GigaScience

SciPipe - A workflow library for agile development of complex and dynamic bioinformatics pipelines

--Manuscript Draft--

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Abstract:	Background: The complex nature of biological data has driven the development of specialized software tools. Scientific workflow management systems simplify the assembly of such tools into pipelines, assist with job automation and aid reproducibility of analyses. Many contemporary workflow tools are specialized or not designed for highly complex workflows, such as with nested loops, dynamic scheduling and parametrization which is common in e.g. machine learning. Findings: SciPipe is a workflow programming library implemented in the programming language Go, for managing complex and dynamic pipelines in bioinformatics, cheminformatics and other fields. SciPipe helps in particular with workflow constructs common in machine learning, such as extensive branching, parameter sweeps and dynamic scheduling and parametrization of downstream tasks. SciPipe builds on Flow-based programming principles to support agile development of workflows based on a library of self-contained, reusable components. It supports running subsets of workflows for improved iterative development, and provides a data-centric audit logging feature that saves a full audit trace for every output file of a workflow, which can be converted to other formats such as HTML, TeX and PDF on-demand. The utility of SciPipe is demonstrated with a machine learning pipeline, a genomics, and a transcriptomics pipeline. Conclusions: SciPipe provides a solution for agile development of complex and dynamic pipelines, especially in machine leaning, through a flexible programming API suitable for scientists used to programming or scripting.d	
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Response to Reviewers:	Dear Editor,	

We were pleased to read the many positive and constructive comments from all the three reviewers; there were several useful suggestions which has improved the manuscript. We have updated the manuscript accordingly and provide below point-by-point responses to the reviewers' comments. With these improvements, we hope You will find it acceptable for publication in GigaScience.

Sincerely,

Samuel Lampa and Co-authors

Reviewer #1

Reviewer #1: The submitted paper presents a workflow engine for scientific computing, with particular emphasis on applications in genomics, bioinformatics, and transcriptomics. The authors do a nice job at emphasizing the usefulness of their particular tool, highlighting limitations of prior art, demonstrating novel features in Scipipe, and suggesting design principles which are useful for others in the space of workflow engine development. The presented tool is written in the elegant and popular Go Programming Language, and proved easy to use for even the Go-novice that is this reviewer. The manuscript is very well written, and was easy to follow.

While I have attached notes and comments below, the only area I feel needs to be addressed which has significant impact the quality and usefulness of this manuscript and tool is that of interoperability. The authors discuss other standards or engines in this area, and while they mention the plan for future integration with the Common Workflow Language, they do not discuss the integration with or adoption of other standards. As there are many workflow engines, and several dominant options in the space of bioinformatics such as Galaxy, while Scipipe may be preferable in some ways the cost for authors to switch is
non-zero. What is the motivation for scientists who have their workflows integrated in one of these other systems to switch? What tools are there or will there be to aid in this process? These are questions which readers and potential users may be thinking, and I believe are important to address.
Regarding interoperability, there are also various standards and tools which exist in other spaces covered here. For instance, there are tools which record or ensure interoperability of provenance records, such as Reprozip for managing file I/O provenance and constructing access graphs of executions, and W3C-PROV for representing records as disambiguated entities. This reviewer also found the representation of command-lines themselves was rather simple, without any type-checking of parameters (which, while not performed directly in Bash by command-line applications, can be of use to prevent connecting nodes which may be incompatible, such as a string output being connected to an input expecting a number, let alone bounds on reasonable values for it), whereas standards exist such as Boutiques that address this for command-line utilities through the use of JSON tool descriptors and utilities which aid in the validation of parameters. Similarly, a common workflow engine in
neuroinformatics, Nipype, exists as a very similar tool to Scipipe but has been written in Python with neuroscience applications in mind, though it is in principle also agnostic to domain. In each of these cases, it would be valuable to consider adopting established standards where possible - or import/export functionality where this isn't possible - and justify the decisions made in Scipipe in their context. While Scipipe presents a novel workflow management system, addressing the above points and interoperability between other frameworks may put to rest any concerns in adopting Scipipe or integrating it within their current practices.

Authors' response

First, thank you for the kind words!

In answer to the raised concerns, we do not see SciPipe as a silver bullet to replace existing successful systems, but rather as a solution to those researchers and developers facing particularly complex workflow challenges - increasingly common

because of the upsurge in machine learning and cross-validation - which might motivate to trade some ease-of-use for the required flexibility to be able to model their computations at all. We thus think the selection of primary target group for SciPipe in itself will ensure the motivation for switching is there.

We do have plans for improved interoperability though, and want to do this primarily as subcommands added to the scipipe helper tool, to avoid cluttering the core library with non-essential functionality. The reason for this is that one core design goal of SciPipe has been to retaining a simple implementation to keep it maintainable with minimal efforts in the long run.

We are thankful for the additional pointers about standards and formats, and have updated the manuscripts brief reviews of these tools, and our plans and views regarding them.

Reviewer #1

Below are my notes on specific sections of the paper which questions or comments. There is some overlap with the above paragraphs as I have tried to identify where I believe some of these points could be well addressed.

Page 1, Line 51, column 2
- Is the implication that Bash, Python, or Perl are more prone to becoming fragile than Go? Is this the case? If so, why?

Authors' response

The comparison (which also follows in the next paragraph) is not made with Go per se, but with workflow tools or libraries. So, the comparison stands between “plain scripts” and workflow tools or libraries, which could sometimes be implemented in scripting languages.

We have reworded the sentence slightly to clarify this intention, as well as removed the paragraph split just after that sentence, to clarify that the explanation follows right after it.

Reviewer #1

Page 2 & 3
- The authors did a very nice and thorough review of many tools in the space of workflow management tools. An alternative that wasn't mentioned here was Nipype, a tool commonly used in neuroscience for workflow management, though in principle it is domain agnostic. In particular, I notice that many of the features described as desired here, including branching, provenance tracking, and enabling reproducible computation, having both a command-line and in-language API, etc., are very similar to those of Nipype. I would like the authors to do a review and comparison of these tools, as well. Another tool or representation of potential interest could be the Common Workflow Language, which I only found brief mention of later on.

Authors' response

Thanks for the suggestion of Nipype. Because of the specific focus on the Neuroimaging community, we had not noticed the generality of Nipype before. Upon reading the paper, we indeed see that it shares many similarities with SciPipe. We have added it to the comparison of existing tools. Regarding CWL, we note that CWL is not really a workflow implementation, but rather a language, with multiple implementations. The language is what will be the limiting factor for what is easy to express though, so we have included a brief mention about it also in the introduction.

Reviewer #1

Page 3, Line 36, column 1
- Broken citation

Authors' response

Fixed, thanks!

Reviewer #1

Page 3, Line 48, column 1
- How does this provenance log compare to those obtained from Reprozip? The authors may wish to do a comparison of provenance standards in the first section, as well.

Authors' response

From our understanding, Reprozip is a complementary approach to SciPipe, which goes much deeper and traces and hijacks system calls to create a completely self-contained reproducible package, based on any tool, not just workflows. SciPipe provenance reports do not take this comprehensive technical approach, but rather gathers the semantics it does handle by each task invocation, and stores a trace of this information for every output from the workflow.

We have updated the manuscript with a bit of comparison to other provenance standards and tools, including W3C-PROV and Reprozip, both in the main text (W3C PROV and Reprozip) and under Known limitations (W3C PROV, Boutiques).

Reviewer #1

Figure 1
- What was the reason behind defining tasks in the way shown on lines 16 and 20? There are some standards, such as Boutiques (boutiques.github.io) and CWL which define task command-lines, including validating data typing, etc., that it seems could be of some use here to make sure that commands are being run meaningfully. For instance, these standards could perhaps enabling checking that all values in the DNA string are A, G, C, or T.
- I successfully re-executed this script after following the installation instructions found on the documentation page.

Authors' response

We have been evaluating the tool syntax tooling in CWL prior to developing our too (code here: https://github.com/NBISweden/workflow-tools-evaluation). Our choice to not prioritize any functionality based on this or similar standards has been an intentional decision because of the nontrivial amount of complexity that this type of parsing tooling typically adds to a tool. For example, the current SciPipe implementation is a completely self-contained Go library, without dependencies on other libraries apart from Bash and a Unix-like operating system.

We think it could be interesting to consider for future development though, in particular if it is possible to implement in the form of a subcommand in the stand-alone scipipe helper tool, as that would still enable to keep the core library (the part that is shipped with workflows) small and easy to maintain. We have updated the text to note this as interesting for future development.

Reviewer #1

Page 6, Line 37-47, column 1
- Are you defining this provenance data with respect to any accepted standard, such as JSON-LD (the W3C-PROV compatible JSON format)? If not, how come, and what are the consequences of this custom definition of metadata?

Authors' response

The data we are storing here are a very straight-forward mapping from the internal data structures in SciPipe, to JSON. This is thus by definition the most compact and generic representation of the provenance data possible based on the data that we have. Our approach has then been to provide any other data formats (including HTML, TeX/PDF and executable Bash scripts) via converters in the scipipe commandline helper tool. We think this would be a very natural choice for how to implement conversion to W3C-PROV serialized as JSON-LD as well. We have updated the manuscript with a mention about this.

Reviewer #1

Remove commas:
- Page 4, Line 48, column 2: after "used"
- Page 6, Line 25, column 2: after "workflow system"
- Page 7, Line 31, column 1: after "programming language"

Authors' response

Fixed, thanks!

Reviewer #2

Reviewer #2: Excellent work, building a workflow system implementing the data flow paradigm for bioinformatics with a fast language (GO) as well. Some minor concerns I have are the following:

- This is obviously targeted to bioinformatics developers, but assuming there is a community that adopts it, would there be a way for someone who can do basic command line to use
it ? I am assuming that is there is a community many workflows will be published and a non developer could run it with a single command by just pointing to his / her datasets?

Authors' response

Thank you for kind words! Just as with Python scripts, Go code, and thus SciPipe workflows, can be made into very easy to use command-line programs, that can be used as easily as any other command-line program. Go additionally has the benefit that workflows can be compiled to self-contained executable files, so that the user does not even need to figure out how to execute a specific interpreter command, such as with Python, R or Perl.

Reviewer #2

- What other dependencies does it need besides GO to be installed ?

Authors' response

SciPipe requires a Unix or Linux like operating system, and the Bash shell. This information is available in the manuscript, under the section “Availability of supporting

source code and requirements”

Reviewer #2

- Can it do parallelism in data chunks similar to Nextflow ? Many bioinformatics files (think for example reads) can be processed in an embarrassingly parallel way, for example if they
are split and aligned to a reference genome.

Authors' response

SciPipe can indeed to parallel processing. SciPipe supports both so called embarrassingly parallel tasks, by enabling scatter/gather types of workflows. There is an example of this in the code repository: https://github.com/scipipe/scipipe/blob/master/examples/scatter_gather/scattergather.go

SciPipe also supports pipeline parallelism, firstly by means of processing multiple stages at once, as long as there are enough data to be travelling through the system that the first stages has work to do even when they have passed on some data to downstream stages. SciPipe additionally supports a features that as far as we know is not included even in Nextflow: Unix pipe-based streaming, using named pipes, to support pipeline parallelism across multiple stages even for single data items. Documentation for this feature is available here: http://scipipe.org/howtos/streaming/

Reviewer #2

- Finally, what about Docker containers? For example Nextflow has build in the option to pull containers "on the fly" with the tools preconfigured from repositories such as Dockstore etc
which have hundreds of pre-made containers. This is especially useful in the case of complex bioinformatics pipelines which have 10-15 different tools. Of course a developer can build a single container with all the tools pre-configured and run SciPipe from within this container, but if container support is available natively within the SciPipe implementation, developers can simply point to available (public or internally) containers with pre-configured tools, which will be started at runtime of the workflow in order to provide the algorithms which the workflow feeds the data
for processing during each different step.

Authors' response

SciPipe already supports running Singularity containers natively, by calling them like command-line programs. The path we have otherwise taken in regards to containers, is is to provide integration with Kubernetes. This is ongoing experimental work, available in a separate branch on GitHub.

Reviewer #2

Some corrections:
Line 33, right column better to use "Fig. 1" with bold letters.
Line 36, left column missing reference.
Line 46, right column, correct as "As can be seen on lines 17, 21 and 25, Fig.1", so that we know which figure we refer to.

Authors' response

Thanks! We have fixed the suggested corrections, except the first one, which we think violates the styling guidelines for the TeX template in use (we have not seen bold letter

used in any other articles using the same template).

Reviewer #3

Reviewer #3: ##Comments to paper

This is a well written paper describing the, to my knowledge, first workflow manager implemented in Go. Although there are many alternative workflow managers, this work is motivated by the limitation of one of the state-of-the-art workflow managers (Luigi) that the authors have previously used and even extended.

The paper describes the design of SciPipe, shows how it is used, and provides use cases. It does not provide any evaluation of SciPipe, nor does it describe system the use cases were run on. The latter should be included, since one of the motivations for SciPipe is the issues encountered with SciLuigi when run on more than 64 workers. The paper also does not describe how many users SciPipe has. Is it just used by the authors? I would also have liked a discussion about workflows, such as ADAM (https://github.com/bigdatagenomics/adam), that are implemented in Spark.

Authors' response

We have updated the paper with a “Usage” section, describing the known usage of SciPipe, including a brief discussion of the systems on which we have run real-world workflows.
We have also extended the introduction with a review of ADAM.

Reviewer #3

A minor issue: on page 3, line 36, there is a missing reference.

Authors' response

Thanks! Fixed.

Reviewer #3

Comments to the source code and documentation

The SciPipe webpage is well designed, with documentation and example workflows. The GitHub repository has 833 commits, with the last commit on August 18th. It has 426 stars and 27 forks, which suggest that there is interest in the community. The install documentation are a bit hard to find in the webpage, especially for someone that has not read the paper. There does not seem to be a test suite for SciPipe.

Authors' response

SciPipe does indeed include a test suite. The test suite in Go does not need to reside in a separate folder, but are put in files ending with “_test.go”. Tests are integrated and run in our continuous integration suite, and continuously updated coverage statistics are available at:
https://codecov.io/gh/scipipe/scipipe

Reviewer #3

I tested SciPipe on my laptop in Ubuntu on Windows. I have very limited knowledge of Go, so I just followed the examples on the webpage. They did work as described.

	I first tested the RNA-seq case study. For it the documentation was less clear, and there were no instructions for how to do it. For example, how to specify the input dataset, which I later found was in the go code. The execution took a while, and it was hard to know if the program was working, or if it has crashed or waiting for input (especially since the first step downloads a 1.7GB file for which the size or progress is not shown). The case study failed, due to a missing library used by STAR. This is not a SciPipe issue, and it would not occur on a production system. SciPipe did however save the logs necessary to understand the issue. --- Authors' response --- We have now updated the individual case study workflow folders with simple README.md files, to help take out the guesswork. Thanks for pointing this out! --- Reviewer #3 --- Second, I tested the drug discovery workflow. It could not be compiled due to: ./utils.go:45: t.Round undefined (type time.Duration has no field or method Round) --- Authors' response --- It turns out that this is caused by using a Go version below 1.9. We have added the version information in the dependencies listing in the manuscript. --- Reviewer #3 --- Finally, I tested the genomics cancer workflow, which also failed due to a version issue in GenomeAnalysisTK.jar. Again, this is a third party installation error. I did not do any more advanced testing of SciPipe, including using my own data, running it on more than one machine, nor stopping and restarting workflow execution.
Additional Information:	
Question	**Response**
Are you submitting this manuscript to a special series or article collection?	No
Experimental design and statistics Full details of the experimental design and statistical methods used should be given in the Methods section, as detailed in our Minimum Standards Reporting Checklist. Information essential to interpreting the data presented should be made available in the figure legends. Have you included all the information requested in your manuscript?	Yes
Resources	Yes

A description of all resources used, including antibodies, cell lines, animals and software tools, with enough information to allow them to be uniquely identified, should be included in the Methods section. Authors are strongly encouraged to cite Research Resource Identifiers (RRIDs) for antibodies, model organisms and tools, where possible. Have you included the information requested as detailed in our Minimum Standards Reporting Checklist?	
Availability of data and materials All datasets and code on which the conclusions of the paper rely must be either included in your submission or deposited in publicly available repositories (where available and ethically appropriate), referencing such data using a unique identifier in the references and in the “Availability of Data and Materials” section of your manuscript. Have you have met the above requirement as detailed in our Minimum Standards Reporting Checklist?	Yes

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Technical Note

TECHNICAL NOTE

SciPipe – A workflow library for agile development of complex and dynamic bioinformatics pipelines

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Abstract

Background: The complex nature of biological data has driven the development of specialized software tools. Scientific workflow management systems simplify the assembly of such tools into pipelines, assist with job automation and aid reproducibility of analyses. Many contemporary workflow tools are specialized or not designed for highly complex workflows, such as with nested loops, dynamic scheduling and parametrization which is common in e.g. machine learning.
Findings: SciPipe is a workflow programming library implemented in the programming language Go, for managing complex and dynamic pipelines in bioinformatics, cheminformatics and other fields. SciPipe helps in particular with workflow constructs common in machine learning, such as extensive branching, parameter sweeps and dynamic scheduling and parametrization of downstream tasks. SciPipe builds on Flow-based programming principles to support agile development of workflows based on a library of self-contained, reusable components. It supports running subsets of workflows for improved iterative development, and provides a data-centric audit logging feature that saves a full audit trace for every output file of a workflow, which can be converted to other formats such as HTML, TeX and PDF on-demand. The utility of SciPipe is demonstrated with a machine learning pipeline, a genomics, and a transcriptomics pipeline.
Conclusions: SciPipe provides a solution for agile development of complex and dynamic pipelines, especially in machine leaning, through a flexible programming API suitable for scientists used to programming or scripting.

Key words: Scientific Workflow Management Systems, Pipelines, Reproducibility, Machine Learning, Flow-based Programming, Go, Golang

Findings

Driven by the highly complex and heterogeneous nature of biological data [1, 2], computational biology is characterized by an extensive ecosystem of command-line tools, each specialized on one or a few of the many aspects of biological data. Because of their specialized nature these tools generally need to be assembled into sequences of processing steps, often called "pipelines", to produce meaningful results from raw data. Due to the increasingly large sizes of biological data sets [3, 4], such pipelines often require integration with High-Performance Computing (HPC) infrastructures or cloud computing resources to complete in an acceptable time. This has created a need for tools to coordinate the execution of such pipelines in an efficient, robust and reproducible manner. This coordination can in principle be done with simple scripts in languages like Bash, Python or Perl but plain scripts can quickly become fragile. When the number of tasks becomes sufficiently large and the execution times long, the risk for failures during the execution of such scripts increases almost linearly with time and simple scripts are not a good strategy for when large jobs need to be restarted from a failure. This is because they lack the ability to distinguish between finished and half-finished files. They also do not provide means to detect if intermediate output files are already created and can be reused to avoid wasting time on redoing already finished cal-

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culations. These limits with simple scripts calls for a strategy with a higher level of automation and more careful management of data and state. This need is addressed by a class of software commonly referred to as "scientific workflow management systems" or simply "workflow tools". Through a more automated way of handling the execution, workflow tools can improve the robustness, reproducibility and understandability of computational analyses. In concrete terms, workflow tools provide means for handling atomic writes (making sure finished and half-finished files can be separated after a crashed or stopped workflow), caching of intermediate results, distribution of tasks to the available computing resources and automatically keeping or generating records of exactly what was run, to make analyses reproducible.

It is widely agreed upon that workflow tools generally make it easier to develop automated, reproducible and fault-tolerant pipelines, although many challenges and potential areas for improvement still do exist with existing tools [5]. This has made scientific workflow systems a highly active area of research. Numerous workflow tools have been developed and many new ones are continuously being developed.

The workflow tools developed differ quite widely in terms of how workflows are defined and what features are included out-of-the box. This probably reflects the fact that different types of workflow tools can be suited for different categories of users and use cases. Graphical tools like Galaxy [6, 7, 8] and Yabi [9] provide easy to use environments especially well-suited for scientists without scripting experience. Text-based tools like Snakemake [10], Nextflow [11], BPipe [12], Cuneiform [13] and Pachyderm [14] on the other hand, are implemented as Domain Specific Languages (DSLs), that can often provide a higher level of flexibility, at the expense of the ease of use of a graphical user interface. They can thus be well suited for "power users" with experience in scripting or programming.

Even more power and flexibility can be gained from workflow tools implemented as programming libraries, which provide their functionality through a programming API accessed from an existing programming language such as Python, Perl or Bash. By implementing the API in an existing language, users get access to the full power of the implementation language as well as the existing tooling around the language. One example of a workflow system implemented in this way is Luigi [15]. Another interesting workflow system implemented as a programming library and which shares many features with SciPipe is Nipype [16].

As reported in [5], although many users find important benefits in using workflow tools, many also experience limitations and challenges with existing tools, especially regarding the ability to express complex workflow constructs such as branching and iteration, as well as limitations in terms of audit logging and reproducibility. Below we briefly review a few existing popular systems and highlight areas where we found that the development of a new approach and tool was desirable, for use cases that includes very complex workflow constructs.

Firstly, graphical tools like Galaxy and Yabi, although being easy-to-use even for users without programming experience, are often perceived to be limited in their flexibility due to the need to install and run a web server to use them, which is not always permitted or practical on HPC systems.

Text-based tools implemented as DSLs, such as Snakemake, Nextflow, BPipe, Pachyderm and Cuneiform do not have this limitation but have other characteristics which might be problematic for for complex workflows.

For example, Snakemake is *dependent* on file naming strategies for defining dependencies, which can in some situations be limiting, and also uses a "pull-based" scheduling strategy (the workflow is invoked by asking for a specific output file, where after all tasks required for reproducing the file will be executed). While this makes it easy to reproduce specific files, it can make the system hard to use for workflows involving complex constructs such as nested parameter sweeps and cross-validation fold generation, where the final file names are hard to foresee, if at all possible. Snakemake also performs scheduling and execution of the workflow graph in separate stages, meaning that it does not support dynamic scheduling.

Dynamic scheduling, which basically means on-line scheduling during the workflow execution [17], is useful both where the number of tasks is unknown before the workflow is executed and where a task needs to be scheduled with a parameter value obtained during the workflow execution. An example of the former is reading row by row from a database, splitting a file of unknown size into chunks or processing a continuous stream of data from an external process such as an automated laboratory instrument. An example of the latter is training a machine learning model with hyper parameters obtained from a parameter optimization step prior to the final training step.

BPipe constitutes a sort of middle-ground in terms of dynamic scheduling. It supports dynamic decisions of what to run by allowing execution-time logic inside pipeline stages, as long as the structure of the workflow does not need to change. Dynamic change of the workflow structure can be important in workflows for machine learning though, e.g. if parametrizing the number of folds in a cross-validation based on a value calculated during the workflow run, such as dataset size.

Nextflow has push-based scheduling and supports dynamic scheduling via the dataflow paradigm and does not suffer from this limitation. It does not, however, support creating a library of reusable workflow components. This is because of its use of dataflow variables shared across component definitions, which requires processes and the workflow dependency graph to be defined together.

Pachyderm is a container-based workflow system which uses a JSON and YAML-based DSL to define pipelines. It has a set of innovative features including a version-controlled data management component with Git-like semantics and support for triggering of pipelines based on data updates, among others. These in combination can provide some aspects of dynamic scheduling. On the other hand, the more static nature of the JSON/YAML-based DSL might not be optimal for really complex setups such as creating loops or branches based on parameter values obtained during the execution of the workflow. The requirement of Pachyderm to be run on a Kubernetes [18] cluster can also make it less suitable for some academic environments where ability to run pipelines also on traditional HPC clusters is required. On the other hand, because of the easy incorporation of existing tools, it is possible to provide such more complex behavior by including a more dynamic workflow tool as a workflow step inside Pachyderm instead. We thus primarily see Pachyderm as a complement to other light-weight workflow systems, rather than necessarily an exclusive alternative.

The usefulness of such an approach where an over-arching framework provides primarily an orchestration role while calling out to other systems for the actual workflows, is demonstrated by the Arteria project [19]. Arteria builds on the event-based StackStorm framework to allow triggering of external workflows based on any type of event, providing a flexible automation framework for sequencing core facilities.

Another group of workflow tools are those designed around the Common Workflow Language (CWL) [20] as their primary authoring interface. These include Toil [21] and Rabix [22], as well as the CWL reference implementation. A detailed review of each of these tools is getting outside the scope for this article. We note though that while CWL provides very important benefits in terms of workflow portability, it can at the same time be too limited for very complex and dynamic workflow constructs because of its declarative YAML-based nature, just

as for Pachyderm.

There is also a class of workflow systems building on Big Data technologies such as the Hadoop ecosystem, where ADAM [23] is one prominent example, using Spark [24] as a foundation for its pipeline component. Through a set of specialized formats, APIs and workflow step implementations for genomics data, ADAM manages to provide impressive scalability of genomics analyses across multiple compute nodes. By relying on Spark which has a programming model where data operations are expressed directly, ADAM is quite a different beast than the other workflow systems reviewed here though. In these other more traditional workflow tools, components are generally instead handled in a black-box fashion and most often being implemented outside of the workflow layer itself. Just as with Pachyderm, the requirement for additional technology layers for distributed computing, like as the Hadoop Distributed File System (HDFS) [25] and the Spark execution system, means that ADAM might not always be a feasible solution for HPC clusters with tight restrictions on system privileges, or for local laptops with limited resources.

Going back to traditional workflow systems, Cuneiform takes a different approach compared to most workflow tools by wrapping shell commands in functions in a flexible functional language (described in [26]), which allows leveraging common benefits in functional programming languages, such as side-effect free functions, to define workflows. It also leverages the distributed programming capabilities of the Erlang Virtual Machine (EVM), to provide automatic distribution of workloads. It is still a new, domain specific language though, which means that tooling and editor support might not be as extensive as for an established programming language.

Luigi is a workflow library developed by Spotify, which provides a high degree of flexibility due to its implementation as a programming library, Python. For example, the programming API exposes full control over file name generation. Luigi also provides integration with many Big Data systems such as Hadoop and Spark, and cloud-centric storage systems like HDFS and S3.

SciLuigi [27] is a wrapper library for Luigi, previously developed by the authors, which introduces a number of benefits for scientific workflows by leveraging selected principles from Flow-based programming (FBP) (named ports and separate network definition) to achieve an API that makes iteratively changing the workflow connectivity easier than in vanilla Luigi.

While Luigi and SciLuigi were shown to be a helpful solution for complex workflows in drug discovery, they also have a number of limitations for highly complex and dynamic workflows. Firstly, since Python is an un-typed, interpreted language, certain software bugs are discovered only far into a workflow run, rather than while compiling the program. Secondly, the fact that Luigi creates separate processes for each worker which communicate with the central Luigi scheduler via HTTP requests over the network, can lead to robustness problems when going over a certain number of workers (around 64 in the authors' experience) leading to HTTP connection time-outs.

Finally Nipype, which is also a programming library implemented in Python and which shares a number of features with SciPipe such as flexible file name generation, separate named inputs and outputs and a rather Flow-based programming like dependency definition, is expected to suffer from some of the same limitations as in Luigi because of the lack of static typing and worse performance of the Python programming language compared to Go.

The mentioned limitations for complex workflows in existing tools is the background and motivation for developing the SciPipe library.

The SciPipe workflow library

SciPipe is a workflow library based on Flow-Based Programming principles, implemented as a library in the Go programming language. The library is freely available as open source on GitHub [28]. All releases of GitHub are also archived on Zenodo [29]. Similarly to Nextflow, SciPipe leverages the dataflow paradigm to achieve dynamic scheduling of tasks based on input data, allowing many workflow constructs not easily coded in many other tools.

Combined with design principles from Flow-based programming such as separate network definition and named ports bound to processes, this has resulted in a productive and discoverable API that enables agile authoring of complex and dynamic workflows. The fact that the workflow network is defined separately from processes, enables building workflows based on a library of reusable components, although the creation of ad-hoc shell-command based components is also supported.

SciPipe provides a provenance tracking feature that creates one audit log per output file, rather than only one for the whole workflow run. This means that it is always easy to verify exactly how each output of a workflow was created.

SciPipe also provides a few features which are not very common among existing tools, or which are not commonly occurring together in one system. These include support for streaming via Unix named pipes, ability to run push-based workflows up to a specific stage of the workflow, and flexible support for file naming of intermediate data files generated by workflows.

By implementing SciPipe as a library in an existing language, the language's ecosystem of tooling, editor support and third-party libraries can be directly used to avoid "reinventing the wheel" in these areas. By leveraging the built-in concurrency features of Go, such as go-routines and channels, the developed code base has been kept small compared with similar tools, and also does not require external dependencies for basic usage (some external tools are used for optional features like PDF generation and graph plotting). This means that the code base should be possible to maintain for a single developer or small team, and that the code base is practical to include in workflow developers' own source code repositories, in order to future-proof the functionality of workflows.

Below, we first briefly describe how SciPipe workflows are created. We then describe in some detail the features of SciPipe that are the most novel or improves most upon existing tools, followed by a few more commonplace technical considerations. We finally demonstrate the usefulness of SciPipe by applying it to a set of case study workflows in machine learning for drug discovery and next-generation sequencing genomics and transcriptomics.

Writing workflows with SciPipe

SciPipe workflows are written as Go programs, in files ending with the `.go` extension. As such, they require the Go tool chain to be installed for compiling and running them. The Go programs can be either compiled to self-contained executable files with the `go build` command, or run directly, using the `go run` command.

The simplest way to write a SciPipe program is to write the workflow definition in the program's `main()` function, which is executed when running the compiled executable file, or running the file as script with `go run`. An example workflow written in this way is shown in in figure 1, which provides a simple example workflow consisting of three processes, demonstrating a few of the basic features of SciPipe. The first process writes a string of DNA to a file, the second computes the base

```go
package main

import (
    "github.com/scipipe/scipipe"
)

const dna = "AAAGCCCGTGGGGGACCTGTTC"

func main() {
    // Initialize workflow, using max 4 CPU cores
    wf := scipipe.NewWorkflow("DNA Base Complement Workflow", 4)

    // Initialize processes based on shell commands:

    // makeDNA writes a DNA string to a file
    makeDNA := wf.NewProc("Make DNA", "echo "+dna+" > {o:dna}")
    makeDNA.SetOut("dna", "dna.txt")

    // complmt computes the base complement of a DNA string
    complmt := wf.NewProc("Base Complement", "cat {i:in} | tr ATCG TAGC > {o:compl}")
    complmt.SetOut("compl", "{i:in|%.txt}.compl.txt")

    // reverse reverses the input DNA string
    reverse := wf.NewProc("Reverse", "cat {i:in} | rev > {o:rev}")
    reverse.SetOut("rev", "{i:in|%.txt}.rev.txt")

    // Connect data dependencies between out- and in-ports
    complmt.In("in").From(makeDNA.Out("dna"))
    reverse.In("in").From(complmt.Out("compl"))

    // Run the workflow
    wf.Run()
}
```

Figure 1. A simple example workflow implemented with SciPipe. The workflow computes the reverse base complement of a string of DNA, using standard UNIX tools. The workflow is a Go program and is supposed to be saved in a file with the `.go` extension and executed with the `go run` command. On **line 4**, the SciPipe library is imported, to be later accessed as `scipipe`. On **line 7**, a short string of DNA is defined. On **line 9-33**, the full workflow is implemented in the program's `main()` function, meaning that it will be executed when the resulting program is executed. On **line 11**, a new workflow object (or "struct" in Go terms) is initiated with a name and the maximum number of cores to use. On **lines 15-25**, the workflow components, or *processes*, are initiated, each with a name and a shell command pattern. Input file names are defined with a placeholder on the form `{i:INPORTNAME}` and outputs on the form `{o:OUTPORTNAME}`. The port-name will be used later to access the corresponding ports for setting up data dependencies. On **line 16**, a component that writes the previously defined DNA string to a file is initiated, and on **line 17**, the file path pattern for the out-port *dna* is defined (in this case a static file name). On **line 20**, a component that translates each DNA base to its complementary counterpart is initiated. On **line 21**, the file path pattern for its only out-port is defined. In this case, reusing the file path of the file it will receive on its in-port named *in*, thus the `{i:in}` part. The `%.txt` part removes `.txt` from the input path. On **line 24**, a component that will reverse the DNA string is initiated. On **lines 27-29**, data dependencies are defined via the in- and out-ports defined earlier as part of the shell command patterns. On **line 32**, the workflow is being run.

complement, and the last process reverses the string. All in all, the workflow computes the reverse base complement of the initial string.

As can be seen in figure 1 on line 11, a workflow object (or struct, in Go terminology) is first initialized, with a name and a setting for the maximum number of tasks to run at a time. Furthermore, on line 15-19, processes are defined with the `Workflow.NewProc()` method on the workflow struct, with name and a command pattern which is very similar to the Bash shell command that would be used to run a command manually, but where concrete file names have been replaced with placeholders, on the form `{i:INPORTNAME}`, `{o:OUTPORTNAME}` or `{p:PARAMETERNAME}`. These placeholders define input and output files, as well as parameter values, and works as a sort of templates, that will be replaced with concrete values as concrete tasks are scheduled and executed.

As can be seen on lines 17, 21 and 25 (figure 1), output paths to use for output files are defined using the `Process.SetOut()` method, taking an out-port name and a pattern for how to generate the path. For simple workflows this can be just a static file name, but for more complex workflows with processes that produce more than one output on the same port – e.g. by processing different input files, or using different sets of parameters – it is often best to reuse some of the input paths and parameter values configured earlier in the command pattern to generate a unique path for each output.

Finally, on lines 27-29, we see how in-ports and out-ports are connected in order to define the data dependencies between tasks. Here, the in-port and out-port names used in the placeholders in the command pattern described above, are used to access the corresponding in-ports and out-ports, and making connections between them, with a syntax on the general form of `InPort.From(OutPort)`.

The last thing needed to do to run the workflow, is seen on line 32, where the `Workflow.Run()` method is executed. Provided that the workflow code in figure 1 is saved in a file named `workflow.go`, it can be run using the `go run` command, like so:

```
$ go run workflow.go
```

This will then produce three output files and one accompanying audit log for each file, which we can be seen by listing the files in a terminal:

```
dna.txt
dna.txt.audit.json
dna.compl.txt
dna.compl.txt.audit.json
dna.compl.rev.txt
dna.compl.rev.txt.audit.json
```

```
{
    "ID": "tuir75c24kxe4rrqmm2p",
    "ProcessName": "Reverse",
    "Command": "cat ../dna.compl.txt | rev \u003e dna.compl.rev.txt",
    "Params": {},
    "Tags": {},
    "StartTime": "2018-07-26T13:02:16.855172344+02:00",
    "FinishTime": "2018-07-26T13:02:16.863536059+02:00",
    "ExecTimeNS": 8363715,
    "OutFiles": {
        "rev": "dna.compl.rev.txt"
    },
    "Upstream": {
        "dna.compl.txt": {
            "ID": "2g7tr2trhu9zubovwlua",
            "ProcessName": "Base Complement",
            "Command": "cat ../dna.txt | tr ATCG TAGC \u003e dna.compl.txt",
            "Params": {},
            "Tags": {},
            "StartTime": "2018-07-26T13:02:16.845769702+02:00",
            "FinishTime": "2018-07-26T13:02:16.854035213+02:00",
            "ExecTimeNS": 8265532,
            "OutFiles": {
                "compl": "dna.compl.txt"
            },
            "Upstream": {
                "dna.txt": {
                    "ID": "vu8ltmoujzo3vn2b39pr",
                    "ProcessName": "Make DNA",
                    "Command": "echo AAAGCCCGTGGGGGACCTGTTC \u003e dna.txt",
                    "Params": {},
                    "Tags": {},
                    "StartTime": "2018-07-26T13:02:16.842112643+02:00",
                    "FinishTime": "2018-07-26T13:02:16.84486747+02:00",
                    "ExecTimeNS": 2754810,
                    "OutFiles": {
                        "dna": "dna.txt"
                    },
                    "Upstream": {}
                }
            }
        }
    }
}
```


Figure 2. Example audit log file in JSON format [30], for a file produced by a SciPipe workflow. The workflow used to produce this audit log in particular, is the one in figure 1. The audit information is hierarchical, with each level representing a step in the workflow. The first level contains meta-data about the task executed last, to produce the output file that this audit log refers to. The field `Upstream` on each level, contains a list of all upstream task of the current task, indexed by the file paths that each of the upstream tasks did produce, and which was subsequently used by the current task. Each task is given a globally unique ID, which helps to deduplicate any duplicate occurrences of tasks, when converting the log to other representations. Execution time is given in nanoseconds. Note that input paths in the command field, is prepended with `../`, compared to how they appear in the Upstream field. This is because each task is executed in a temporary directory created directly under the workflow's main execution directory, meaning that to access existing data files, it has to first navigate up one step out of this temporary directory.

The file `dna.txt` should now contain the string `AAAGCCCGTGGGGGACCTGTTC`, and `dna.compl.rev.txt` should contain `GAACAGGTCCCCCACGGGCTTT`, which is the reverse base complement of the first string. In the last file above, the full audit log for this minimal workflow can be found. An example content of this file is shown in figure 2.

In this code example, it can be seen that both of the commands we executed are available, and also that the *Reverse* process lists its "upstream" processes, which are indexed by the input file names in its command. Thus, under the `dna.compl.txt` input file, we find the *Base Complement* process together with its meta-data, and one further upstream process (the *Make DNA* process). This hierarchic structure of the audit log ensures that the complete audit trace, including all commands contributing to the production of an output file, is available for each output file from the workflow.

More information about how to write workflows with SciPipe is available on the documentation website [31]. Note that the full documentation on this website is also available in a folder named `docs` inside the SciPipe Git repository, which ensures that documentation for the version currently used is always available.

Dynamic scheduling

Since SciPipe is built on the principles from Flow-based programming (see the methods section for more details), a SciPipe program consists of independently and concurrently running processes, which schedule new tasks continually during the workflow run. This is here referred to as *dynamic scheduling*. This means that it is possible to create a process that obtains a value and passes it on to a downstream process as a parameter, so that new tasks can be scheduled with it. This feature is important in machine learning workflows, where hyper parameter tuning is often employed to find an optimal value of a parameter, such as `cost` for Support Vector Machines (SVM), which is then used to parametrize the final training part of the workflow.

Reusable components

Based on principles from Flow-based programming, the workflow graph in SciPipe is defined by making connections between port objects bound to processes. This enables to keep the dependency graph definition *separate* from the process definitions. This is in contrast to other ways of connecting dataflow processes, such as with dataflow variables, which are shared between process definitions. This makes processes in flow-based programming fully self-contained, meaning that libraries of reusable components can be created and that components can be loaded on-demand when creating new workflows. A graphical comparison between dependencies defined with dataflow variables and flow-based programming ports, is shown in figure 3.

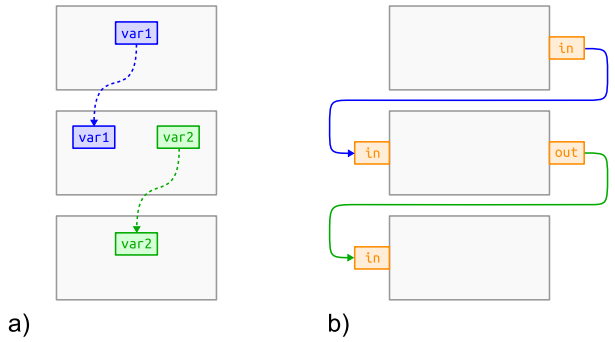

Figure 3. Comparison between dataflow variables and Flow-based programming ports in terms of dependency definition. a) shows how dataflow variables (blue and green) shared between processes (in gray) make the processes tightly coupled. In other words, process- and network definitions get intermixed. b) shows how ports (in orange) bound to processes in Flow-based programming allows keeping the network definition separate from process definitions. This enables processes to be reconnected freely without changing their internals.

Running subsets of workflows

With pull-based workflow tools like Snakemake or Luigi, it is easy to on-demand reproduce a particular output file, since the scheduling mechanism is optimized for the use case of asking for a specific file and calculating all the tasks required to be executed based on that.

With push-based workflow tools though, reproducing a specific set of files without running the full workflow is not always straight-forward. This is a natural consequence of the push-based scheduling strategy, and dataflow in particular, as the identities and quantities of output files might not be known before the workflow is run.

SciPipe provides a mechanism for partly solving this lack of "on demand file generation" in push-based dataflow tools, by allowing to reproduce all files of a specified process, on-demand. That is, the user can tell the workflow to run all processes in the workflow upstream of, and including, a specified process, while skipping processes downstream of it.

This has turned out very useful when iteratively refactoring or developing new pipelines. When a part in the middle of a long sequence of processes need to be changed, it is helpful to be able to test-run the workflow up to that particular process only, not the whole workflow, to speed up the development iteration cycle.

Other characteristics

Below are a few technical characteristics and considerations that are not necessarily unique to SciPipe, but could be of interest to potential users assessing whether SciPipe fits their use cases.

Data centric audit log

The audit log feature in SciPipe collects meta data about every executed task (concrete shell command invocation) which is passed along with every file that is processed in the workflow. It writes a file in the ubiquitous JSON format, with the full trace of tasks executed for every output in the workflow, with the same name as the output file in question but with the additional file extension `.audit.json`. Thus, for every output in the workflow, it is possible to check the full record of shell commands used to produce it. An example audit log file can be seen in figure 2.

This data-oriented provenance reporting contrasts to provenance reports common in many workflow tools, which often provide one report per workflow run only, meaning that the link between data and provenance report is not as direct.

The audit log feature in SciPipe in many aspects reflects the recommendations in [32] for developing provenance reporting in workflows, such as producing a coherent, accurate, inspectable record for every output data item from the workflow. By producing provenance records for each data output rather than for the full workflow only, SciPipe could provide a basis for the problem of iteratively developing workflow variants, as outlined in [33].

SciPipe also loads any existing provenance reports for existing files that it uses, and merges these with the provenance information from its own execution. This means that even if a chain of processing is spread over multiple SciPipe workflow scripts, and executed at different times by different users, the full provenance record is still being kept and assembled, as long as all workflow steps were executed using SciPipe shell command processes. The main limitation to this "follow the data" approach, is for data generated externally to the workflow, or by SciPipe components implemented in Go. For external processes, it is up to the external process to generate any reporting. For Go-based components in SciPipe, these can not currently dump a textual version of the Go code executed. This constitutes an area of future development.

SciPipe provides experimental support for converting the JSON-structure into reports in HTML and TeX format, or into executable Bash scripts that can reproduce the file which the audit report describes from available inputs or from scratch. These tools are available in the `scipipe` helper command. The TeX report can be easily further converted to PDF using the `pdflatex` command of the pdfTex software [34]. An example of such a PDF report, is shown in figure 4, which was generated from the audit report for the last file generated by the code example in figure 1.

Note that JSON format used natively by SciPipe is not focused on adhering to a standard such as the W3C recommended standard for provenance information, W3C PROV [35]. To follow the approach taken with the scipipe helper tool, support for W3C PROV serialized e.g. to JSON-LD [36] would be a most suitable additional conversion target, and is planned for future development.

Note also that the provenance log in SciPipe can be seen as complementary to much more technically comprehensive but also more low-level approaches such as ReproZip [37]. ReproZip monitors not just shell command executions but every system call made during a workflow run to enable capturing all required dependencies and packing these into a reproducible archive. One way to contrast these two approaches is

that while the primary goal of ReproZip is reproducible *execution*, the provenance report in SciPipe serves *multiple purposes*, where *understandability* of executed analyses has a much more pronounced role than in ReproZip.

Atomic writes

SciPipe ensures that cancelled workflow runs do not result in half-written output files being mistaken for finished ones. It does this by executing each task in a temporary folder, and moving all newly created files into their final location *after* the task is finished. By using a folder for the execution, any extra files created by a tool that are not explicitly configured by the workflow system are captured and treated in an atomic way. Examples of where this is needed is for the five extra files created by `bwa index` [38], when indexing a reference genome in FASTA format.

Streaming support

In data intensive fields like Next-Generation Sequencing, it is common that intermediate steps of pipelines produce large amounts of intermediate data, often multiplying the storage requirements considerably compared to the raw data from sequencing machines [39]. To help ease these storage requirements, SciPipe provides the ability to optionally stream data between two tasks via Random Access Memory (RAM) instead of saving to disk between task executions. This approach has two benefits. Firstly, the data does not need to be stored on disk, which can lessen the storage requirements considerably. Secondly, it enables the downstream task to start processing the data from the upstream task immediately as soon as the first task has started to produce partial output. It thus enables to achieve *pipeline parallelism* in addition to *data parallelism*, and can thereby shorten the total execution time of the pipeline.

Flexible file naming and data "caching"

SciPipe allows flexible naming of the file path of every intermediate output in the workflow, based on input file names and parameter values passed to a process. This enables creating meaningful file naming schemes, to make it easy to manually explore and sanity-check outputs from workflows.

Configuring a custom file naming scheme is not required though. If no file path is configured, SciPipe will automatically create a file path that ensures that two tasks with different parameters or input data will never clash, and that two tasks with the same command signature, parameters and input-files, will reuse the same cached data.

Usage

SciPipe has successfully been used by the authors to train machine learning models for off-target binding profiles for early hazard detection of candidate drug molecules in early drug discovery [40]. This study was run on a single HPC node on the Rackham cluster [41] at UPPMAX HPC center at Uppsala University, which has two CPUs with 10 physical and 20 virtual cores each, and 128-256 GB of RAM (we had access to nodes with different amounds of RAM, and were using whatever our application needed).

Due to some changes in how we performed the training we did not get the opportunity to try out the exact same situation that we were struggling with SciLuigi before, but based on experiments done on compute nodes on the same HPC cluster, it has been verified that SciPipe is able to handle up to 4999 concurrent idle shell commands (which could be e.g. monitoring jobs on the SLURM resource manager [42]), as opposed to the maximum of around 64 concurrent commands with SciLuigi.

Apart from that and the occasional workflow in the wild [43], the SciPipe library has not yet seen much adoption outside of the authors' research group just yet. Based on the high interest for the library on GitHub (462 stars and 30 forks at the time of writing this), we think this is a matter of time though. We also think the interest in workflows implemented in compiled languages will increase as datasets continue to increase in size and performance and robustness issues grow more and more important.

Since SciPipe is a somewhat more complex tool than the most popular ones such as Galaxy, we are planning to produce more tutorial material such as videos and blog posts, to help newcomers get started.

Known limitations

Below we list a number of known limitations of SciPipe that might affect the decision whether to use SciPipe for a particular use case or not.

Firstly, the fact that writing SciPipe workflows requires some basic knowledge of the Go programming language can be off-putting to users who are not well acquainted with programming. Go code, although having taken inspiration from scripting languages, is still markedly more verbose and low-level in nature than Python, and can take a little longer to get used to.

Secondly, the level of integration with HPC resource managers is currently quite basic compared to some other workflow tools. The SLURM resource manager can readily be used by using the `Prepend` field on processes to add a string with a call to the `salloc` SLURM command, but more advanced HPC integration is planned to be addressed in upcoming versions.

Thirdly, the way commands are defined in SciPipe is quite simplistic compared to some other approaches. Approaches such as the Common Workflow Language tool description format [44] and the Boutiques [45] framework, provide more semantically comprehensive description of the commandline format. Boutiques also provide certain features for validation of inputs, which can help avoid connecting workflow inputs and outputs which are not compatible. We see this as an exciting area for future development, and where community contributions to the open source code will be especially welcome.

Furthermore, reproducing specific output files is not as natural and easy as with pull-based tools like Snakemake, although SciPipe provides a mechanism to partly resolve this problem.

Finally, SciPipe does not yet support integration with the Common Workflow Language [20] for interoperability of workflows, and with the W3C PROV [35] format for provenance information. These are prioritized areas for future developments.

Case Studies

To demonstrate the usefulness of SciPipe, we have used it to implement a number of representative pipelines from drug discovery and bioinformatics with different characteristics and hence requirements on the workflow system. These workflows are available in a dedicated git repository on GitHub [46].

Machine learning pipeline in drug discovery

The initial motivation for building SciPipe stemmed from problems encountered with complex dynamic workflows in machine learning for drug discovery applications. It was thus quite natural to implement an example of such a workflow in SciPipe. To this end we re-implemented a workflow implemented previously for the SciLuigi library [27], which was itself

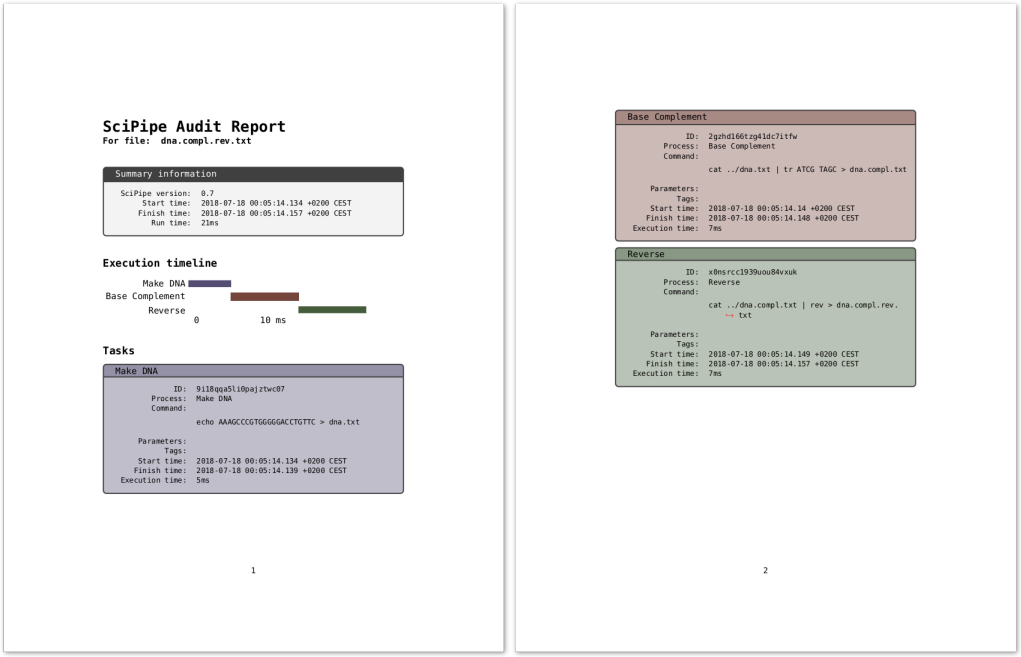

Figure 4. Audit report for the last file generated by the code example in figure 1, converted to TeX with SciPipe's experimental `audit2tex` feature and then converted to PDF with pdfTeX. In the top, the PDF file includes summary information about the SciPipe version used and the total execution time. After this follows an execution time line, in a gantt-chart style, that shows the relative execution times of individual tasks in a graphical way. After this follows a comprehensive list of tables with information for each task executed towards producing the file for which the audit report belongs. The task boxes are color coded and ordered in the same way that the tasks appear in the timeline.

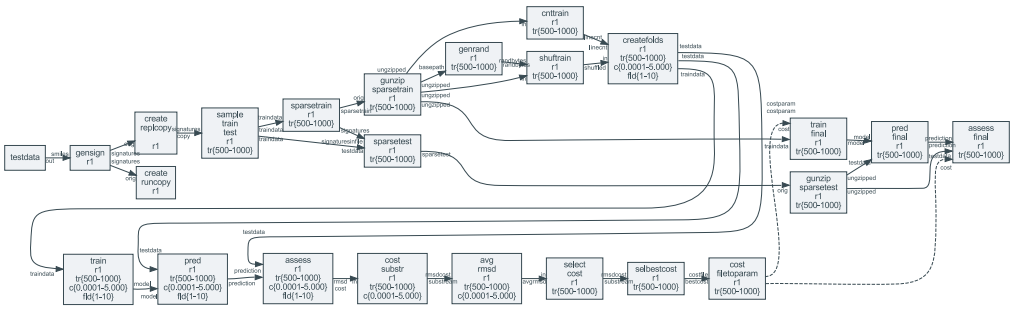

Figure 5. Directed graph of the machine learning drug discovery case study workflow, plotted with SciPipe's workflow plotting function. The graph has been modified for clarity by collapsing the individual branches of the parameter sweeps and cross validation fold-generation. The layout has also been manually made more compact to be viewable in print. The collapsed branches are indicated by intervals in the box labels. `tr{500-8000}` represent branching into training dataset sizes 500, 1000, 2000, 4000, 8000. `c{0.0001-5.0000}` represent cost values 0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.25, 0.5, 0.75, 1, 2, 3, 4 and 5, while `fld{1-10}` represent cross validation folds 1-10. Nodes represent processes, while edges represent data dependencies. The labels on the edge heads and tails represent ports. Solid lines represent data dependencies via files, while dashed lines represent data dependencies via parameters, which are not persisted to file, only transmitted via RAM.

based on an earlier study [47].

In short, this workflow trains predictive models using the LIBLINEAR software [48] with molecules represented by the signature descriptor [49]. For linear SVM a cost parameter needs to be tuned, and we tested 15 values (0.0001, 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.25, 0.5, 0.75, 1, 2, 3, 4, 5) in a 10-fold cross-validated parameter sweep. Five different training set sizes (500, 1000, 2000, 4000, 8000) were tested and evaluated with a test set size of 1000. The raw data set consists of 10,000 logarithmic solubility values chosen randomly from a dataset extracted from PubChem [50] according to details in [27]. The workflow is schematically shown in figure 5 and was plotted using SciPipe's built-in plotting function. The figure has been modified for clarity by collapsing the individual branches of the parameter sweeps and cross validation folds, as well as by manually making the layout more compact.

The implementation in SciPipe was done by creating components which are defined in separate files (named `comp_COMPONENTNAME` in the repository), which can thus be reused in other workflows. This shows how SciPipe can successfully be used to create workflows based on reusable, externally defined components.

The fact that SciPipe supports parametrization of workflow steps with values obtained during the workflow run, meant that the full workflow could be kept in a single workflow definition, in one file. This also made it possible to create audit logs for the full workflow execution for the final output files, and to create the automatically plotted workflow graph shown in figure 5. This is in contrast to the SciLuigi implementation, where the parameter sweep to find the optimal cost, and the fi-

nal training, had to be implemented in separate workflow files (`wffindcost.py` and `wfmm.py` in [51]), and executed as a large number of completely separate workflow runs (one for each dataset size) which meant that logging became fragmented into a large number of disparate log files.

Genomics cancer-analysis pipeline

Sarek [52] is an open-source analysis pipeline to detect germline or somatic variants from whole genome sequencing, developed by the National Genomics Infrastructure and National Bioinformatics Infrastructure Sweden which are both platforms at Science for Life Laboratory.

To test and demonstrate the applicability of SciPipe to genomics use cases the pre-processing part of the Sarek pipeline was implemented in SciPipe. See figure 6 for a directed process graph of the workflow, plotted with SciPipe's workflow plotting function.

The test data in the test workflow consists of multiple samples of normal and tumor pairs. The workflow starts with aligning each sample to a reference genome using BWA [38] and forwarding the results to Samtools [53] which saves the result as a sorted BAM file. After each sample has been aligned, Samtools is again used, to merge the normal- and tumor samples into a one BAM [53] file for tumor samples, and one for normal. Picard [54] is then used to mark duplicate reads in both the normal- and tumor sample BAM files, whereafter GATK [55] is used to recalibrate the quality scores of all reads. The outcome of the workflow is two BAM files; one containing all the normal samples and one containing all the tumor samples.

Genomics tools and pipelines have their own set of requirements, which was shown by the fact that some aspects of SciPipe had to be modified in order to ease development of this pipeline. In particular, many genomics tools produce additional output files apart from those specified on the command-line. One example of this is the extra files produced by BWA when indexing a reference genome in FASTA format. The `bwa index` command produces some five files, which are not explicitly defined on the command-line (with the extensions of `.bwt`, `.pac`, `.ann`, `.amb` and `.sa`). Based on this realization, SciPipe was amended with a folder-based execution mechanism which executes each task in a temporary folder, that keeps all output files separate from the main output directory until the whole task has completed. This ensures that also files that are not explicitly defined and handled by SciPipe, are also captured and handled in an atomic manner, so that finished and unfinished output files are always properly separated.

Furthermore, agile development of genomic tools often requires being able to see the full command that is used to execute a tool, because of the many options that are available to many bioinformatics tools. This workflow was thus implemented with ad-hoc commands, which are defined in-line in the workflow. The ability to do this shows that SciPipe supports different ways of defining components, depending on what fits the use case best.

The successful implementation of this genomics pipeline in SciPipe, thus both ensures and shows that SciPipe is works well for tools common in genomics.

RNA-seq / transcriptomics pipeline

To test the ability of SciPipe to work with software used in transcriptomics, some of the initial steps of a generic RNA-sequencing workflow were also implemented in SciPipe. Common steps that are needed in transcriptomics is to run quality controls and generate reports of the analysis steps.

The RNA-seq case study pipeline implemented for this paper uses FastQC [56] to evaluate the quality of the raw data being used in the analysis before aligning the data using STAR [57]. After the alignment is done it is evaluated using QualiMap [58], while the Subread package [59] is used to do a feature counting.

The final step of the workflow is to combine all the previous steps for a composite analysis using MultiQC [60], which will summarize the quality of both the raw data and the result of the alignment into a single quality report. See figure 7 for a directed process graph of the workflow, plotted with SciPipe's workflow plotting function.

The successful implementation of this transcriptomics workflow in SciPipe ensures that SciPipe works well for different types of bioinformatics workflows and is not limited to one specific sub-field of bioinformatics.

Conclusions

SciPipe is a programming library that provides a way to write complex and dynamic pipelines in bioinformatics, cheminformatics, and more generally in data science and machine learning pipelines involving command-line applications.

Dynamic scheduling allows parametrizing new tasks with values obtained during the workflow run, and the Flow-based programming principles of separate network definition and named ports allow creating a library of reusable components. By having access to the full power of the Go programming language to define workflows, existing tooling is leveraged.

Scipipe adopts state-of-the art strategies for achieving atomic writes, caching of intermediate files and a data-centric audit log feature that allows identifying the full execution trace for each output, that can be exported into either human-readable HTML or TeX/PDF formats, or executable Bash-scripts.

SciPipe also provides some features not commonly found in many tools such as support for streaming via Unix named pipes, ability to run push-based workflows up to a specific stage of the workflow, and flexible support for file naming of intermediate data files generated by workflows. SciPipe workflows can also be compiled into standalone executables, making deployment of pipelines maximally easy, requiring only Bash and any external command-line tools used, to be present on the target machine.

By being a small library without required external dependencies apart from the Go tool chain and Bash, SciPipe is expected to be possible to be maintained and developed in the future even without a large team or organization backing it.

The applicability of SciPipe for cheminformatics, genomics and transcriptomics pipelines has been demonstrated with case study workflows in these fields.

Methods

The Go Programming Language

The Go Programming Language (referred to as just "Go") was developed by Robert Griesemer, Rob Pike and Ken Thompson at Google, to provide a statically typed and compiled language that makes it easier to build highly concurrent programs, that can also make good use of multiple CPU cores (i.e. "parallel program"), than what is the case in widespread compiled languages like C++ [61]. It tries to provide this by providing a small, simple language, with concurrency primitives — go-routines and channels — built-in to the language. Go-routines, which are so called light-weight threads, are auto-

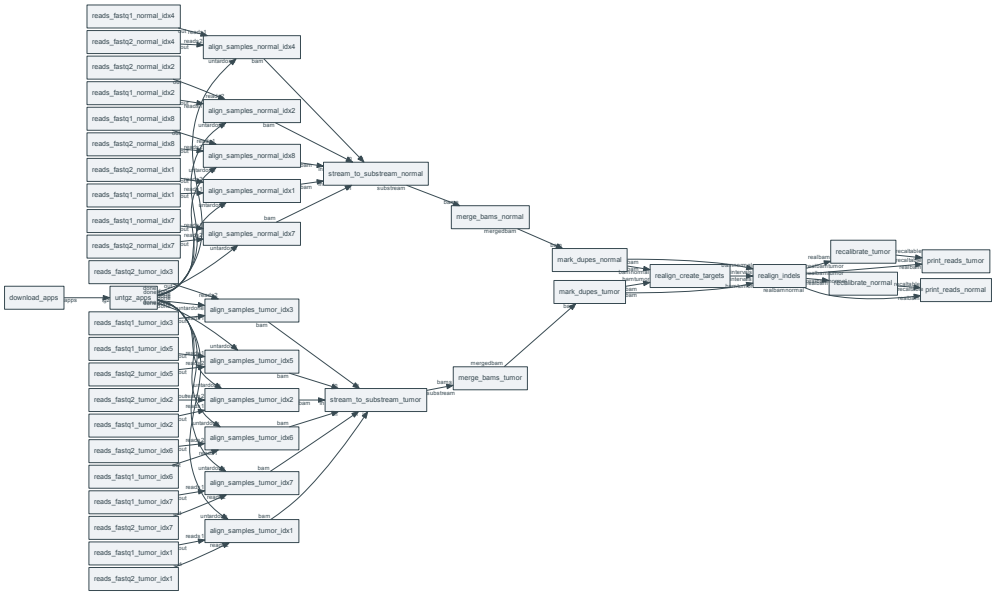

Figure 6. Directed graph of workflow processes in the Genomics / Cancer Analysis pre-processing pipeline, plotted with SciPipe's workflow plotting function. Nodes represent processes, while edges represent data dependencies. The labels on the edge heads and tails represent ports.

Figure 7. Directed graph of workflow processes in the RNA-Seq Pre-processing workflow, plotted with SciPipe's workflow plotting function. Nodes represent processes, while edges represent data dependencies. The labels on the edge heads and tails represent ports.

matically mapped, or multiplexed, onto physical threads in the operating system. This means that very large numbers of go-routines can be created while maintaining a low number of operating system threads, such as one per CPU core on the computer at hand. This makes Go an ideal choice for problems where many asynchronously running processes need to be handled at the same time, or "concurrently", and for making efficient use of multi-core CPUs.

The Go compiler is statically linking all its code as part of the compilation. This means that all dependent libraries are compiled into the executable file. Because of this, SciPipe workflows can be compiled into self-contained executable files without external dependencies apart from the Bash shell and any external command line tools used by the workflow. This makes deploying Go programs (and SciPipe workflows) to production very easy.

Go programs are very performant, often an order of magnitude faster than interpreted languages like Python, and in the same order of magnitude as the fastest languages, like C, C++ and Java [62].

Dataflow and Flow-based programming

Dataflow is a programming paradigm oriented around the idea of independent, asynchronously running processes, that only talk to each other by passing data between each other. This data passing can happen in different ways, such as via dataflow variables, or via first-in-first-out channels.

Flow-Based Programming (FBP) [63] is a paradigm for programming developed by John Paul Morrison at IBM in the late 60s / early 70s, to provide a composable way to assemble programs to be run at mainframe computers at customers such as large banks.

It is a specialized version of dataflow, adding the ideas of separate network definition, named ports, channels with bounded buffers and information packets (representing the data) with defined lifetimes. Just as in dataflow, the idea is to divide a program into independent processing units called "processes", which are allowed to communicate with the outside world and other processes solely via message passing. In FBP, this is always done over channels with bounded buffers which are connected to named ports on the processes. Importantly, the network of processes and channels is in FBP described "separate" from the process implementations, meaning that the network of processes and channels can be reconnected freely without changing the internals of processes.

This strict separation of the processes, the separation of network structure from processing units, and the loosely-coupled nature of its only way of communication with the outside world (message passing over channels) makes flow-based programs extremely composable, and naturally component-oriented. Any process can always be replaced with any other process that supports the same format of the information packets on its in-ports and out-ports.

Furthermore, since the processes run asynchronously, FBP is, just like Go, very well suited to make efficient use of multi-core CPUs, where each processing unit can suitably be placed in its own thread or co-routine to spread out on the avail-

able CPU-cores on the computer. FBP has a natural connection to workflow systems, where the computing network in an FBP program can be likened to the network of dependencies between data and processing components in a workflow [27]. SciPipe leverages the principles of separate network definition and named ports on processes. SciPipe has also taken some inspiration for its API design from the GoFlow [64] Go-based flow-based programming framework.

Availability of supporting source code and requirements

- Project name: SciPipe
- Documentation and project home page: http://scipipe.org
- Source code repository: https://github.com/scipipe/scipipe
- Persistent source code archive: https://doi.org/10.5281/zenodo.1157941
- Case study workflows: https://github.com/pharmbio/scipipe-demo
- Operating system(s): Linux, Unix, Mac
- Other requirements: Go 1.9 or later, Bash, GraphViz (for workflow graph plotting), LaTeX (for PDF generation)
- License: MIT

Availability of supporting data

- The raw data for the machine learning cheminformatics demonstration pipeline is available at: https://doi.org/10.5281/zenodo.1324443
- The applications for the machine learning in drug discovery case study is available at: https://doi.org/10.6084/m9.figshare.3985674.v1
- The raw data and tools for the genomics and transcriptomics workflows are available at: https://doi.org/10.5281/zenodo.1324426

Declarations

List of abbreviations

- API: Application programming interface
- CPU: Central processing unit (the core part of every computer)
- CWL: Common Workflow Language
- DSL: Domain-specific language
- EVM: Erlang virtual machine
- FBP: Flow-based programming
- HDFS: Hadoop distributed file system
- HPC: High-performance computing
- RAM: Random access memory
- SVM: Support vector machine

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Authors' Contributions

OS and SL conceived the project and the idea of component-based workflow design. SL came up with the idea of using Go and Flow-based programming principles to implement a workflow library, designed and implemented the SciPipe library, and implemented case study workflows. MD contributed to the API design and implemented case study workflows. JA implemented the TeX/PDF reporting function and contributed to case study workflows. OS supervised the project. All authors read and approved the manuscript.

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