TECHNICAL NOTE

Unifying package managers, workflow engines, and containers: Computational reproducibility with BioNix

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Abstract

Motivation: A challenge for computational biologists is to make our analyses reproducible—i.e. to rerun, combine, and share, with the assurance that equivalent runs will generate identical results. Current best practice aims at this using a combination of package managers, workflow engines, and containers. **Results:** We present BioNix, a lightweight library built on the Nix deployment system. BioNix manages software dependencies, computational environments, and workflow stages together using a single abstraction: pure functions. This lets users specify workflows in a clean, uniform way, with strong reproducibility guarantees. **Availability and Implementation:** BioNix is implemented in the Nix expression language and is released on GitHub under the 3-clause BSD license: https://github.com/PapenfussLab/bionix (biotools:BioNix) (BioNix, RRID:SCR_017662).

Introduction

There are many aspects to the ongoing reproducibility crisis in science—imprecise laboratory protocols, selective reporting, poor use of statistical methods [1,2]—but for researchers in bioinformatics the most important of these is computational reproducibility. Three main challenges exist in practice:

i. Managing software versions and dependencies. This is commonly handled with "package managers" (e.g., Conda [3]), which provide both a central repository of software and tools to manage installation on a user's system. Extra repositories for software such as BioConda [4] exist for providing domain-specific software.

ii. Managing computational environments. This is commonly handled with "containers" (e.g., Docker [5], Singularity [6]) or "virtual machines"; these provide controlled environments within which workflows can be executed. Environments can also be managed in a more lightweight fashion using environment variables and per-process namespaces.

iii. Managing workflows. This is commonly handled with "workflow engines" (e.g., Toil [7], SnakeMake [8], WDL [9], Cromwell [10], NextFlow [11], Ruffus [12], and Rubra [13]), which manage stages (we define a "stage" as the concrete execution of ≥ 1 executable on ≥ 1 input file, producing ≥ 1 output file) and their execution, providing features such as parallelism, remote building, resumability, and logging.

Some tools tackle >1 of these challenges: Conda, for example, began life as a Python package manager but more recently aims to manage both software and environments in a language-agnostic way [3].

All of these challenges need to be addressed at scale: bioinformatics workflows are computationally demanding and often need to be executed on computing clusters, on remote computing farms, or in the cloud. The combination of technologies used to address these challenges are called a "reproducibility stack" by Grüning et al. [14].

Our contributions

We present BioNix, a lightweight library that cleanly deals with all 3 of these challenges within the one system.

Two aspects of BioNix's design enable these improvements. The first is that BioNix is built on Nix, a next-generation cross-platform software deployment system. The second is that in BioNix, stages of a workflow are modelled as "pure functions"—i.e., functions that are free of adverse effects: workflow stages cannot modify shared state, and so are extremely modular.

These design choices give BioNix several novel features, which we explain using the complete workflow and associated build graph depicted in Example 1:

i. BioNix manages both software and workflows within the one system. The build graph in Example 1 has nodes corresponding not just to workflow stages and inputs but also to software dependencies.
ii. Each stage of a BioNix workflow implicitly specifies its entire computational environment. Dependencies are tracked down to the kernel level, and each stage is executed in its own sandbox, resulting in strong reproducibility guarantees and obviating the need for containers (containers and static binaries can still be used in a BioNix workflow if required, but they are generally avoided to reduce adverse effects). In Nix, sandboxing is enabled by default and may be explicitly disabled for either any specific build or globally.
iii. Nix tracks the entire tree of runtime and build time dependencies with fine-grained versioning. In the example pipeline this means that not only the version of bwa, but also the specific versions of gcc and bash under which bwa was compiled, are captured. All of these versions are fixed by specifying which versions of BioNix and Nixpkgs we use (by their commit hashes): the code on the right forms a fully reproducible specification of the associated workflow.
    At the same time, it is straightforward to specify specific versions of software for distinct stages and to use distinct versions of a given piece of software in parallel.
iv. BioNix uses a simple, purely functional domain-specific language—the Nix expression language—for specifying workflows. Constructing a workflow is reduced to function composition; stages, workflows, and software dependencies are all represented as pure functions from dependencies to outputs. Because of purity, stages are guaranteed not to influence each other except through their inputs and outputs and so can be safely recombined. An example of this in Example 1 is our ability to compose workflow steps using the higher-order map and pipe functions.
    The Nix expression language can be considered a compromise between the safety of static configuration files and the expressiveness of a general-purpose programming language. Configuration files are predictable, but writing them can involve a lot of boilerplate and repetition. General-purpose programming languages allow one to abstract away much of this verbosity, but at the cost of some safety and predictability, e.g., when they allow workflows to modify unrelated parts of the filesystem. Domain-specific languages like Nix aim to be sufficiently expressive without the error-prone power of a general-purpose programming language.

BioNix includes many features found among the most powerful existing workflow managers. Intermediate files do not need to be named or managed. Multiple versions of the same piece of software can be used simultaneously. BioNix workflows are automatically parallelizable, can be executed in high-performance computing (HPC) environments or in the cloud, and are fully resumable in cases of interrupted execution. BioNix also allows for conditional execution: i.e., different stages may be executed depending on previous stages' outputs.

BioNix includes the following components over and above base Nix:

i. A framework for specifying workflows in the Nix expression language.
ii. A library containing some commonly used bioinformatics tools and helpful workflow specification utilities.
iii. A module allowing workflows to be executed on HPC clusters.
iv. Basic typing to capture metadata and prevent invalid workflow specifications.

The rest of the article first explains the basics of the Nix system and associated expression language. Next, we describe the design and implementation of BioNix. Finally, we describe an example workflow and compare Bionix with existing bioinformatics workflow managers.
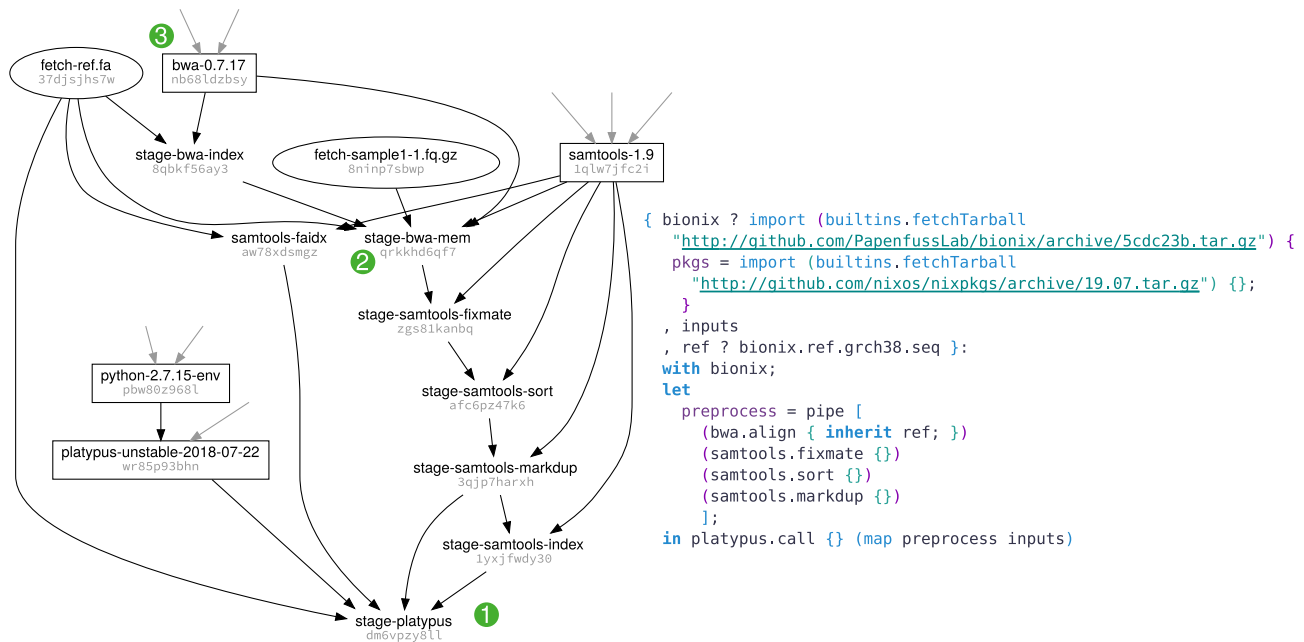
Preliminaries

The Nix deployment system

The Nix deployment system emerged from the work of Dolstra [15] and Dolstra et al. [16]. Nix was originally designed as a software package manager but has since been adapted to managing OS configurations (the NixOS project [17, 18]). BioNix represents a further extension of Nix to manage bioinformatics workflows.

The Nix system has 3 main components:

i. "Build products" or "outputs" may be any kind of directory, file, or collection of files. When Nix is being used as a traditional package manager, the build products typically consist of the compiled binaries and libraries associated with an application. In our case, build products are any output associated with a bioinformatics workflow or stage.
ii. "Derivations" are static configuration files (ending in .drv) that specify all of the inputs and procedures required to produce a given build product. If a build product has prerequisites, then its derivation will refer to the derivations corresponding to those prerequisites.
iii. "Nix expressions" are written in a simple, high-level domain-specific language designed for specifying and manipulating derivations. Derivations are represented in the Nix language as collections of name-value pairs—similar to JSON objects—called "sets." Nix expressions may also make use of various built-in design patterns to provide further extensibility and flexibility.

The basic build process in Nix is as follows: a Nix expression is instantiated to yield a tree of derivations describing how to generate the associated build products. Derivations are then realized by the build system to produce the build products themselves. Nix expressions, derivations, and build products are

```
{ bionix ? import (builtins.fetchTarball
  "http://github.com/PapenfussLab/bionix/archive/5cdc23b.tar.gz") {
  pkgs = import (builtins.fetchTarball
    "http://github.com/nixos/nixpkgs/archive/19.07.tar.gz") {};
  }
, inputs
, ref ? bionix.ref.grch38.seq }:
with bionix;
let
  preprocess = pipe [
    (bwa.align { inherit ref; })
    (samtools.fixmate {})
    (samtools.sort {})
    (samtools.markdup {})
    ];
in platypus.call {} (map preprocess inputs)
```

Example 1: An example workflow specified in BioNix (*right*) with a portion of the resulting build graph (*left*). In the build graph, rectangular nodes correspond to software dependencies and elliptical nodes to data files. Grey arrows indicate dependencies that are not illustrated in the figure. The workflow on the right corresponds to the terminal node in the build graph annotated with (1). The node annotated (2) in the graph corresponds to a single stage in workflow and the corresponding BioNix code can be found in Example 4. The final node annotated (3) corresponds to a software dependency provided by Nixpkgs with the corresponding code in Example 6.

somewhat analogous to source code, object files, and compiled binaries.

The Nix expression corresponding to a given build product will generally take the form of a pure function from dependencies to the corresponding output derivation. Using ML-style notation for types, one can represent this as

$$\text{Dependencies} \rightarrow \text{Output}.$$

Nix ensures that derivations are precisely specified by giving both derivations and build products hash-based names. The hash of a derivation is a function of all of the steps required to produce the associated build product, as well as the hashes of all of its dependencies.

The "Nix store," usually located on the filesystem at /nix, provides a single, flat namespace for all derivations and build products and is writable by only the Nix system. Users typically access the store through "environments": organized collections of soft links exported to $PATH.

The Nix community maintains an online repository of prebuilt software called Nixpkgs [18], which contains >40,000 software packages.

The Nix expression language

We briefly introduce those parts of the Nix expression language required to understand the rest of the article.

"Sets" are the most important datatype in Nix and correspond to what are sometimes called associative arrays, records, or dictionaries in other languages. Set elements can be accessed by name: { a=1; }.a == 1.

"Lists" are delimited by square brackets and may contain elements of heterogeneous types separated by whitespace, e.g., [1 2 3 ''a'' ''b'' ''c'' true false].

The Nix language makes heavy use of anonymous functions (also called "λ expressions"). The following denotes a function that increments its argument: x: x + 1. Nix does not support functions of multiple arguments; instead, it is common for functions to take a set as input. This is written { a, b, c, ...}: .... Nix allows defaults to be provided for some elements, which are used if the function is called without providing the element. This is denoted using a question mark: the function { a ? 5 }: ... will by default assign a the value 5. Alternatively, one can mimic multi-argument functions using higher-order functions, i.e., functions that return functions. For example, x: y: x + y denotes a function that adds its 2 arguments together.

Values can be bound to variable names using the let ... in ... construction. We could bind the example above to a name and then invoke it on some parameters: let f = x: y: x + y; in f 1 2. Function application is denoted with whitespace (with lower precedence than list elements) and associates to the left; e.g., a b c denotes (a(b))(c). Pattern matching allows simultaneous binding of elements contained in a set: let {a, b} = {a = 1; b = 2;}; in a + b == 3. Finally, the with x; ... construction brings the field names of a set x into scope in the subsequent expression.

Implementation

The BioNix library itself is designed as a tree of functions, with each function representing 1 stage of processing. The BioNix tree follows the pattern of Nixpkgs; bioinformatics software (e.g., BWA, samtools) forms the top level, and stages based on subcommands form the second level (e.g., bwa.align). As in Nixpkgs, defaults can be overridden throughout the whole tree easily.

We step through 3 examples of (slightly simplified) BioNix code that generates the build graph in Example 1: the workflow

specification, a stage specification, and an expression for a software dependency.

Specifying a workflow

Example 1 shows a simple variant-calling workflow using BWA [19, 20] for alignment, samtools [21] for sorting and duplicate marking, and platypus [22] for variant calling. The whole workflow is a single anonymous function, taking dependencies and inputs—the set spanning the first 8 lines—to an output (the final line):

$$(Inputs, Options, \& Dependencies) \rightarrow Output.$$

The output of this workflow is the output of platypus, which is a .vcf file.

One of the dependencies of the workflow is BioNix itself. If the user does not specify a version to use, the workflow defaults to using the specific commit indicated. Similarly, if the user does not specify a reference, the workflow defaults to GRCh38. Fixing a version of BioNix and Nixpkgs automatically fixes versions of all software used in the pipeline, although these can be individually specifically altered if desired (see Examples 2 and 3).

```
let
  oldnix = import (fetchFromGitHub {
    owner = "NixOS";
    repo = "nixpkgs";
    rev = "83a893c38a83877588e3ca7ccfeabaa973c30acd";
    sha256 = "0q7214hag7h95irvhkdb648m09b9jspb0raw1qjrx7y4grzb165h";

  }) { };

  jre = oldnix.openjdk7;

in ...
```

Example 2: This example is an extract from the MuTect stage and demonstrates how specific software versions can be referenced. Here the deprecated JDK 7 required by MuTect is accessed through an old revision of Nixpkgs.

Each stage, e.g., `bwa.align`, `samtools.fixmate`, or `platypus.call`, is represented by a higher-order function that takes options and dependencies and returns a function from inputs to outputs. The type of a stage (functional programmers will recognize this as a "curried" version of the type of a workflow) can be represented as

$$(Options \& Dependencies) \rightarrow (Inputs \rightarrow Output).$$

```
let
  octopus-git = octopus-caller.overrideAttrs (attrs: {
    src = fetchFromGitHub {
      owner = "luntergroup";
      repo = "octopus";
      rev = "f88d35b9b93d11a086eb87bb3722874a3ea5250e";
      sha256 = "171cmpx6x8p1q4d0k9lj2mwcyhhrc20cskqhwdyl6fa1clx40b7r";
    };
  });
in ...
```

Example 3: Nixpkgs has a flexible overrides system that allows derivations to be selectively modified. Here the Octopus variant caller switched to the latest development branch (as of 20 March 2020) instead of the current release.

BioNix dependencies by default include the BioNix tree itself—to allow use of other (sub-)stages—as well as the `Nixpkgs` collection, which provides the necessary general-purpose software. For most of our stages we do not pass in any additional

options, and so the first argument is {}. However, `bwa.align` requires that we specify a reference, and so we explicitly pass in the `ref` declared at the beginning of the workflow.

We make use of several helpful abstractions from functional programming. For example, we define a new function, `preprocess`, that takes a sample and performs alignment, matefixing, sorting, and duplicate-marking. We also use the `pipe` function in BioNix to sequentially compose a list of functions. Finally, we `map` this function over all our inputs. The Nix expression language allows for this abstraction and modularity without introducing adverse effects.

Specifying a stage

```
{ bionix
, ref
, bamOutput ? true
}:

{ input1
, input2 ? null
}:

with bionix;
with lib;

stage {
  name = "bwa-mem";
  buildInputs = with pkgs; [ bwa ] ++
    optional bamOutput samtools;
  buildCommand = ''
    ln -s ${ref} ref.fa
    for f in ${bionix.bwa.index {} ref}/* ; do
      ln -s $f
    done

    bwa mem -t $NIX_BUILD_CORES \
      ref.fa \
      ${input1} \
      ${optionalString (input2 != null) input2} \
      ${optionalString bamOutput "| samtools view -b"} \
      > $out
  '';
}
```

Example 4: Specifying an alignment stage using BWA-mem. The expression defines a function mapping parameters (e.g., a choice of reference genome) and the fastq inputs to a derivation produced by the `stage` function. The `stage` function takes as arguments a build script and the requisite software.

Example 4 illustrates an example stage in BioNix. In line with our design pattern, the whole stage is represented by an anonymous higher-order function: it takes a record of options and dependencies and returns a function that takes inputs (in this case, a pair of FASTQ files representing read pairs) and returns a derivation. Note that we give the reference as part of the first argument to the stage (options and dependencies) rather than as part of the second argument (inputs). This is because often an entire workflow will be parametrized by a single reference genome.

Links are created for both the reference and its associated BWA indices to deal with the standard bioinformatics convention that indices are located in the same directory as the associated indexed file.

Finally, the output is optionally converted to the .bam format within the shell script associated with the derivation. BioNix

cannot stream data between stages of a workflow: both inputs and outputs of a stage must be a file or set of files.

```
stage {
    name = "picard-markDuplicates";
    buildInputs = with pkgs;
        [ picard-tools ];
    outputs = [ "out" "metrics" ];
    buildCommand = ''
        picard MarkDuplicates \
            I=${inputBam} \
            O=$out \
            M=$metrics
        '';
}
```

Example 5: Extract from the definition of the mark duplicates expression for picard tools demonstrating multiple outputs. The output attribute names the build products, which are assigned unique paths in the store and exposed to the build script via environment variables of the same name.

Example 4 has multiple inputs and only a single output (the BAM file); however, multiple outputs are also supported by Nix derivations. Example 5 demonstrates multiple outputs for picard tools [23] with metrics in addition to the main output. The extra output can be accessed via the metrics attribute in the returned derivation.

Specifying a software dependency

For completeness, we also show how to specify a software dependency. In our example workflow, the BWA software is provided by Nixpkgs and Example 6 shows a simplified version of its specification there.

The expression is an anonymous function from dependencies—in this case, the utility libraries stdenv and fetchurl and the C library dependency zlib—to outputs—in this case, the compiled binary for bwa. The function body is just a single call to the helper function mkDerivation. Because bwa follows the first 2 parts of the common ./configure; make; make install pattern for building unix software, only the final install phase needs to be specified. Here, the resulting binary is copied into the bin/ directory.

```
{ stdenv, fetchurl, zlib }:

stdenv.mkDerivation rec {
  name = "bwa-${version}";
  version = "0.7.17";

  src = fetchurl {
    url = "mirror://sourceforge/bio-bwa/${name}.tar.bz2";
    sha256 = "1zfhv2zg9v1icdlq4p9ssc8k01mca5d1bd87w71py2swfi74s6yy";
  };

  buildInputs = [ zlib ];

  installPhase = ''
    install -vD bwa $out/bin/bwa
  '';
}
```

Example 6: Specifying a software dependency for bwa-mem. This is a simplified version of the expression found in Nixpkgs. The expression defines the build requirements (zlib) and the steps required to build the software. A standard build process (configure, make, make install) is assumed, so only non-standard commands need to be specified. BWA does not support the standard make install for installation, so an install script is defined in the expression.

HPC queue integration

While the Nix build system provides support for both local and remote building, bioinformatics workflows are commonly executed on traditional HPC infrastructure managed by job schedulers. These systems require users to submit jobs to a queue, along with specified resource limits.

BioNix provides support for queuing systems via a function that takes resource limits and a derivation and returns a new derivation that will submit the build process as a job to the queuing system instead of building it directly. This design allows arbitrary derivations to be lifted to the queue and also allows users to combine submission to the queue and building via the Nix build system directly. However, because submission is a (relatively benign) side effect, builds cannot be realized using sandboxing. This is because the default sandbox prevents the build from using software not specified in the expression, and submitting jobs to the scheduler requires interacting with the daemon running outside the build environment. This restriction only applies to cluster execution; local and remote builds fully support sandboxing.

Failures in the queue are handled similarly to execution failures: the build is aborted and reported to the user. This includes when jobs are terminated due to resource limits. The jobid of the submission is recorded in the build log along with any output produced by the job to aid the user in tracing the error.

Tracking types of build products

BioNix gives build products optional types in order to prevent errors in workflow specification and to track useful metadata such as the reference used for an alignment. This is a lightweight version of the approach taken by Bioshake [24]. Types are implemented as an abstract data type (ADT) and are tracked using Nix's passthru features.

Discussion
Real-world use of BioNix

Small variant calling workflow
We have used BioNix to manage a workflow that performs somatic variant calling and copy number variant (CNV) calling on whole-genome deep sequencing human data using Minimap2 [25] for alignment, samtools [21] for sorting and marking duplicates, Strelka [26] for somatic variant calling, and CNVkit [27] for CNV calling.

This workflow was executed on HPC infrastructure managed with the TORQUE resource manager [28] using the extensions presented earlier. A total of 1.1 TB of (compressed) fastq input was processed, producing 755 GB of results (including alignments). The workflow is detailed in Example 7, and a full example executing the workflow on a publicly available melanoma dataset [29] is available in the BioNix repository.

Structural variant calling at scale
We have also used BioNix to execute a workflow that processes 6.8 TB of whole-genome sequencing data from mice, performing quality checking, alignment, and merging, and structural variant calling using gridss [30] with a range of parameters. This resulted in a total of 5.3 TB of results. See Example 8 for the workflow used.

```
{bionix ? import <bionix> {}, pair, fetch}:

with bionix;
with lib;
with types;

with minimap2;
with samtools;
with snpeff;

let
  preprocess = s: pipe s [
    fetch
    (align { preset = "sr"; ref = ref.grch38.seq; flags = "-R'@RG\\tID:${s.type}\\tSM:${s.type}'"; })
    (fixmate {})
    (sort { })
    (markdup { })
  ];

  dropErrors = input: stage {
    name = "drop-errors";
    buildCommand = ''
      grep -v "ERROR_" ${input} > $out
    '';
    passthru.filetype = input.filetype;
  };

  bams = mapAttrs (_: preprocess) pair;

  variants = let
    somatic = strelka.callSomatic { } bams; in mapAttrs (_: flip pipe [
      (compression.uncompress { })
      (snpeff.annotate { db = ref.grch38.snpeff.db; })
      dropErrors
      (snpeff.dbnsfp { dbnsfp = ref.grch38.snpeff.dbnsfp; })
    ]) {
      "snvs.vcf" = somatic.snvs;
      "indels.vcf" = somatic.snvs;
      "germline.vcf" = strelka.call { } [bams.normal];
    };

  cnvs = cnvkit.callCNV { } { normals = [ bams.normal ]; tumours = [ bams.tumour ]; };

in linkOutputs {
  inherit variants;
  alignments = linkOutputs (mapAttrs' (n: nameValuePair (n + ".bam")) bams);
  cnvkit = cnvs;
}
```

Example 7: The tumour-normal small variant calling workflow used for calling variants on clinical samples. Reads are aligned using Minimap2 [25], variants called using Strelka [26], and finally CNVs with CNVkit [27]. The inputs are a pair of samples (as an attribute set containing `normal` and `tumour` attributes), a method `fetch` for fetching the reads associated with a given sample, and BioNix.

Limitations of BioNix

BioNix leverages the underyling Nix system to achieve its reproducibility, and consequently is subject to the same limitations present in Nix.

A given stage may only write to the store location assigned to it, so streaming data between 2 distinct stages is not possible. Streaming steps must therefore be combined into 1 stage, which can be constructed with higher-order functions. Streaming between 2 independent builds would be difficult to support: the distributed design of Nix implies that different builds may be executing on independent machines.

Nix and BioNix will currently rebuild an output unnecessarily when dependencies of its inputs have changed but the inputs themselves have not. The reason is that the Nix store is not content addressed; store locations are based on the cryptographic hash of all inputs used in building an output, rather than the output itself. This has been referred to as an "extensional" model [16]. The proposed "intensional" store model [16] introduces content addressable storage and hash

```
{ bionix, baseUrl, mice ? import ../metadata/mice.nix }:

with bionix;
with lib;

let
  # Utility function
  update = f: x: x // (f x);

  # Process fastqs ########################################
  fetch = { filename, sha256sum, ... }:
    fetchFastQGZ {
      url = baseUrl + filename;
      sha256 = sha256sum;
    };

  updateFastq = update (fq: { fastqcOutput = fastqc.check { } (fetch fq); });

  # Process sample run ####################################
  fetchInputs = { fq1, fq2, ... }: {
    input1 = fetch fq1;
    input2 = fetch fq2;
  };

  alignSortSampleRun = sr:
    pipe sr [
      fetchInputs
      (bwa.align {
        ref = ref.grcm38.seq;
        flags = "-R'@RG\\tID:${sr.id_col}\\tSM:${sr.sample_id}'";
      })
      (samtools.sort { })
    ];

  updateSampleRun = update (sr: {
    sampleRunBam = alignSortSampleRun sr;
    # recurse
    fq1 = updateFastq sr.fq1;
    fq2 = updateFastq sr.fq2;
  });

  # Process samples #######################################
  mergedBam = flip pipe [ (map (sr: sr.sampleRunBam)) (samtools.merge { }) ];

  updateSample = update (sample:
    let updated_sample_runs = map updateSampleRun sample.sample_runs;
    in {
      sample_runs = updated_sample_runs;
      mergedBam = mergedBam updated_sample_runs;
    });

  # Process mice ##########################################
  updateMouse = update (mouse: rec {
    gridssCalls =
      gridss.callAndAssemble (map (sample: sample.mergedBam) samples);
    samples = map updateSample mouse.samples;
  });

in map updateMouse mice
```

Example 8: Structural variant calling for a mouse dataset. Stages include quality checking with FastQC [31], alignment with BWA [19], merging with samtools [21], and finally structural variant calling with GRIDSS [30]. The inputs to the expression are BioNix, a base URL where the fastq files can be found, and the metadata describing the experimental design, sequencing data, and hashes. This workflow is structured so that metadata are "annotated" with build products, analogous to building up a data structure in a general-purpose language. Because Nix is lazy, the build products will only be built when requested. Comparing with Example 7 shows how flexibly workflows can be specified within BioNix.

rewriting, allowing better sharing of components and reducing unnecessary builds. This feature is currently under implementation and is not available in the latest Nix release (2.3.1).

The Nix language, although extremely simple, has an idiosyncratic syntax that draws from both curly brace and functional programming languages; some may find this unfamiliar or off-putting.

Finally, Nix does not have an advanced type system. BioNix provides type safety for many of its stages through an implementation of ADTs, but because these data types are implemented in Nix itself the error reporting can be obscure.

```
{ bionix ? import <bionix> {} }:

with bionix;
with lib;

let

  prepare = splitString "\n" (removeSuffix "\n" (readFile (stage {
    name = "prepare";
    buildInputs = [ pkgs.python3 ];
    buildCommand = ''
      python -c "print('one\ntwo\nthree\nfour', end='')" > $out
    '';
  })));

  analysis = str: removeSuffix "\n" (readFile (stage {
    name = "analysis";
    buildInputs = [ pkgs.python ];
    buildCommand = ''
      python -c "print('_${str}_')" > $out
    '';
  }));

  gather = strs: stage {
    name = "gather";
    buildCommand = ''
      echo ${concatStringsSep " " strs} > $out
    '';
  };

in gather (map analysis prepare)
```

```
task prepare {
  command <<<
    python -c "print('one\ntwo\nthree\nfour')"
  >>>
  output {
    Array[String] array = read_lines(stdout())
  }
}
task analysis {
  String str
  command <<<
    python -c "print('_${str}_')"
  >>>
  output {
    String out = read_string(stdout())
  }
}

task gather {
  Array[String] array
  command <<<
    echo ${sep=' ' array}
  >>>
  output {
    String str = read_string(stdout())
  }
}

workflow example {
  call prepare
  scatter (x in prepare.array) {
    call analysis {input: str=x}
  }
  call gather {input: array=analysis.out}
}
```

Example 9: Verbatim scatter-gather example from WDL [46] documentation with the BioNix implementation on the left and WDL on the right. The workflow generates some input data using Python, parses it into lines, transforms each line via a simple Python script, then collects all lines into a final output. It is unusual to parse and split using the Nix language—typically this would instead be done through a build—but we have done so to maintain a closer translation of the WDL example. In BioNix we must specify the Python dependency: because the entire software environment is managed, a failure to specify software will result in a failed build. The BioNix example also shows how different software versions can be combined: Python 3 is used in the `prepare` stage, but Python 2 is used in the `analysis` stage.

Related work

We discuss here 2 categories of work related to our own. The first consists of other projects making use of the Nix deployment system to manage data processing workflows; the second concerns existing workflow management tools popular in bioinformatics and computational biology.

Similar adaptations of the Nix system

Several groups have made use of Nix to manage the environments in which computational workflows are executed. Researchers at GRICAD at the Université Grenoble Alpes have made use of Nix as an HPC package management system [32, 33]. The Pipelines in Genomics (PiGx) project [34] uses Guix—an implementation of the Nix system using GNU Scheme in place of the Nix expression language—to produce a set of reproducible "turn-key" workflows for bioinformatics and computational biology, configured via simple static config files. Similar uses of Nix for reproducible research have also been suggested by Blair Archibald of the Software Sustainability Institute [35, 36] and Bruno Vieira at the Mozilla Foundation [37].

However, none of these approaches use Nix to specify workflows themselves; instead, Nix is used as a replacement for package managers and containers. BioNix takes the next step and embeds the workflows into the Nix system.

Two projects that we know of make use of Nix to manage workflows themselves: Mix, a Nix-based system for specifying data processing pipelines developed at SoundCloud [38], and Fractalide, a service programming platform using dataflow graphs [39].

Mix is built on the `hnix` project [40] and implements a new builder dedicated to data workflows. Mix redefines derivations to remove the Nix store and allow storage of products on a distributed file system. Consequently, Mix cannot take advantage of `Nixpkgs` and focuses entirely on the workflows, without capturing the associated computational environments.

Fractalide is an effort to provide a dataflow graph programming platform with an initial focus on microservices and the internet of things. Though it builds on Nix, it also extends the base language with a new language for specifying the dataflow graphs, and relies on bindings to other languages to provide an interface to the actual data processing (i.e., the microservice). By contrast, BioNix focuses on Bioinformatics workflows, is implemented entirely within the existing Nix ecosystem, and calls existing pieces of software via their command line interfaces.

GWL [41, 42] is in many ways the workflow manager closest in approach to BioNix. GWL, like PiGx, is built on Guix and so inherits the reproducibility guarantees of a Nix-like system. Unlike PiGx, GWL manages workflows themselves using Guix, rather than using it only to provide the necessary software environment. However unlike BioNix, stages in GWL are not represented by functions but by data structures; workflows are specified via manual construction of the associated build graph; and workflow stages are untyped.

Existing workflow managers for computational biology

There are a large number of existing workflow systems in use today [43, 44]. A complete review of the existing systems is out of scope of this article; however we briefly review the more commonly used systems [45].

```
{ bionix ? import <bionix> {}
, input ? ./sample.fa}:

with bionix;
with lib;

let
  splitSequences = fa: stage {
    name = "splitSequences";
    buildInputs = [ pkgs.gawk ];
    buildCommand = ''
      awk '/^>/{f="seq_"++d} {print > f}' ${fa}
      mkdir $out
      cp seq* $out
    '';
  };

  reverse = fa: stage {
    name = "reverse";
    buildCommand = ''
      ${pkgs.utillinux}/bin/rev ${fa} > $out
    '';
  };

in pipe [
  splitSequences
  (each reverse)
] input
```

```
params.in = "$baseDir/data/sample.fa"
sequences = file(params.in)

/*
 * split a fasta file in multiple files
 */
process splitSequences {

    input:
    file 'input.fa' from sequences

    output:
    file 'seq_*' into records

    """
    awk '/^>/{f="seq_"++d} {print > f}' < input.fa
    """

}

/*
 * Simple reverse the sequences
 */
process reverse {

    input:
    file x from records

    output:
    stdout result

    """
    cat $x | rev
    """

}

/*
 * print the channel content
 */
result.subscribe { println it }
```

Example 10: Nextflow basic pipeline example [47] (*right*) taken verbatim from the documentation and translated to BioNix (*left*). The example splits a single FastA file into a collection of FastA files, each containing exactly 1 sequence. The sequences are then reversed (in parallel) and then gathered back into 1 file in the final step. The BioNix `pipe` function implements reverse function composition for the easy specification of sequences of stages. The BioNix expression requires us to specify which `awk` implementation to use; here we chose GNU Awk.

```
task hello_world {
  String name = "World"
  command {
    echo 'Hello, ${name}'
  }
  output {
    File out = stdout()
  }
  runtime {
    docker: 'ubuntu:latest'
  }
}

workflow hello {
  call hello_world
}
```

```
{ bionix }:

bionix.stage {
  name = "hello";
  str = "World";
  buildCommand = ''
    echo "Hello, $str" > $out
  '';
}
```

Example 11: WDL example using Docker for software management (*left*) taken verbatim from the Cromwell documentation [48] and the equivalent BioNix expression describing the build (*right*). The software in WDL is fixed by specifying which Docker container to use (which could be referred to with a specific hash), while in the BioNix example the software is fixed when a concrete `bionix` is passed to the function.

Leipzig [45] categorizes workflow systems into 2 main categories: implicit or explicit syntax. Those with explicit syntax detail the workflow between stages explicitly; BioNix would fall into this category because our modelling of a workflow as function composition explicitly links the steps together into a workflow, as does WDL [9]. The other category, implicit syntax, are those systems whereby the stages are connected through abstract rules linking stages with their dependencies. Examples of implicit workflows are SnakeMake [8] and Nextflow [11]. We choose a representative selection of these broad categories in the following.

As already mentioned, current best practice aims at reproducibility using a combination of package managers, containers, and workflow engines. BioNix combines the functionality of all of these, and in this sense is difficult to compare with existing workflow management tools.

However, we can compare the syntax of BioNix with that of existing workflow managers by implementing toy piplines in each. Examples 9 and 10 illustrate 2 simple examples from the documentation of WDL [9] and NextFlow [11] alongside the equivalent BioNix expression. BioNix necessarily defines the software used in the execution of the workflow, and software outside of Nix is unavailable. By contrast, the WDL and NextFlow examples presented are valid workflow specifications without software definitions, although they do support software environment management via containers (e.g., Docker) or package managers (e.g., Conda). Example 11 demonstrates support for Docker in WDL.

BioNix might also be compared with CWL [49], which is a standard specification language intended for describing workflows in a portable way. However, CWL is increasingly used as a target for other build systems rather than being written directly. In this sense, CWL increasingly plays a role similar to Nix's derivation files, which are complete, portable, machine-readable specifications that can be built on local or remote systems.

Galaxy [50] is a popular workflow platform that provides a web-based GUI for specification of workflows and execution controls. Galaxy provides facilities to manage the computational environment via various package management tools, with Conda being popular. Nix can be integrated into Galaxy, which would allow Galaxy to leverage the strong reproducibility guarantees of Nix [15, 16]. This would be similar to the approach taken by PiGx.

Cuneiform [51, 52] is a functional programming language for large-scale data analysis workflows. In Cuneiform, as in BioNix, workflow stages are modelled as pure functions. Cuneiform also has an elegant foreign function interface (FFI), allowing the seamless use of code snippets from a variety of languages—bash, Python, R, and others—as well as a language-level static type system. On the other hand, Cuneiform does not manage software dependencies and so lacks the reproducibility guarantees that BioNix leverages from Nix.

Finally, SciPipe [53] is a recent workflow library that focuses on dynamic execution and streaming. Like Bionix, SciPipe provides logs at the resolution of each build and allows incremental (partial) builds. On the other hand, SciPipe has a strong focus on streaming, which is not supported in Nix between independent builds (see Limitations of BioNix).

Conclusions

We have presented BioNix, a framework built on Nix in which workflows are specified using pure functions. BioNix captures software versions and dependencies, manages computational environments, and composes the various stages of workflows all within the one framework and language. Previous approaches to computational reproducibility have relied on a combination of technologies such as containers, package managers, and workflow engines to achieve the same ends. BioNix unites these functionalities under the one framework, making it simple to specify computational biology workflows with strong reproducibility guarantees.

BioNix is available at http://github.com/PapenfussLab/bionix under the 3-clause BSD license.

Availability of Supporting Source Code and Requirements

Project name: BioNix

Project home page: https://github.com/PapenfussLab/BioNix
License: 3-clause BSD
Operating system(s): Not applicable
Other requirements: Nix
RRID:SCR_017662
BioTools: biotools:BioNix

Availability of Supporting Data and Materials

A GigaDB archival snapshot is available [54].

Abbreviations

ADT: abstract data type; BWA: Burrows-Wheeler Aligner; CNV: copy number variant; CWL: Common Workflow Language; GUI: graphical user interface; GWL: Guix Workflow Language; HPC: high-performance computing; PiGx: Pipelines in Genomics; WDL: Workflow Description Language.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All authors conceived the study and wrote the manuscript. JB and LDS conceived the initial design of BioNix. JB contributed code and documentation to BioNix.

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