GitHub2PROV: Provenance for Supporting Software Project Management

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Abstract

Software project management is a complex task that requires accurate information and experience to inform the decision-making process. In the real world software project managers rarely have access to perfect information. In order to support them, we propose leveraging information from Version Control Systems and their repositories to support decision-making. In this paper, we propose a PROV model GitHub2PROV, which extends Git2PROV with details about *GitHub commits* and *issues* from GitHub repositories. We discuss how this model supports project management decisions in agile development, specifically in terms of Control Schedule Reviews and workload.

CCS Concepts • **Theory of computation → Data provenance**; • **Software and its engineering →** *Agile software development*.

Keywords process provenance data, software project management, PROV

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1 Introduction

Software project management is the application of knowledge, skills, and tools to manage activities to meet project requirements [6]. It requires managers to balance cost, scope, and schedule, to meet these requirements. This balance is difficult to achieve and poor management results in financial losses. The Project Management Institute (PMI) reports that 9.9% of every dollar invested in projects is wasted[1], and around $1 million is wasted every 20 seconds or $2 trillion every year[2].

The PMI attributes wastage to three factors: 1) Failing to bridge the gap between strategy design and delivery; 2) Executives do not recognise that their strategy is delivered through projects; and the most relevant to this paper 3) the "importance of project management as the driver of an organization's strategy isn't fully realized"[1]. To enable software project managers to make rational critical decisions, they require complete, unbiased and accurate data. However, in the real world decision makers rarely have access to perfect information, and data may be so poorly presented that a decision is not obvious[3]. It can be hard for managers to access data because of the opacity of software engineering tools. They usually make decisions under time pressure and with inadequate data of questionable accuracy. Often decisions are based on a manager's experience and trusted parties' opinions[3].

Version Control Systems (VCS) such as Git, are commonly used for project development. They use branching, the duplication of a commit, for developing new features in parallel along both branches. These VCS repositories are typically hosted on cloud services such as GitHub, because they provide additional tools for development teams to manage and track their projects. Both VCS and hosting services offer flexibility in their use, and thus teams' working practices can vary greatly especially because there is no standardised process on how to interact with them.

Provenance data models describe the linage of data and this can describe the software engineering process. The Git2PROV [3] tool already models Git processes using PROV but this model data does not describe collaborations relating to decisions behind commits. Git process handles the versioning of files, whereas GitHub provides all of the social aspects of development, such as issue reporting and development collaboration. The complexity of these social interactions is compounded by the number and types of development branches (see Figure 1[4]), and distributed development. In

[1]PMI Report 2018: https://www.pmi.org/-/media/pmi/documents/public/pdf/learning/thought-leadership/pulse/pulse-of-the-profession-2018.pdf?sc_lang_temp=en

[2]Brightline Initiative: https://www.worldfinance.com/strategy/the-brightline-initiative-gives-life-to-ideas

[3]PMI Critical Decision Making Skills for Project Managers: https://www.pmi.org/learning/library/critical-decision-making-skills-project-managers-5798

[4]A successful Git branching model: https://nvie.com/posts/a-successful-git-branching-model/

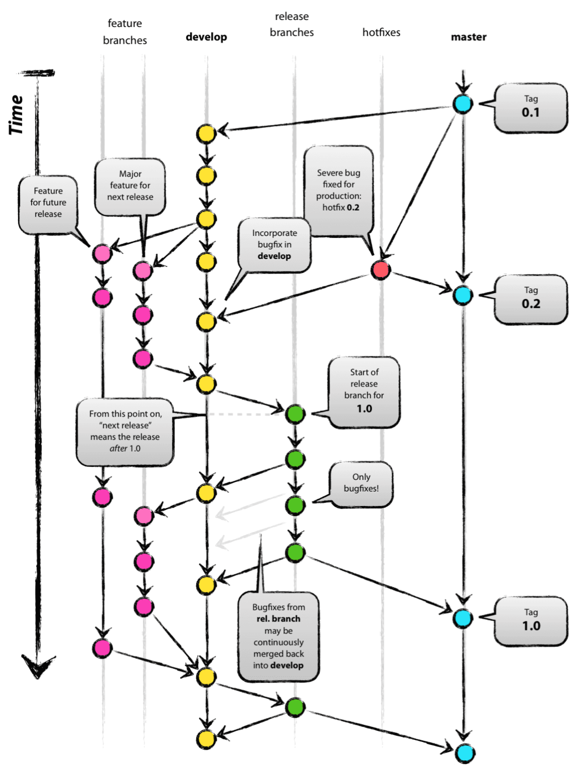

feature branches
develop
release branches
hotfixes
master
Time
Tag 0.1
Major feature for next release
Feature for future release
Severe bug fixed for production: hotfix 0.2
Incorporate bugfix in develop
Tag 0.2
Start of release branch for 1.0
From this point on, "next release" means the release after 1.0
Only bugfixes!
Bugfixes from rel. branch may be continuously merged back into develop
Tag 1.0

Figure 1. Complexity of managing branches [4] license: Creative Commons.

order for software project managers to track and analyse the development of features they require more social information than Git2PROV can provide to predict the time required to develop features for creating schedules. In order to better support them, we propose GitHub2PROV. It uses PROV to model social interactions influencing software project development, specifically issues. Concretely, in this paper we:

1. Present a PROV model called GitHub2PROV, which extends the Git2PROV model;
2. Show how GitHub2PROV can provide insights into software development from multiple sources, both GitHub API and git file;
3. Evaluate our model against metrics described in related work to support decision-making in agile development.

The rest of the paper is as follows. In Section 2 we describe software development management in terms of Agile development using Git and Git web hosted repositories. We then, in Section 3 describe related work including PROV, Git2PROV, PROV workflows and process provenance. Then in Section 4, we present our model GitHub2PROV. Following that, in Section 5 we discuss how our model can support project managers. In Section 6 we provide a discussion about our model, it's uses and limitations. Finally, in Section 7 we conclude and present our future work.

2 Software Development Management

Adaptive life cycles, also known as agile methods, are intended to respond to high levels of change. They are iterative and incremental, and unlike other methods, their iterations are very rapid with iterations usually have a duration of 2 to 4 weeks [6]. Git manages low-level version control transactions. It is the de facto standard for agile software development when it comes to version control systems[5]. It supports a range of workflows and allows changes to be quickly pushed down the development pipeline.

There are many tools that are used to support Agile software engineering from communication through source repository. We now discuss the popular tools, Git and GitHub, an example of a web hosted repository.

2.1 Git and Web Hosted Repositories

Git is a VCS, where users can create a snapshot of files by committing them to Git. Typically a user would follow this process to create a *git commit*[6] :

1. They create files on their local machine;
2. Then they stage these files ready for a commit;
3. The staged files are then pushed to a Git repository. This Git repository can be hosted either locally or on an online repository hosting service.

Each committed snapshot is stored within a Git repository, allowing users to view changes between commits and revert code to previous versions. A series of commits can be described as a graph, where it is possible to create separate chains of commits, called branches. A repository will usually have a main or Master branch that is considered the primary version of the code. Additional branches allow users to diverge from the Master branch so that work can continue on features without changing the Master. Software projects and developers have different approaches to using branches to manage the evolution of a codebase. For example, Gitflow[7] proposes a Master branch to hold production-ready code, and a Develop branch where the code is assembled until it has reached a stable point suitable for merging to Master. Development work on features and bug fixes is conducted on separate branches after which developers will merge to Master.

Web services such as GitHub[8] and Bitbucket[9], allows users to publish their Git repositories online. Git repositories are commonly hosted on web services because they allow users to collaborate on the development of features, and report

[5]Atlassian Agile Coach: https://www.atlassian.com/agile/software-development/git
[6]The numbered stages be described using Git2PROV
[7]https://nvie.com/posts/a-successful-git-branching-model/
[8]GitHub: http://github.com
[9]BitBucket: http://bitbucket.com

issues. The way in which users interact with GitHub and similar services can vary greatly due to a team's working practices and the range of features offered to manage changes; there is no standardised process for interacting with Git.

2.2 Agile Software Engineering and Management Metrics

Software project managers require tools to make sense of project development. There are numerous third party tools available via GitHub's marketplace, these tools however provide limited customisation on the data provided. The focus of our work is to develop a model that is flexible enough for managers to construct their own queries. These queries can be used to create a Control Schedule to monitor the status of the project [6]. The goal of this process is to identify any deviations from the plan so that corrective and preventive actions can be taken.

A **Control Schedule** (taken from *A Guide to the Project Management Body of Knowledge* (PMBOK) [6]) determines:

P1 The total amount of work delivered;
P2 The rate at which deliverables are produced;
P3 Whether deliverables are validated; and
P4 The velocity of a team.

3 Background and Related Work

In order to model provenance, we will be using the W3C standard language PROV [4]. PROV describes provenance using a conceptual model PROV-DM, which can be serialized using the PROV formats PROV-O, PROV-XML, PROV-N, and queried using PROV-AQ. It has three core concepts, `prov:Entity`, `prov:Activity`, and `prov:Agent`, and their relationships.

The Git2PROV tool [3] was developed to map a Git repository to the PROV format. The tool generates PROV (see Figure 2) describing:

1. The activity of committing a set of files. This is expressed as a `prov:Activity` that connects two `prov:Entity` objects, expressed through `prov:used` and `prov:wasGeneratedBy` relations. Figure 2 shows PROV of a commit c which uses a file f_{c-1} and generates a file f_c [3];
2. The version of the files that were committed and how they relate to the previous versions. This is represented using a dependency between two objects expressed as the relationship between two `prov:Entity` objects using the relations `prov:wasDerivedFrom` and `prov:specializationOf`, where a file f_c was derived from another previous file f_{c-1}, both are a specialization of a certain file f [3];
3. Agents who authored and committed the files, are expressed as `prov:Agent` which created the Entity using the relations `prov:wasAttributedTo` and `prov:wasAssociatedWith`, modeling the two potentially distinct roles of a author and a committer [3].

While Git2PROV describes the chain of commits within a Git repository, on both locally and cloud-hosted services, it does not describe the collaborations that those cloud-hosted services facilitate.

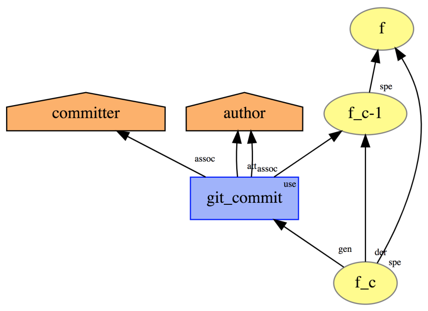


Figure 2. Git2PROV, attributes are not shown for clarity.

In addition to the Git2PROV, the provenance community has also explored PROV to document the Software Development Process (SDP), this research area was identified in 2010 as an emerging field in [9] and it has not yet filtered through into software project management. The following related work discusses provenance and SDP.

Miles et al. [8] propose PRiME, a technique that adapts application designs to enable them to interact with a provenance middleware layer. They detail how to apply PRiME and analyse its effectiveness using two case studies. Wendel et al. [11] present a solution to common failures in software development processes based on PRiME. Notably, they identify that users are concerned with quality reassurance, process validation, statistical analysis, and process optimisation. Junaid et al. [5] propose using a system, called iSPuP, that intercepts users actions with suggestions of possible future tasks, based on captured provenance. iSPuP aims to improve processes and their focus is to support software process execution, monitoring, and analysis phases to improve software processes.

Costa et al.'s [2] work investigates whether process provenance data can provide information to support software process execution, monitoring, and analysis phases, contributing to the process improvement as a whole. Notably, their paper conducted a survey of approaches describing software process execution and found 16 publications. These papers either suggested the use of generic tools for process management or adopt proprietary solutions. None of these proposals uses data provenance.

Costa et al. [1] presents an approach for visualising software process provenance data, called SPPV. To evaluate their work they run an exploratory analysis using two real-world industry processes, with positive feedback from the process

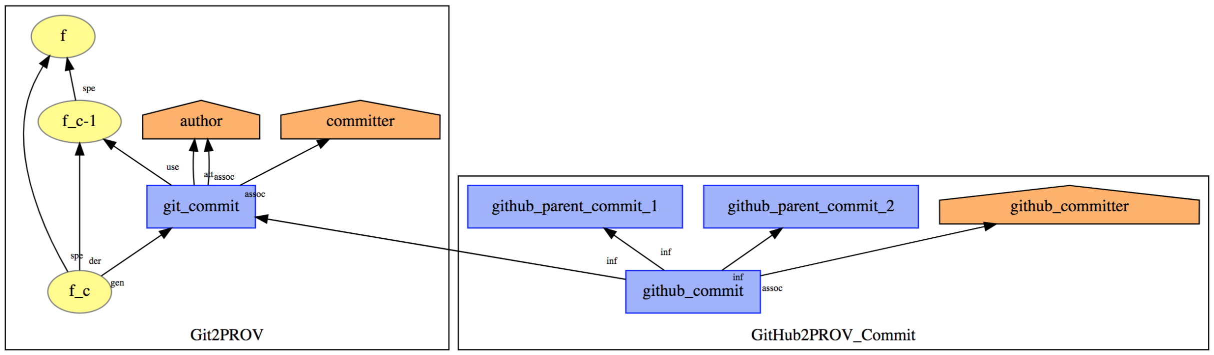


Figure 3. Github2PROV and Git2PROV commit, attributes for type, state and label not shown for clarity.

experts. In their evaluation they investigated whether provenance data could support managers in identifying problems with **workloads**, using the following questions [1]:

Q1 How many entities/artifacts were manipulated by the agent?
Q2 How often are these entities manipulated by the agent over time?
Q3 How many activities/tasks were completed by the agent?
Q4 How often are these activities performed by the agent over time?
Q5 How many activities/tasks, related to new requests, were started by the client?

4 Mapping of GitHub to PROV

In order to investigate whether PROV models can inform software project management, we use the GitHub's API[10]. We selected GitHub because it has become a de facto standard for software development, with over 31 million developers and 96 million repositories in 2018[11], and its API is RESTful which allows resources to be modeled as resolvable elements in a PROV graph. Our model, GitHub2PROV, makes use of two core resources within a GitHub project, Commits, and Issues. We describe the mapping of these two resources in the following two sections.

4.1 Commits

In this paper, we discuss Commit resources which are referred to by both Git2PROV and our GitHub2PROV model. We will use the naming convention *Git commit* and *GitHub commit* to describe commits provided by Git2PROV and GitHub2PROV models. While we make the distinction between *Git commit* and *GitHub commit*, these two activities describe the same commit activity. Git2Prov's *Git commit* is not resolvable, hence we utilise the URL provided by GitHub's API to describe the *GitHub commit* entity. Concretely, resolving a *GitHub commit* entity's URL provides details about the committer, author, message, and verification.

GitHub's API describes a *GitHub commit* resource and provides details including the *GitHub commit*'s message, any comments, build status, the author and committer. Our mapping is shown in Figure 3, and the two classes that we used are identified below. For each class, we describe how provenance can be expressed using concepts from the PROV Data Model [10]:

1. Communication - where $github\_commit$ is informed by $github\_parent\_commit\_1$ and $github\_parent\_commit\_2$. Where $github\_parent\_commit\_2$ is optional. Having two parent *GitHub commits* represents a merge.
2. Attribution - where the $github\_commit$ activity is attributed to $github\_committer$ using the `prov:wasAssociatedWith` relation.

In order to map our model onto Git2PROV, we use a communication relation, $wasInformedBy$, between a *Git commit* and *GitHub commit* (see Figure 3).

4.2 Issues

GitHub has an issue tracking system which manages and maintains lists of issues. It is useful in Agile development because they support collaboration, particularly in large or geographically distributed communities. GitHub's API describes an issue resource and details a list of events that have occurred against that issue. In order to model issues, we have identified three cases:

1. **A new issue** (see Figure 4), where an issue has been created in a project. We describe our model using concepts from the PROV Data Model [10]:
   a. Communication - where $annotator\_commit$ is informed by $issue\_event\_annotation$.
   b. Attribution - where $github\_annotator$ was attributed to $issue\_version\_annatotion$.
   c. Dependency - issue $issue\_version$ is a specialization of a certain issue $issue$.
   d. Activities - an event $issue\_event$ generates a new issue version $issue\_version$;

[10]GitHub API v3 https://developer.github.com/v3/
[11]https://octoverse.github.com/

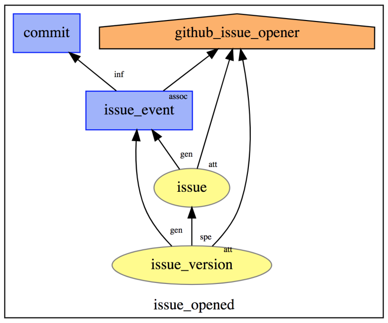


Figure 4. Github2PROV new issue, attributes for type, state and label not shown for clarity.

2. **A new issue event** (see Figure 5a), where an event has happened on an existing issue. The API has 26 different event types[12]. For example, when an issue was: assigned, closed, milestoned, referenced, renamed, reopened, and subscribed. We describe our model using concepts from the PROV Data Model:
   a. Communication - where *commit* is informed by *issu e_event*.
   b. Attribution - where *github_issue_opener* was attributed to *issue* and *issue_version*.
   c. Dependency - where, an issue *issue_version* was derived from another previous file *issue_version*, both are a specialization of a certain issue *issue*.
   d. Activities - where an event *issue_event_annotation* generates a new issue version *issue_version_annot–ation*;
3. **A new event with type marked as duplicate**, which is a special case of Case 2. We model this case because software project managers benefit from understanding the development effort on the same or similar issues. An issue is marked as a duplicate so that users can track similar issues and remove unnecessary overheads of managing two issues. This type of event will use the combination of models in Figures 5a and 5b. The alternate relationship between *issue_version _annotation* and *previous_issue* describes when an issue is marked as a duplicate of another issue because it details aspects of the same issue.

The following table describes the attributes for the issue entities and issue event activities:

PROV element	Type	Description
Issue Entity	prov:type	title of issue
	state	open/closed
Issue Event Activities	prov:type	title of issue
	endTime	xsd:dateTime

[12]List of issue event types: https://developer.github.com/v3/issues/events/

5 Applying the GitHub2PROV Model

In order to evaluate Git2PROV, we discuss how it can support (i) the compilation of a Control Schedule Review (see Section 2.2), and (ii) workload (see Section 3), using metrics derived from the GitHub2PROV. We note that the metrics we discuss in this Section are useful in project management, however, none of them provide insight into the causes of the results but they do provide discussion points to evaluate a team's progress.

In order to evaluate our metrics, we have generated GitHub 2PROV and Git2PROV models for the LibVips project[13], a popular imaging processing library which was first developed in 1995 and its Git repository was first pushed to GitHub in 2007. At the time of generating the model, it had 5,684 *github commits*, 51 open issues, and 998 closed issues. In Figure 6 we depict an excerpt of the LibVips provenance.

5.1 Control Schedule Review

In order to discuss how our model can support a Control Schedule Review, we first identify metrics that can be used (see Section 2.2):

M1 Open/close rates - how many issues are reported and how many issues closed within a specific time period. This metric describes the volume of work that has been completed and supports $P1$.

M2 Lead Time - how long it takes for a feature to be in the delivered software. This metric supports $P2$, which can be used to provide context on the rate at which deliverable is produced on the project.

M3 Cycle Time - how long it takes for a change to be made to the software system and deliver that change into production. This metric helps describe the rate at which deliverable is produced, thus supporting $P2$.

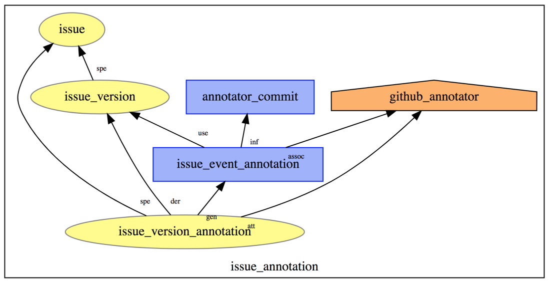
M4 Team velocity - how many "units" of software the team typically completes in an iteration. This supports $P4$.

The above metrics do not address item $P3$, this is because our model, for now, does not describe validation processes. We plan to address this in future work.

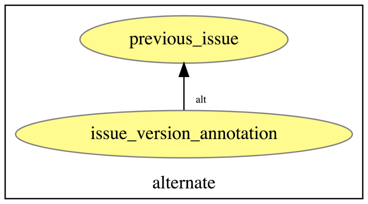
A common requirement in the evaluation of metrics used for a Control Schedule Review is the start and end time for a given activity such as the development of a feature. The use of our model allows the explicit timing information derived from a traditional issue tracker to be combined with the implicit timing provided by other activities such as commits. The *activity start* is defined as the earliest activity directly attributable to the issue. The *activity end* would usually be the point in time that code is merged to production, after which CI/CD pipelines or code release processes take over.

In Table 1, we present a description of our metrics, which PROV elements are used to calculate the metrics, and metric values taken from the month of January 2019 from the

[13]LibVips: https://jcupitt.github.io/libvips/



(a) New issue event



(b) Marked as duplicate

Figure 5. Github2PROV new event and marked as duplicate, where attributes type, state and label not shown for clarity.

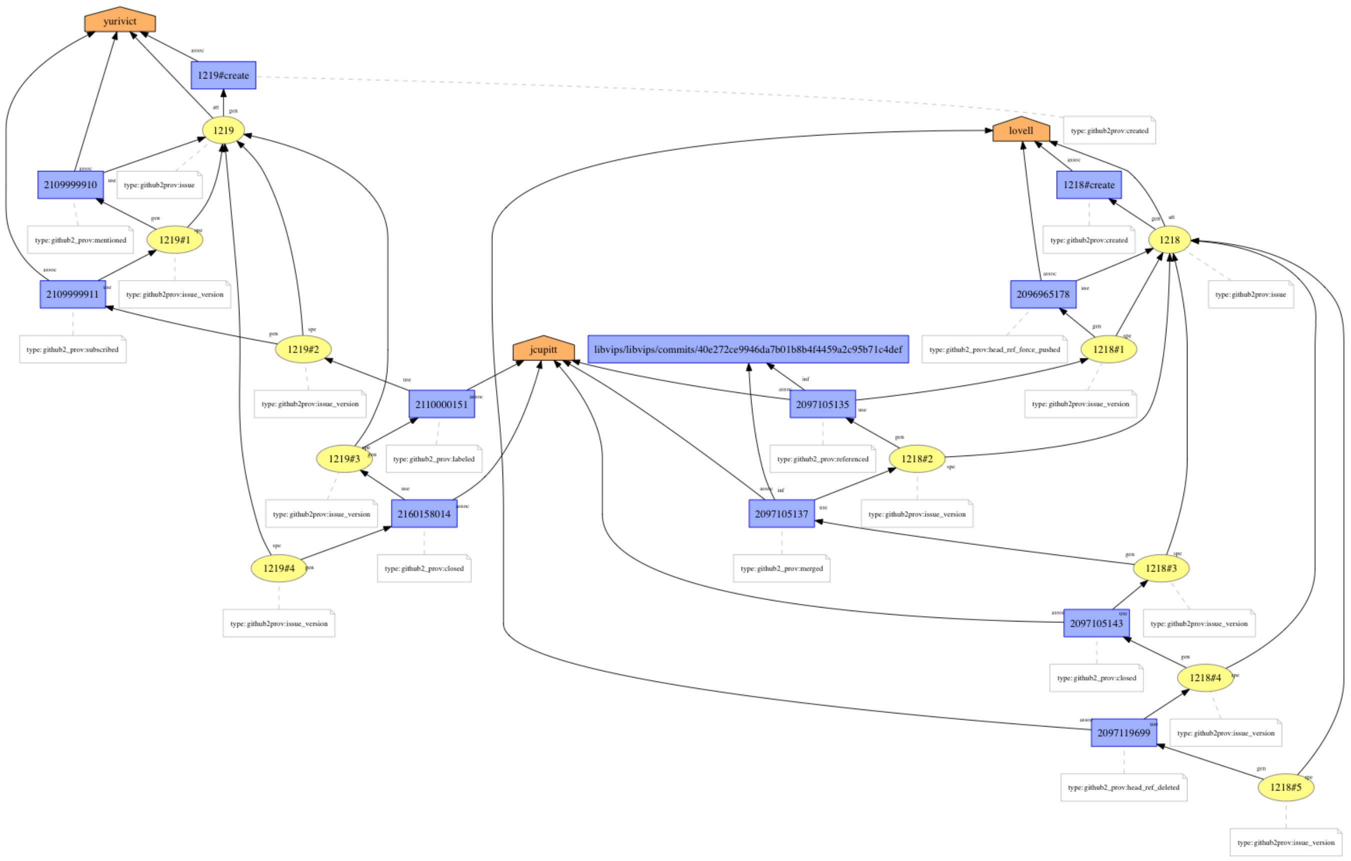


Figure 6. GitHub2PROV LibVips excerpt

LibVips exemplar. We have omitted for Team Velocity M4 from the table because the we were unable to calculate it from the LibVips PROV model. To calculate M4 we would require each issue to be annotated with the number of software development "units", which is usually estimated by one or more team members. We queried the models using SPARQL, and the following is an example query for open rates (M1):

```
SELECT ?i ?st
 WHERE {
  ?i a github2prov:issue.
  ?i prov:wasGeneratedBy ?ca.
  ?ca prov:startedAtTime ?st.
 FILTER (( ?st >= "2019-01-01T00:00:00+00:00"^^xsd:dateTime) &&
        ( ?st < "2019-02-01T00:00:00+00:00"^^xsd:dateTime))
}
```

5.2 Workload

In Section 3 we describe metrics used to determine the workload of users in project development scenarios. These metrics could be used to support the allocation of work during a Control Schedule Review. To make the metrics more directly applicable to our model, we defined them in terms of

Metric	Description	Features used in PROV	LibVips results
M1	**Open/Close Rates** derived from the issue creation time and the close issue annotation event.	**GitHub2PROV:** issue_event activity startTime attribute and issue_event activity attribute where status = closed	**Opened:** 21 **Closed:** 23
M2	**Lead Time** The start time is defined as the earliest of the issue creation time and the activity start time.	**GitHub2PROV:** issue_event activity startTime attribute	**Days:** 22.78
M3	**Cycle Time** Start time is taken as the activity start time.	**GitHub2PROV:** issue_event activity startTime attribute	**Days:** 20.71

Table 1. Control Schedule Review Metrics

files and commits (described by Git2PROV), issues and issue events (described by our GitHub2PROV model). These metrics are presented in Table 2, this table also defines the PROV elements used, and metric values taken from the month of January 2019 from the LibVips exemplar using SPARQL.

Metric	Description	Features used in PROV	LibVips Results
M5	The number of files that were edited by an agent (Q1)	**Git2PROV**: file entities, and committer agents	**Developer 1:** 122 **Developer 2:** 7 **Developer 3:** 8 **Developer 4:** 2 **Developer 5:** 2
M6	The frequency of files which are manipulated by an agent (Q2)	**Git2PROV:** file entities, and committer agents	**Developer 1:** 99.34 **Developer 2:** 0.36 **Developer 3:** 1.02 **Developer 4:** 1.00 **Developer 5:** 1.00
M7	The number of events an agent is associated with (Q3).	**GitHub2PROV:** issue_event activity, annotator/opener agents	**Developer 1:** 86 **Developer 2:** 3 **Developer 3:** 27 **Developer 4:** 5 **Developer 5:** 10
M8	The frequency of events associated with an agent (Q4).	**Git2HubPROV:** issue_event activity, commit activities, annotator/opener/ committer agents	**Developer 1:** 38.30 **Developer 2:** 3.14 **Developer 3:** 4.63 **Developer 4:** 4.00 **Developer 5:** 4.00
M9	The number of events relating to new issues that an agent is associated with (Q5).	**Git2HubPROV:** issue_event activity, commit activities, annotator / opener	**Developer 1:** 71 **Developer 2:** 1 **Developer 3:** 11 **Developer 4:** 4 **Developer 5:** 0

Table 2. Workload Metrics

6 Discussion

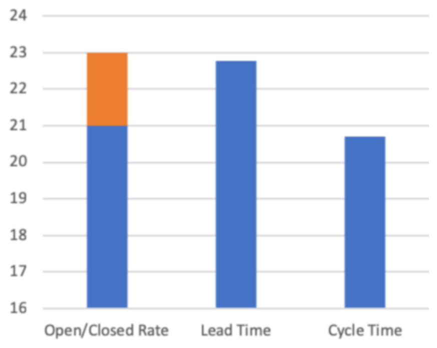
Our approach uses the GitHub API to populate the GitHub2PROV model. Thus it contains the same data as the GitHub API, however, our model benefits from the linage of data provided by the PROV-DM, which was used to support queries M2 and M3. Another alternative to querying our model using SPARQL, is to place all statements into a relational database, however 2 out of our 8 use cases requires graph traversal and using a database would be harder in terms of lines of code and query complexity.

Our model describes *GitHub commits* and issues, both of which are core to project development. It does not model every possible interaction with GitHub, we took this design choice for two reasons: First, we wanted to evaluate whether the information about *GitHub commits* and issue tracking would be useful, without investing in modeling GitHub's extensive API; Second, our model describes core concepts that are common to online Git hosting services so that our model could be re-purposed for other services.

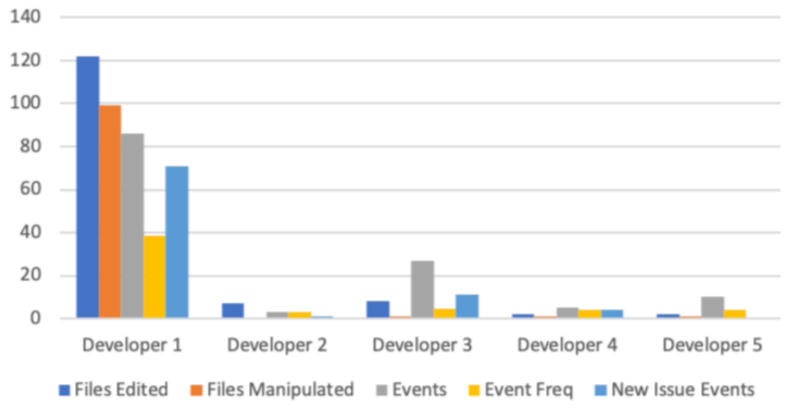
It is possible to extend GitHub2PROV so that it describes other resources made available via the GitHub API, however it is a challenge to capture the complete provenance of this process because project development is often distributed over a number of non-integrated tools. Provenance capture may not be complete, thus making it difficult to draw conclusions from these sources or it maybe extremely time-consuming to collect due to the scale of available data.

The results form the metrics can be displayed in tables or graphs so that software project managers can quickly assess the metrics (see Figure 7). The metrics derived from the project management perspective (see Section 5.1) required more complex queries than the metrics derived from related provenance research (see Section 5.2). The former metrics were more complex because it was necessary to traverse the directed graph of Git commits to determine when development on an issue started and this required insight into a project's development process. While we have calculated measures for the LibVips repository, where we have generated our figures for the time period of a month, this may not be representative of development iterations. This knowledge should, however, be available to a project manager using this model. Even without the knowledge of these development details, our model can still provide an insight into the activity of a project, the evolution of a team, and the resolution of issues. This insight can provide users with details about whether the code base is maintained and whether the developers are reactive to issues. It also allows users to compare GitHub code libraries for use in their projects.

We were also unable to generate a metric M4 from our exemplar, team velocity, because the developers did not provide information in the repository about development units. If the developers choose to include this level information in their issues, this could be calculated. The richness of PROV



(a) Control Schedule Review Metrics



(b) Workload Metrics

Figure 7. Graphs showing the Metrics for the LibVips project

captured by our model depends on how developers interact with GitHub. For instance, if the development is led by a single developer, and they do not report issues through the issue tracker then this information is lost. In this case, a better strategy would be to use the time derived from tasks completed tasks for project managing workload.

While our model extends the Git2PROV model, it is not required to query a GitHub2PROV model. That said, Git2PROV provides interesting insights into Git repositories. The combination of Git2PROV models of multiple user repositories and GitHub2PROV model provide interesting insights into team behaviour. We also note that GitHub2PROV would not be able to support the Metrics M5 and M7 without the Git2PROV model. Other provenance models could be combined with the GitHub2Prov model to enrich it and more applicable for other purposes. For instance, the work of Miao et al. [7] presents a model for data scientists to model the evolution of their datasets, the dataset version could be connected to a *GitHub commit*.

7 Conclusions and Future Work

In this paper, we present GitHub2PROV, a PROV model which describes *GitHub commits* and Issue resources. It extends the Git2PROV model. We discuss how our model can support project management decisions using metrics and we calculated these metrics for our LibVips exemplar.

For future work, we plan to extend our model by including other core concepts from the GitHub API namely pull requests, other user interactions, and information from continuous integration tools describing validation. By including these concepts in our model, we can provide better support to software project managers. We plan to explore addition use cases for our model, including Software Sustainability for open source projects.

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