By eliminating most of the setup costs of reconstructing the original researchers' computing environment, Davos also lowers barriers to entry for members of the scientific community and the public who seek to run shared code.

Beyond research applications, Davos is also useful in pedagogical settings. For example, in programming courses, instructors and students may use the Davos package to ensure their notebooks will run correctly on others' machines. When combined with online notebook-based platforms like Google Colaboratory, Davos provides a convenient way to manage dependencies within a notebook, without requiring any software (beyond a web browser) to be installed on the students' or instructors' systems. For the same reasons, Davos also provides an elegant means of sharing ready-to-run notebook-based demonstrations or tutorials that install their dependencies automatically.

Since its initial release, Davos has found use in a variety of applications. In addition to managing computing environments for multiple prior and ongoing research stud-

ies [32, 33, 34], Davos is being used by both students and instructors in programming and methods courses such as Storytelling with Data [35] (an open course on data science, visualization, and communication) and Laboratory in Psychological Science [36] (an open course on experimental and statistical methods for psychology research) to simplify distributing lessons and submitting assignments, as well as in online demos such as `abstract2paper` [37] (an example application of GPT-Neo [38, 39]) to share ready-to-run code that installs dependencies automatically. The 2023 offering of Neuromatch Academy [40] also included an “experimental” module that uses Davos to manage dependencies related to a large language model-based tutor [41].

Our work also has several more subtle “advanced” use cases and potential impacts. Whereas Python’s built-in `import` statement is agnostic to packages’ version information, `smuggle` statements (when combined with onion comments) are version-sensitive. And because onion comments are parsed at runtime, required packages and their specified versions are installed in a just-in-time manner. Thus, it is possible in most cases to `smuggle` a specific package version or revision even if a different version has already been loaded. This enables more complex uses that take advantage of multiple versions of a package within a single interpreter session (e.g., see Sec. 3 and Fig. 4). This could be useful in cases where specific features are added or removed from a package across different versions, or in comparing the performance or functionality of particular features across different versions of the same package.

A second more subtle impact of our work is in providing a proof-of-concept of how the ability to add new “keyword-like” operators to the Python language could be specifically useful to researchers. With Davos, we accomplish this by leveraging IPython notebooks’ internal code parsing and execution machinery. We note that, while other popular packages similarly use these mechanisms to providing notebook-specific functionality (e.g., [26, 42]), this approach also has the potential to be exploited for more nefarious purposes. For example, a malicious user could design a Python package that, when imported, substantially changes the notebook’s functionality by adding new *unexpected* keyword-like objects (e.g., based around common typos). We also note that this implementation approach means Davos’s functionality is currently restricted to IPython notebook environments. However, there have been early-stage discussions of providing this sort of syntactic customizability as a core feature of the Python language, including a draft proposal [43]. In addition to enabling Davos to be extended for use outside of notebooks, this could lead to exciting new tools that, like Davos, extend the Python language in useful and more secure ways.

4.1. Pitfalls and limitations

While Davos enables developers to conveniently specify all project dependencies, there are some edge cases and limitations that are worth considering. First, reproducibility is not solely about dependency management. In addition to ensuring that project dependencies are satisfied, the user running a given notebook must also execute the code in the indicated order. For example, the cells in a notebook may be manually run out of order. If different cells in a Davos-enhanced notebook made use of different versions of the same package, this could result in *more* confusion or *greater* replication failure rates relative to standard Jupyter notebooks. Therefore an important consideration when using Davos is that it is perhaps even more important to execute notebook cells in order than would be the case in the standard (non-Davos) setup. One approach to mitigating this risk for notebooks that use several versions of the same library would be to include `smuggle`

statements in the same cell(s) where the library was called. A second approach would be for developers who wish to use Davos to include notes regarding which cells must be executed in sequence. This is already a common practice for notebooks that include system calls to install required packages and dependencies, and the same approach would work well for Davos-enhanced notebooks as well.

A second limitation of Davos relates to how packages are installed and managed. As of this writing, Davos can install packages using `pip`, but not other standard Python package management systems such as `conda`. Therefore packages that are not installable via `pip` are currently unsupported by Davos. We anticipate adding support for other package management systems, including `conda`, in a future release.

A third limitation of Davos is that it cannot be used to manage projects that depend on non-Python software. For example, system software or libraries from other languages (e.g., in a mixed Python and R notebook), cannot be `smuggled` by Davos. A notebook that utilizes or depends on non-Python software would therefore need to use existing non-Davos approaches to managing those requirements.

5. Conclusions

The Davos package supports reproducible research by providing a novel, lightweight system for sharing notebook-based code. But perhaps the most exciting uses of the Davos package are those that we have *not* yet considered or imagined. We hope that the research and scientific Python communities will find Davos to provide a convenient means of managing project dependencies to facilitate code sharing and collaboration. We also hope that some of the more advanced applications of our package might lead to new insights or discoveries.

Author Contributions

Paxton C. Fitzpatrick: Conceptualization, Methodology, Software, Validation, Writing - Original Draft, Visualization. **Jeremy R. Manning:** Conceptualization, Resources, Validation, Writing - Review & Editing, Visualization, Supervision, Funding acquisition.

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Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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