

I would suggest we avoid the comparison to sequence databases or genome sequence platforms (e.g. assembly, gene annotation etc). We really don't have the capacity to replace EnteroBase, Genbank, IRIDA, etc. I see Spfy as a repository of E.coli phenotypes important for public health. It allows users to rapidly predict phenotypes and retrieve the phenotypes of historical strains to: track trends, observe context among evolutionary related strains, identify biomarkers, etc. In other words, Spfy provides WGS-based phenotypes + big picture comparative genomics. The big picture is only possible by 1. recomputing everything everytime, or 2. storing the results as genomes are analysed. With size of WGS data, option 2 is only viable option Title may need work. Should it mention comparative genomics? Can't be too long thou

Spfy: an integrated graph database for real-time prediction of *Escherichia coli* phenotypes and downstream comparative analyses

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Abstract

Public health laboratories are currently moving to whole-genome sequencing based analyses, and require rapid prediction of relevant pathogen phenotypes impacting health. Current workflows in comparative computational genomics rely on chaining different analysis software together, but lack storage and retrieval methods for the generated results. **Reference laboratories do not care about data retrieval, only real-time results. Researchers care more about context and thus would use a historical record of phenotypes for all predicted strains** To solve this problem, we have created Spfy, which uses a graph database to store and retrieve results from computational workflows. The newly developed Spfy platform facilitates rapid phenotype identification, as well as the efficient storage and downstream comparative analysis of tens of thousands of genome sequences. Though generally applicable to bacterial genome sequences, Spfy currently contains 10,243 *Escherichia coli* genomes, for which *in-silico* serotype and Shiga-toxin subtype, as well as the presence of known virulence factors and antimicrobial resistance determinants have been computed. Spfy links the results and metadata to the genome sequences through a standardized ontology, which facilitates hypothesis testing in fields ranging from population genomics to epidemiology, while mitigating the recomputing of analyses. The graph approach is flexible, and can accommodate new analysis software modules as they are developed, and easily link new results to those already stored. Integrated data storage and analyses are currently necessary to match the rapid accumulation of whole genome sequences in public databases.

Database URL: <https://lfz.corefacility.ca/superphy/spfy/>.

1 Introduction

Whole genome sequencing (WGS) can in theory provide the entire genetic content of an organism. This unparalleled resolution and sensitivity has recently transformed public-health surveillance and outbreak response [1, 2]. Additionally, the identification of novel disease mechanisms [3, 4], and rapid clinical diagnoses and reference lab tests based on the specific mechanism of disease are now possible. [5, 6].

The rapid characterization and comparison of bacterial pathogens relies principally on the combination of outputs from multiple software programs that are targeted for specific applications. Examples include the identification of known antimicrobial resistance (AMR) genes, through software such as the Resistance Gene Identifier (RGI) [7], [8], [9], and ARIBA [10]; or the identification of known virulence factor genes (VF) through software such as VirulenceFinder [8], SRST2 [11], and GeneSippr [12]. For clinical diagnoses and comparisons, individual species can be first divided into subtypes with complementing AMR and VF results. Software methods for subtyping rely on pre-selected intraspecies genes or genomic regions, and are targeted through software such as Phylotyper [13], SerotypeFinder [14], the EcOH dataset applied through SRST2

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[15], and V-Typer [16]. These methods represent *in-silico* analogues of traditional wet-lab tests, which allows new WGS results to be viewed in the context of historical tests, and greatly expedites the analyses of newly sequenced genomes.

Comprehensive platforms that combine individual programs into a cohesive whole also exist. These include free platforms such as the Bacterium Analysis Pipeline (BAP) [17], and the Pathosystems Resource Integration Center (PATRIC) [18]. Commercial applications, such as Bionumerics, which is used by PulseNet International for the analyses of WGS data in outbreak situations also exist, and offer support as well as accredited, standardized tests [19]. These platforms are designed to be applied to individual projects.

Many of the comparative analyses that are currently used in the study of bacterial genomes are broadly useful, and therefore computed multiple times for the same genomes. An effective method to mitigate the recomputing of analyses, is to make the storage and retrieval of results part of the analyses platform, and effectively linked to the genomes of interest through a standardized ontology. Such measures can help ensure the rapid response times required for public health applications, and allow results to be integrated and progressively updated as new data becomes available.

We have previously developed Superphy [20], an online predictive genomics platform targeting *E. coli*. Superphy integrates pre-computed results with domain-specific knowledge to provide real-time exploration of publicly available genomes. While this tool has been useful for the thousands of pre-computed genomes in its database, the current pace of genome sequencing requires real-time predictive genomic analyses of tens-, and soon hundreds-of-thousands of genomes, and the long term storage and referencing of these results, something that the original SuperPhy platform was incapable of.

In this article, we present a new platform merging Superphy’s pre-computed results with a novel data storage and processing architecture, which we call Spfy; Spfy integrates a graph database with real-time analyses to avoid recomputing identical runs. Graph-based result storage also allows retrospective comparisons across stored results as more genomes are sequenced or populations change, and is flexible, accommodating new analysis modules as they are developed. The database is available at <https://lfz.corefacility.ca/superphy/spfy/>.

2 FUNCTIONALITY

Spfy provides rapid *in-silico* versions of common reference laboratory tests for the analyses of *E. coli*. It supports the following *in-silico* subtyping options: serotyping, through both O- and H-antigen identification using ECTyper https://github.com/phac-nml/ecoli_serotyping as well as VF gene determination; Shiga-toxin 1 (Stx1), Shiga-toxin 2 (Stx2), and Intimin typing using Phylotyper [13], and AMR annotation using the RGI program [7]. Spfy also performs pangenome analyses using Panseq [21], with the entire pangenome stored in the database and associated with source genomes.

Spfy handles all of the analyses tasks by dividing them into subtasks, which are subsequently distributed across a built-in task queue. Results are converted into individual graphs and stored within a larger graph database according to the standard ontologies GenEpiO [22], FALDO [23], and TypOn [24], where metadata including genotypes, biomarkers, host, source, and statistical significance testing of genome markers for user-defined groups are stored.

By integrating task distribution with graph storage, Spfy enables large-scale analyses, such as epidemiological association studies. Any data type or relation in the graph is a valid option for analysis. This means that genomes can be compared on the basis of the presence or absence of pan-genome regions, serotype, subtyping

data, or provided metadata such as location or host-source. All results are displayed to users in real-time, usually within 2-3 minutes.

3 IMPLEMENTATION

The server-side code for Spfy, graph generation, and analysis modules, are developed in Python, with the front-end website developed using the React JavaScript library <https://facebook.github.io/react/>. When new data is added to the database, the following steps are taken:

- i) The upload begins through the website, where user-defined analysis options are selected. The results of these analyses are immediately reported to the user following their completion, while all other non-selected analyses are subsequently completed in the background and stored in the database without interaction from the user. The public web service accepts uploads of up to 200 MB (approximately 50 *E. coli* genomes uncompressed, or 120 genomes compressed) at a time, though an unlimited amount of data can be submitted to a local instance.
- ii) User-selected analyses are enqueued into the Redis Queue <http://python-rq.org/> task queue. Redis Queue consists of a Redis Database <https://redis.io/> and task queue workers which run as Python processes.
- iii) The workers dequeue the analyses, run them in parallel, and temporarily store results in the Redis database.
- iv) Python functions parse the results and permanently store them in Blazegraph <https://www.blazegraph.com/>, the graph database used for Spfy.

3.1 Data Storage

Semantic web technologies describe the relationships between data [25], and graph databases for the storage of this information has been proposed as an open standard for sharing public information [26]. For biological data, individual data points can be a genome, contiguous DNA sequence, or gene, and these are linked together in a searchable graph structure using existing ontologies. This system is flexible and allows novel data to be incorporated into the existing graph.

The permanent storage of results is as a one-time cost to avoid recomputation when the same analysis is re-run. For analyses, Spfy searches the graph for all data points annotated with the queried ontology term. This graph data is then converted into the required structure, usually numerical arrays, or as required for the given analysis module. In a graph database, a search can begin at any node or attribute. This is in contrast to a SQL database which requires a predefined schema, or a NoSQL database which treats data as documents with varying structure. For example, the addition of a new analysis module would typically require a new table definition in a SQL database, or the addition of a new document type in a NoSQL database. With a graph database, new nodes or attributes are added and then connected to existing data, removing the need for explicit joins or data conversions. Additionally, data can be added to Spfy in parts, and the database will infer the correct connections between the data.

3.2 Web design

The front-end website is written as a single-page application. To ensure a familiar user interface, we followed the Material Design specification <https://material.io/>, published by Google, surrounding a card-based design. (see Figure 2) Both the task selection and result displays follow the same design pattern: while data storage is graph-based, the results of various analysis modules are presented to users in a familiar tabular structure and available for download as .csv spreadsheet files. (see Figure 3)

No account creation is required to use the platform. A sharable token is automatically created for users upon entering the website, and is embedded into the website address. Users can share results by copying their URL, and files submitted from different computers using the same token will be visible to anyone with the same link.

3.3 Service Virtualization

Docker <https://www.docker.com/> is a virtualization technology to simulate self-contained operating systems on the same host computer, without the overhead of full hardware virtualization [27]. The Spfy platform depends on a series of webservers, databases, and task workers, and uses Docker to compartmentalize these services, which are then networked together using Docker-Compose <https://docs.docker.com/compose/>. (see Figure 4) Docker integration ensures that software dependencies, which are typically manually installed [28, 21, 11, 29], are instead handled automatically.

One of the key benefits of using common-place technologies is the compatibility with other infrastructure resources. Docker containers are widely supported by cloud computing services: Amazon Web Services (AWS) <https://aws.amazon.com/docker/>, Google Cloud Platform (GCloud) <https://cloud.google.com/container-engine/docker/>.

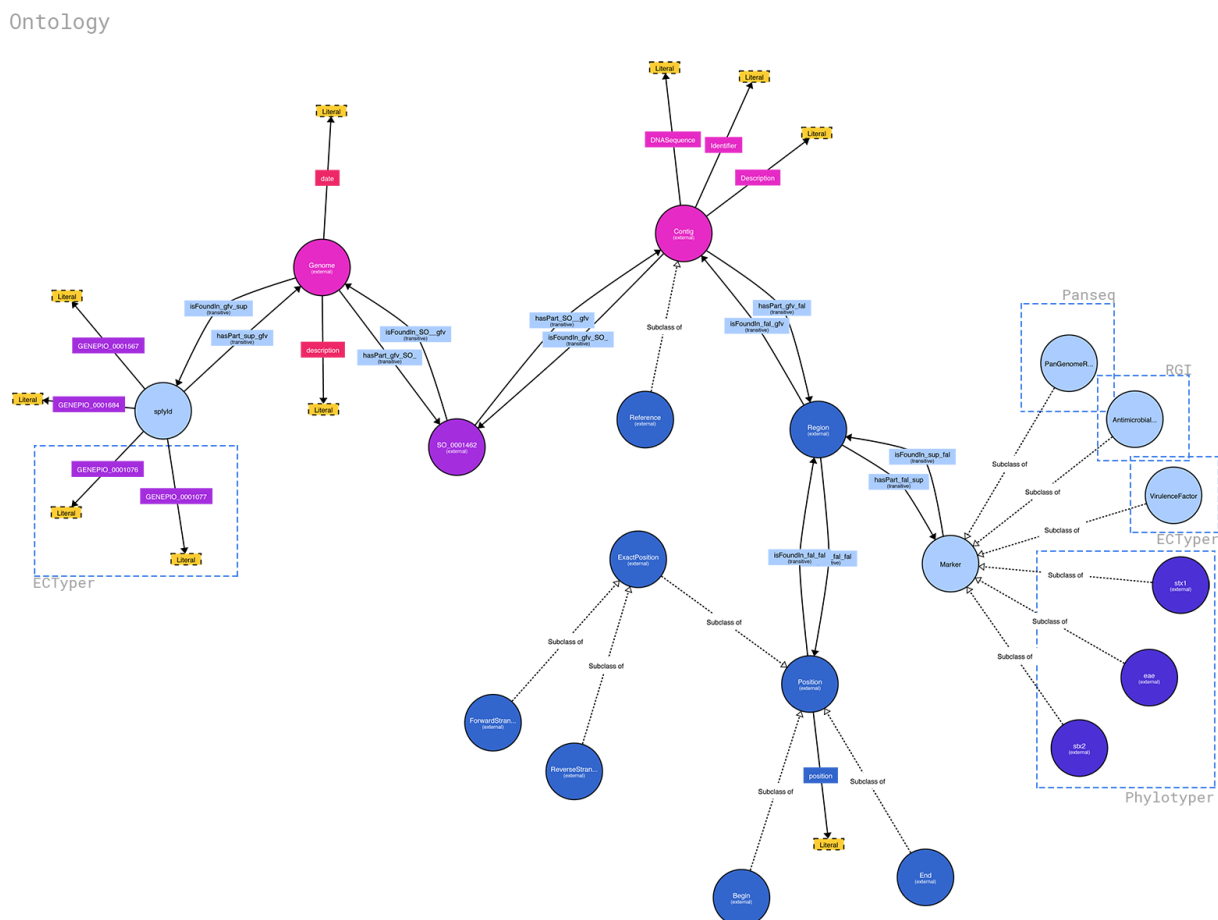


Figure 1: Structure of Spfy’s graph database. Brackets highlight the source of different data points and the software it was generated from. These parts are added in as the analysis modules complete, at varying times, and the overall connections are inferred by the database. Non-bracketed sections are sourced from the uploaded genome files or user-supplied metadata.

com/container-engine/, and Microsoft Azure <https://azure.microsoft.com/en-us/services/container-service/>, and self-hosted cloud computing technologies such as OpenStack <https://wiki.openstack.org/wiki/>

The screenshot shows the Spfy interface with a sidebar containing 'Tasks' and 'Results' tabs. The main content area displays four task cards:

- Task 1:** Icon 'da', Title 'Database status as of: 11:43:34 AM', Submitted: 11:43:34 AM, Status: COMPLETE, JobId: fdef2756-ef67-4366-975b-16bafdc9a597. Button: SEE RESULT.
- Task 2:** Icon 'Su', Title 'GCA_001911775.1_ASM191177v1_genomic.fna with pi: 90 for Serotype VF', Submitted: 11:43:42 AM, Status: COMPLETE, JobId: blob7151249537150029571. Button: SEE RESULT.
- Task 3:** Icon 'fi', Title 'O157 vs O169 for https://www.github.com/superphy#AntimicrobialResistanceGene', Submitted: 11:44:22 AM, Status: COMPLETE, JobId: 79382759-b2b5-4a2f-b3e6-5adade6eda29. Button: SEE RESULT.
- Task 4:** Icon 'Su', Title '10 Files with pi: 90 for Serotype VF AMR', Submitted: 11:44:45 AM, Status: Pending, JobId: blob4433578772837076418.

Figure 2: First entry into the results interface for submitted tasks. Cards represent individual tasks and the entire collection can be viewed by sharing the URL with the embedded token.

The screenshot shows the Spfy interface with a sidebar containing 'Tasks' and 'Results' tabs. The main content area displays a table with the following columns: Filename, Contig ID, Analysis, Hit, Orientation, Start, Stop, and Cutoff. The table contains 20 rows of data:

| Filename | Contig ID | Analysis | Hit | Orientation | Start | Stop | Cutoff |
|---|----------------|----------------|----------|-------------|-------|-------|--------|
| GCA_001911825.1_ASM191182v1_genomic.fna | n/a | Serotype | O88:H25 | n/a | n/a | n/a | n/a |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheA | - | 50899 | 50899 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheB | - | 44076 | 44076 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheR | - | 44939 | 44939 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheW | - | 48914 | 48914 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheY | - | 43012 | 43012 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | cheZ | - | 42612 | 42612 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhA | - | 40625 | 40625 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhB | - | 41766 | 41766 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhC | - | 53419 | 53419 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhD | - | 53781 | 53781 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhE | - | 38547 | 38547 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhA | - | 76587 | 76587 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhS | + | 80325 | 80325 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhT | + | 80690 | 80690 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhY | - | 75183 | 75183 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | flhZ | - | 75858 | 75858 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | motA | - | 52714 | 52714 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | motB | - | 51830 | 51830 | 90 |
| GCA_001911825.1_ASM191182v1_genomic.fna | LGMU01000001.1 | Virulence F... | tar/cheM | - | 48266 | 48266 | 90 |

Figure 3: An expanded result for a subtyping task. While data storage in Spfy is graph-based, a familiar tabular structure is presented to users. The result can also be shared using the URL with the embedded token.

Docker. Spfy packages compute nodes as reproducible Docker containers, and allows the platform to easily scale to demand.

3.4 Continuous integration

Our tests for functionality and backwards compatibility run on TravisCI <https://travis-ci.io>, a continuous integration (CI) platform. The individual tests use PyTest <https://doc.pytest.org/>, and the current build status can be checked either on our GitHub repository or at <https://travis-ci.org/superphy/backend>. TravisCI also builds the core Docker images for Spfy, and uploads them to Docker Hub <https://hub.docker.com/u/superphy/>.

4 RESULTS

Spfy was tested with 10,243 public *E. coli* assembled genomes from Enterobase, storing every sequence and the results for all included analysis modules. This included: serotyping (O-antigen, H-antigen), toxin subtyping (Shiga-toxin 1, Shiga-toxin 2, and Intimin), the identification of VF and AMR determinants, and determination of the pan-genome content of *E. coli*. The resulting database has 17,820 nodes and 3,811,473 leaves, with 1,125,909,074 object properties. Spfy has been up since May 2017. The server accepts assembled *E. coli* genomes with the *.fasta* or *.fna* extensions. Submissions are subjected to quality control, ensuring the submitted genomes are *E. coli* sequences before subsequent analyses are run.

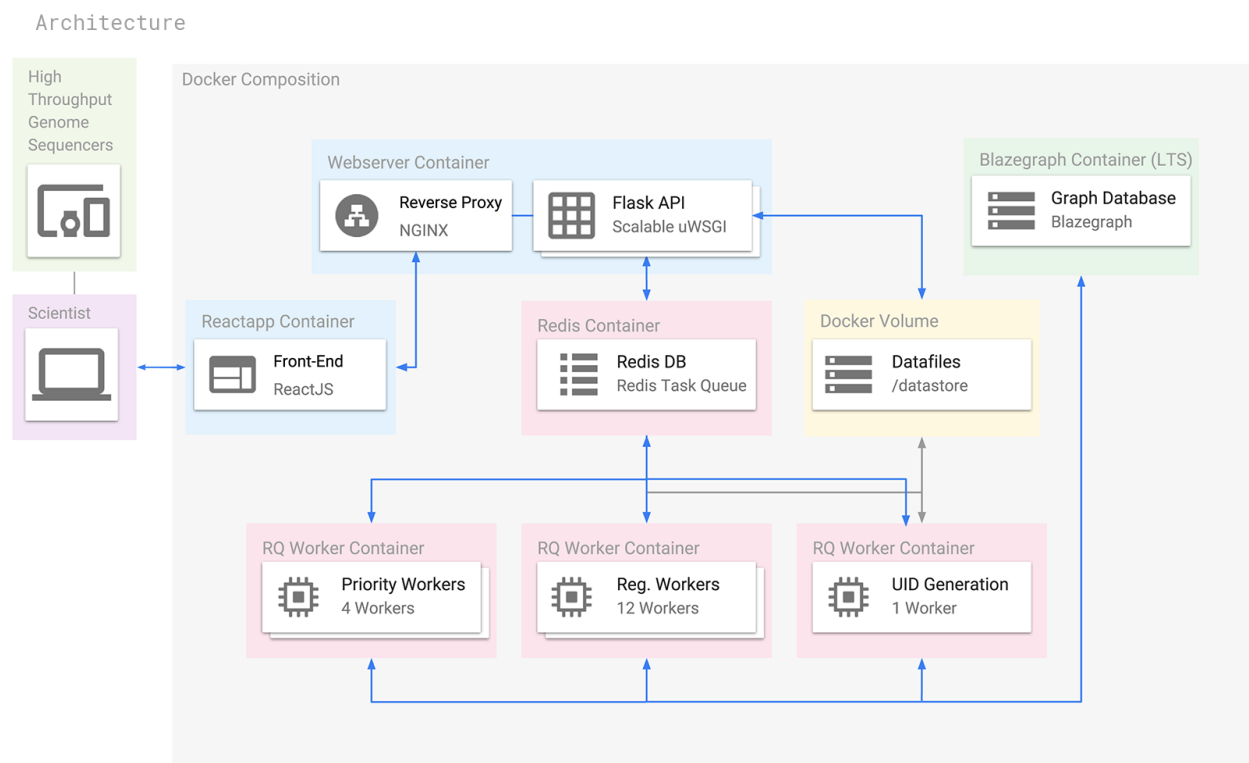


Figure 4: The various Docker containers used in Spfy. Arrows represent the connections between different containers, and the entire platform can be recreated with a single command using its Docker-Compose definition.

5 DISCUSSION

Many bioinformatics software programs have been developed *ad hoc*, with individual researchers and laboratories developing software specific to their environment [30]. Such tools were often script-based, with custom data formats, and only suitable for small collections of data [30]. Recent efforts [31, 17] have focused on providing a common web interface for these programs, while still returning the same result files. However, many subsets of biology now require the analyses of big-data, where inputs are taken from a variety of analysis programs, and involve large-scale data warehousing [32]. The ability to integrate data from different source technologies, merge submissions from other labs, and distribute computations over fault-tolerant systems are now required for the types of analyses that need to be performed [32].

One of the key goals in developing Spfy was to accommodate and store a variety of result formats, and then to make the data from these results retrievable and usable as inputs for downstream analyses, such as predictive biomarker discovery. We have shown how a graph database can accommodate the results from a variety of bioinformatics programs, and how Spfy is performant for data retrieval on the results for multiple analyses among over 10,000 genomes, providing results from big-data comparisons in the same efficiency as old analyses on single files.

5.1 Impact on Public Health Efforts

The isolation and characterization of bacterial pathogens are critical for Public Health laboratories to rapidly respond to outbreaks, and to effectively monitor known and emerging pathogens through surveillance programs. Until recently, public-health agencies relied on laboratory tests such as serotyping, pulsed-field gel electrophoresis (PFGE), PCR-based amplification of known VFs, and disc-diffusion assays to identify AMR, for the characterization of bacterial isolates in outbreak, surveillance, and reference laboratory settings [1]. Current efforts are focused on predictive genomics, where the relevant phenotypic information can be determined through examination of the whole-genome sequence without need for the traditional laboratory tests.

Spfy provides rapid and easy predictive genomic analyses of *E. coli* genomes while also addressing the problem of large scale comparisons. With the larger datasets involved in population genomics, it is no longer viable for individual researchers to download data to perform comparisons. Instead, efforts have focused on storing biological data online and enabling analyses on that data [32]. By using a graph database, Spfy can integrate results from different technologies including software predicted phenotypes as well as laboratory results and user-submitted metadata. In addition, datasets can be built and submitted from multiple labs for joint analyses.

5.2 Comparison with other bioinformatic pipeline technologies

The automated analyses of WGS is currently facilitated by existing scientific workflow technologies such as Galaxy [31]. Galaxy aims to provide a reproducible, computational interface which is accessible to individuals without programming knowledge. Galaxy defines a formal schema for linking different analysis software together, so the entire pipeline can be replicated and also extended as new tools are developed. The Galaxy workflow focuses on running an individual analysis pipeline. It does not include functionality to store and collate analysis results for large-scale comparative studies.

Table 1: Database statistics for the various types of nodes, leaves, and associated entries in the graph database, Blazegraph. The database stores all results from every included analysis module and associated metadata. Numbers are representative for analysis of 10,243 assembled genomes.

| name | indexType | m | height | nnodes | nleaves | nentries | nodeBytes | leafBytes | totalBytes |
|------------------|-----------|------|--------|--------|---------|-----------|-----------|-------------|-------------|
| __globalRowStore | BTree | 32 | 1 | 1 | 6 | 102 | 193 | 8537 | 8730 |
| kb.lex.BLOBS | BTree | 692 | 2 | 17 | 6727 | 3227686 | 90596 | 60187016 | 89331537662 |
| kb.lex.ID2TERM | BTree | 905 | 2 | 88 | 39912 | 18080577 | 515355 | 293436043 | 2058798455 |
| kb.lex.TERM2ID | BTree | 193 | 3 | 1153 | 147978 | 18080577 | 5596557 | 1152764154 | 1158360711 |
| kb.spo.JUST | BTree | 284 | 3 | 13213 | 2042532 | 299426518 | 77979362 | 15527483178 | 15605462540 |
| kb.spo.OSP | BTree | 708 | 3 | 1649 | 639325 | 262364538 | 11448125 | 3760927987 | 3772376112 |
| kb.spo.POS | BTree | 990 | 2 | 864 | 463188 | 262364538 | 8347594 | 2246478879 | 2254826473 |
| kb.spo.SPO | BTree | 1024 | 2 | 835 | 471805 | 262364538 | 10308603 | 2661857997 | 2672166600 |

The Bacterium Analysis Pipeline (BAP) [17] provides an integrated analysis pipeline for bacterial WGS data as a web service. It provides an individual per-genome report of the determined species, multilocus sequence type, VF and AMR genes [17].

Spfy is similar to these technologies in that it automates workflows for users, and as in Galaxy, uses task queues to distribute selected analyses. On a per file basis, Spfy performs at a similar speed to BAP on predictive genomics tasks, usually completing within 2-3 minutes, though Spfy does not provide genome assembly services. However, unlike these workflow managers, Spfy is designed to help solve the needless recomputation of analyses by storing results in a graph database for downstream comparative studies. This allows Spfy to perform population-wide analyses, regardless of the individual software used to generate the results for a given genome.

Table 2: Comparison of various bioinformatic pipelines and their underlying database. Functionally, Spfy integrates different analysis modules as in BAP while also merging large datasets as in PATRIC.

| | Spfy | Galaxy | BAP | PATRIC |
|----------|---------------------|---------------------|---------------------|---------------------|
| Database | Blazegraph | PostgreSQL | MySQL + File System | MongoDB + Shock |
| Type | Graph | SQL | SQL + File System | NoSQL |
| Focus | Integrated Analyses | Workflow Technology | Batch Analysis | Integrated Analyses |

PATRIC [18] and Spfy share the same goal of integrated analyses. PATRIC adds support for comparing up to nine user-submitted genomes against a reference genome, targeting various gene annotations. The platform indexes a NoSQL document store to compare similar document types and is beneficial for comparative genomics. Unlike PATRIC, Spfy is targeted towards statistical comparisons of any permutation of a population group based on the chosen data types, and Spfy’s graph database has no limit on the number of genomes grouped for comparison. For example, Spfy can compare all genomes with a particular subtype for gene annotations, source metadata targets for gene annotations, or any two (or more) node or attribute types as shown in 5.

The screenshot shows the Spfy web interface. On the left is a sidebar with a 'spfy' logo and two menu items: 'Tasks' and 'Results'. The main content area is titled 'Group: 0' and contains a 'Define a relation' section. This section has a 'Negate' toggle (currently off), a 'Relations' dropdown menu (currently showing 'O-Type'), and an 'Attributes' dropdown menu (currently showing 'O157'). Below this is a section for 'Group: 1' with similar controls, showing 'O-Type' for Relations and 'O26' for Attributes. At the bottom is a 'Target' section with a 'Select a Target' dropdown menu showing 'Virulence_Factor'. A blue 'SUBMIT' button is located at the bottom right of the main content area.

Figure 5: Genomes can be grouped by any node or attribute type for comparisons, and Spfy has no upper bound for the number of genomes in a group. Different types can also be joined into a group through logical connectives AND, OR, Negation, and any data type is also a valid target. This approach can be used to compare any data regardless of source software.

6 CONCLUSIONS

Future work will focus on adding additional analysis modules to aid genotype to phenotype predictions using machine learning modules, and supporting bacterial species such as *Salmonella*, and *Campylobacter*. While the integrated approach of storing and retrieving results provides enormous benefits, the developed analyses modules are self-contained and be transferred to existing platforms such as Galaxy. The source code for Spfy is hosted at <https://github.com/superphy/backend>, and is available for free under the open-source Apache 2.0 license. A developer guide is provided at <https://superphy.readthedocs.io/en/latest/>.

Conflict of interest. None declared.

7 ACKNOWLEDGEMENTS

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8 APPENDIX