# Software Testing and Verification

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- Individual modules may be cited as *Speaker, Module Title*, in *Tutorial Title*, …

## Acknowledgements

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Formalization of the process intimidates people because they think of writing tests as an overhead

# How to Think About Building Tests

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Next you think about how you are going to be able to tell whether the code is exhibiting correct behavior

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Let us work through an example …

- You want a large prime number for encryption
- As a part of the development, you first write a function that checks if a given number is prime

Correct behavior: input 13 returns true, input 15 returns false
Incorrect behavior: input 15 returns true

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- You write a "main" that reads in a number, calls the functions and prints true or false
- You can automate it by including a series of known primes and non-primes and their corresponding true or false values
- This is your "unit test" for the function

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- Now you have a more complex test that involves several correctly working components
- This is your "integration test"

# Types of Tests

**Well known tests for enterprise software**

- Unit tests – verify a single function, extremely quick to run

- Integration tests – verify functions working together

- System tests – verify functionality of the entire software

- Acceptance tests – verify that the client needs are met

- Regression tests – verify that there is no degradation in code capabilities

# Types of Tests

**Additional types of tests needed for research software**

- Composite unit tests – are tests for specific functionalities and/or capabilities

- Granular tests – are integration tests at various granularities verifying correct behavior of interoperating functional units

- Restart tests – verify that a run can restart transparently from a checkpointed state

- Performance tests – apply to high-performance computing codes, verify that there is no performance loss

# Classes of Tests

- White box testing – when you know the internals and can modify the code you are testing
  - Likely to be the code you and your collaborators are developing
  - You can insert assertions
  - You can insert code snippets that make testing easier

- Black box testing – when you do not know the internals of the code being tested, and cannot modify the code
  - Third party software or legacy code
  - The only means of verification available is reasoning about output to be obtained from supplied input

# Test Driven Development
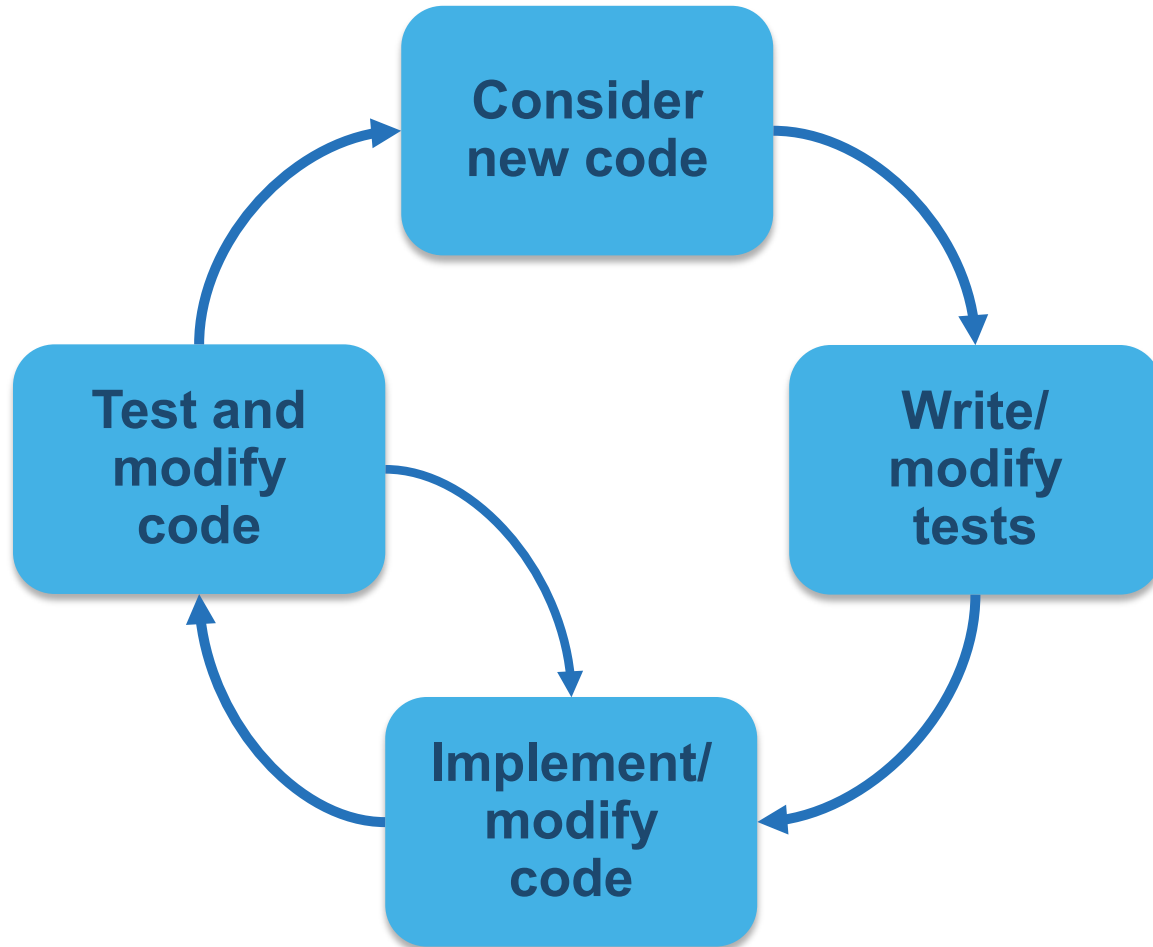


- Documented specifications and requirements of the code

- Ensures that thought is given to what it means for the program to be correct, rather than just what the program should do

- More efficient development cycle

- Much less debugging

- Requires:
  - Care in writing tests
  - Frequent running of tests
  - Wide adoption by development team

# What is Continuous Integration (CI)



https://docs.gitlab.com/ee/ci/introduction/

19
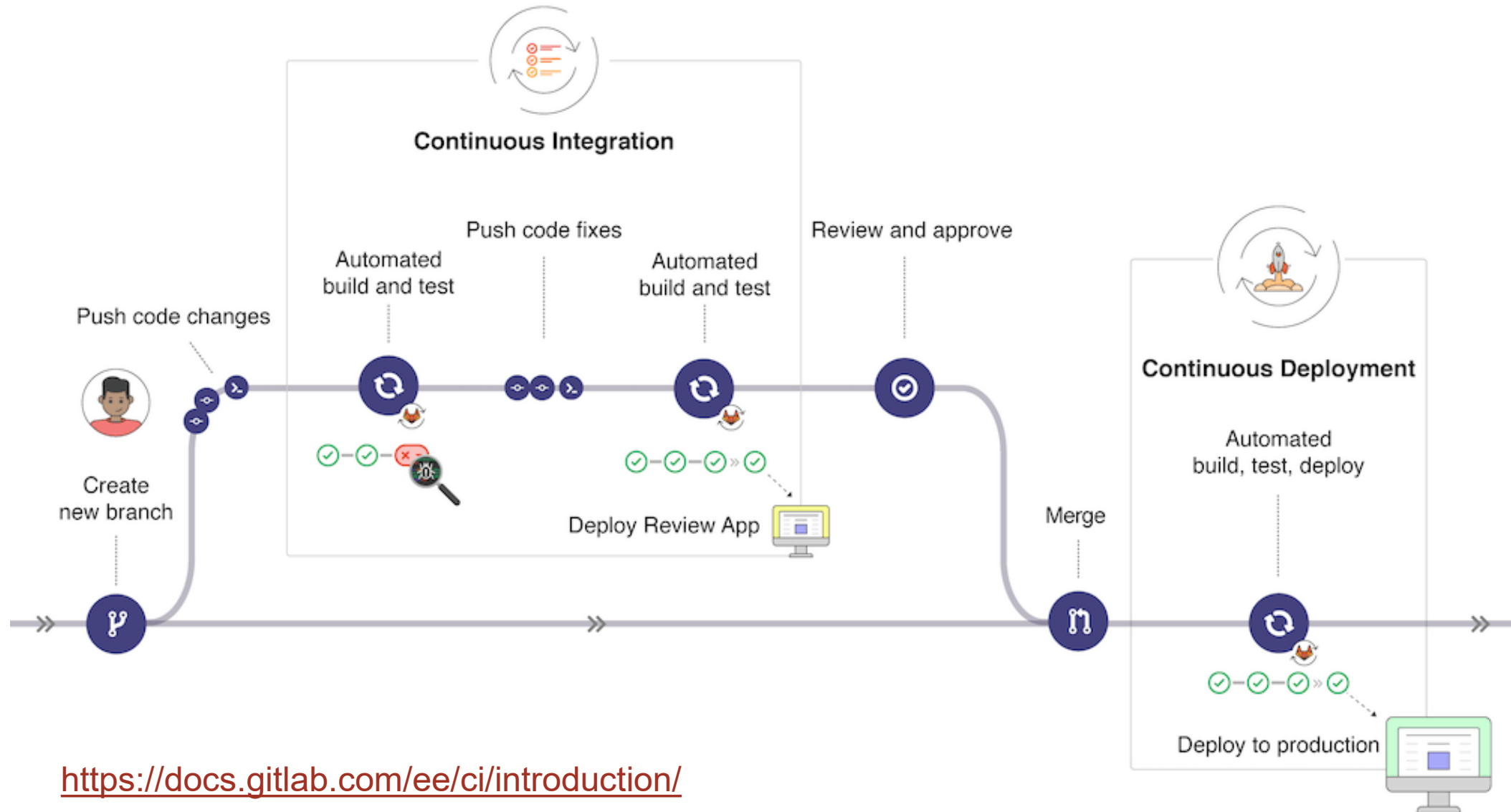
# CI Components

- Testing
  - Focused, critical functionality (infrastructure), fast, independent, orthogonal, complete, …
  - Existing test suites often require re-design/refactoring for CI

- Integration
  - Changes across key branches merged & tested to ensure the "whole" still works
    - Integration can take place at multiple levels
      - Individual project
      - Spack
      - E4S
  - Develop, develop, develop, merge, merge, merge, test, test, test…NO!
  - Develop, test, merge, develop, test, merge, develop, test, merge…YES!

- Continuous
  - Changes tested every commit and/or pull-request (like auto-correct)

- CI generally implies a lot of <u>automation</u>

# Test Driven Development vs. Automated Testing vs. CI

- ***Test Driven Development:*** A development methodology where functional test are written before the code
  - Works well with CI as tests are written and committed and are automatically run (failing)
  - Code that implements the functionality being tested retriggers the tests automatically

- ***Automated Testing***: Software that automatically performs tests on a regular basis and reliably detects and reports anomalous behaviors/outcomes.
  - Examples: Auto-test, CTest/CDash, nightly testing, etc.
  - May live "next to" your development workflow
  - Potential issues: change attribution, timeliness of results, multiple branches of development

- ***Continuous Integration (CI)***: automated testing performed at high frequency and fine granularity
  - Aimed at preventing code changes from breaking key branches of development (e.g. main)
  - Lives "within" your development workflow
  - Potential issues: extreme automation, test granularity, coverage, 3rd-party services/resources

# Examples…



**Automated Nightly Testing Dashboard**
**Lives "next to" your development work**

**CI Testing**
**Lives embedded in your development work**

22

# What can make CI difficult

| Common situations | Advanced situations |
|---|---|

**Common situations**

- Just getting started
  - Many technologies/choices; often in the "cloud"
  - Solution: start small, simple, build up
- Developing suitable tests
  - Many project's existing tests not suitable for CI
  - CI testing is a balance of thoroughness and responsiveness
  - Solution: Simplify/refactor and/or sub-setting test suite
- Ensuring sufficient coverage
  - Some changes to code never get tested – CI can provide a false sense of security
  - Solution: tools to measure it, enforce always increasing

**Advanced situations**

- Defining failure for *many* configurations / inconsistent failures
  - Bit-for-bit (exact) match vs. fuzzy match
  - Solution: absolute/relative tolerances → AI/ML
- Numerous 3rd party libraries (TPLs)
  - Compiling takes too long
  - Solution: cache pre-built TPLs, containers
- Performance testing
  - Avoid time-, space-, scaling-performance degradation
  - Solution: Performance instrumentation and *scheduled* testing

# CI Resources (Where do jobs run?)

- Free Resources
  - GitHub, BitBucket, GitLab, etc. provide shared runners
  - AWS, Azure Pipelines have free tiers that can be used
  - All launch a VM (Linux variants, Windows and OSX)
    - Constrained in time/size, hardware (e.g. GPU type/count)
    - Not a complete solution for many HPC/scientific codes, but a useful starting point.

- Site-local Resources
  - Group, department, institution, computing facility
  - Examples: CADES @ ORNL, Bamboo @ LLNL, Jenkins @ ANL, Travis+CDash @ NERSC
  - ECP Program: GitLab-CI @ ANL, LANL, LLNL, NERSC, ORNL, SNL

- Create your own by setting up resources/services

# Examples…



codecov.io

aws

github.com
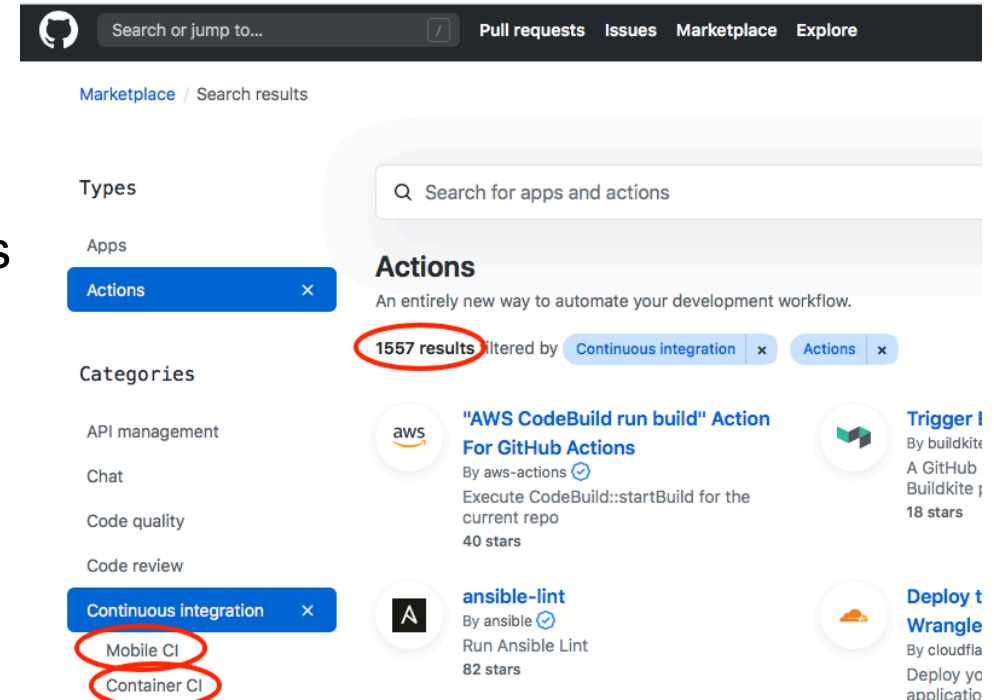
Your code repository

Your CI Resources

LLNL

bitbucket.llnl.gov

You

NERSC

gitlab.nersc.gov

25
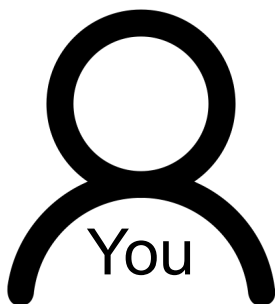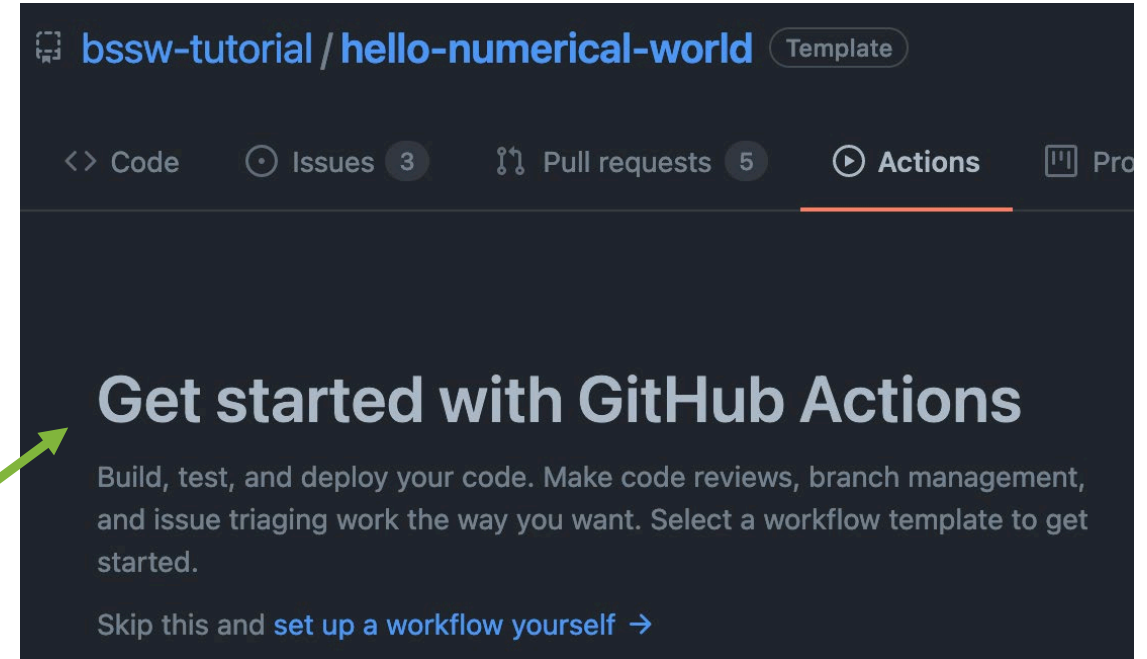
# Getting started with CI

- What *configuration* is most important?
  - Examples: gcc, icc, xlc? MPI-2 or MPI-3? Python 2, 3 or 2 & 3?

- What *functionality* is most important?
  - Examples: vanilla numerical kernels? OpenMP kernels? GPU kernels? All of these?

- Good candidates…
  - A "hello world" example for your project
  - At a minimum, even just building the code can be a place to start!
  - Once you've got the basics working, its easy to build up from there

# Getting started with CI:

| Setting up CI |
|:---:|

| Service | Interface | |
|---|---|---|
| GitHub Actions | Repo YAML file | .github/workflows/ <test_name>.yml |
| GitLab | Web page configurator + repo YAML file [& repo scripts] | /.gitlab-ci.yml in root of repo |
| Bamboo | Web page configurator + repo scripts | |
| Travis | repo YAML file [& repo scripts] | /.travis.yml in root of repo |
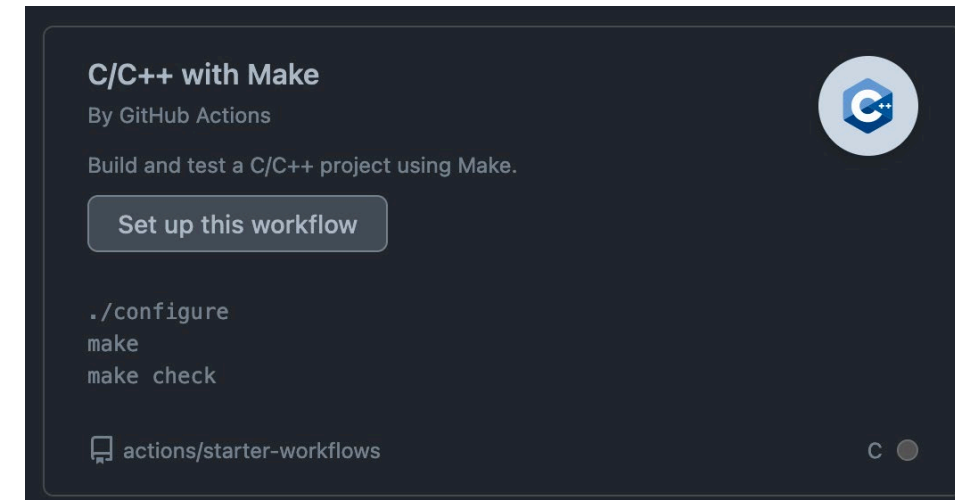


bssw-tutorial / **hello-numerical-world**  (Template)

<> Code    ⊙ Issues  3    ⑂ Pull requests  5    ⊙ Actions    ▥ Pr

## Get started with GitHub Actions

Build, test, and deploy your code. Make code reviews, branch management, and issue triaging work the way you want. Select a workflow template to get started.

Skip this and set up a workflow yourself →



**C/C++ with Make**
By GitHub Actions

Build and test a C/C++ project using Make.

Set up this workflow

./configure
make
make check

actions/starter-workflows

# Getting started with GitHub Actions:

```
19 lines (15 sloc) | 359 Bytes

 1    name: Check Results
 2
 3    on:
 4      push:
 5        branches: [ main ]
 6      pull_request:
 7        branches: [ main ]
 8
 9    jobs:
10      build:
11
12        runs-on: ubuntu-latest
13
14        steps:
15        - uses: actions/checkout@v2
16        - name: make coverage
17          run: make CXXFLAGS=--coverage LDFLAGS="--coverage -lm" check_all
18        - name: upload coverage
19          run: bash <(curl -s https://codecov.io/bash)
```

# github.com          # codecov.io

# GitHub Actions – results of workflow test runs

# GitHub Pull Request Status Indicators

Filters ▾    🔍 is:pr is:open                                          🏷 Labels 26    ⛙ Milestones 3    **New pull request**

⇅ 17 Open    ✓ 1,018 Closed                    Author ▾   Label ▾   Projects ▾   Milestones ▾   Reviews ▾   Assignee ▾   Sort ▾

⇅ **Allow string args to external fuctions** ✕                                    ⓘ 1                    💬 1
#1904 opened 19 hours ago by eslickj • Review required

⇅ **Port Cloning** ✓                                                             ⓘ 1                    💬 3
#1899 opened 3 days ago by michaelbynum • Approved

⇅ **Remove pyomo.solvers.tests.core** ✓                                                                 💬 2
#1897 opened 3 days ago by mrmundt • Approved

⇅ **[WIP] Model partition package** 🟡                                                                  💬 1
#1895 opened 4 days ago by rahuljoglekar47 • Review required

# What is CI Good For

- The purpose of CI is to identify problems early
  - Prevent code that would "break the build" or adversely impact other developers being introduced
  - Need to provide sufficient confidence, but run quickly – balance varies by project

- CI should complement (not replace) more extensive automated testing
  - Use scheduled testing for more and more detailed tests, more configurations and platforms, performance testing, etc.

- CI for TDD is a natural fit
  - Writing tests before the code works well with CI

- Many options for where to execute CI tests
  - Free services are a good (easy) place to start
  - But may not be sufficient in the long run (especially large HPC/scientific codes)

- <u>Start simple</u> to get automation working, then build out what you need
  - Focus initially on key software configurations and aspects of the code to be tested
  - Make sure your testing expands to cover new code, use TDD

# Building a Test-suite

**Elements of test development**

- For some tests assertions will suffice
- For others you will need to compare the output against baselines
    - Building a comparison utility is extremely useful
- Also useful to develop diagnostics – indirect ways of verifying behavior
    - Conservation of physical quantities
    - No non-physical values

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**Building baselines for comparison**

- From a known analytical solution
- Manufacture a solution
- Visualize and inspect output and anoint as baseline
- Run a test case up to point A and drop a checkpoint. Run another test case up to a later point B.
    - Use point A to restart and B as the anointed baseline

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Apply scaffolding for selection of tests … explained next

# Example – Shock Hydrodynamics with Adaptive Mesh Refinement

**Components needed**

- Mesh

- Hydrodynamics solver

- Equation of state

- Parallelization

Strategy for development
Think of an application with
analytical solution

# Example – Shock Hydrodynamics with Adaptive Mesh Refinement

## Components needed

- Mesh

- Hydrodynamics solver

- Equation of state

- Parallelization



Density (g/cm³)

Strategy for development
Think of an application with analytical solution
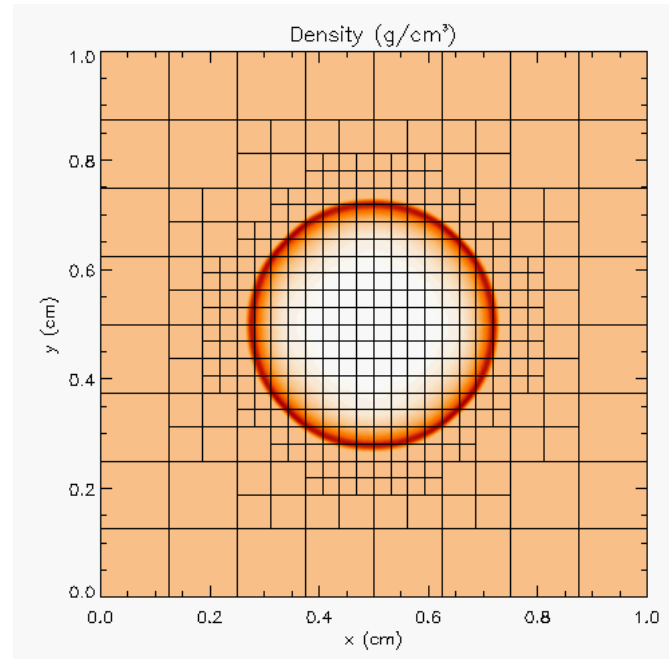
- Sedov blast wave
- High pressure at the center
- Shock moves out in a circle
- Analytical solution for how far the shock has travelled

# Step 1 – Equation of State

- Initialize density and internal energy with known values

- Compute pressure and temperature using EOS

- Next use density and computed pressure as input and compute internal energy and temperature using EOS

- Compare computed values against initialized values

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We have a unit test

# Step 2 – Mesh

- Start with uniform grid

- Domain decomposition for parallelization
  - Halo fill operation

- Initialize the interior (red) with a known function

- Apply halo fill

- Compute values for the halo using the known function

- Compare against filled values

rank 1

rank 2

halo cells

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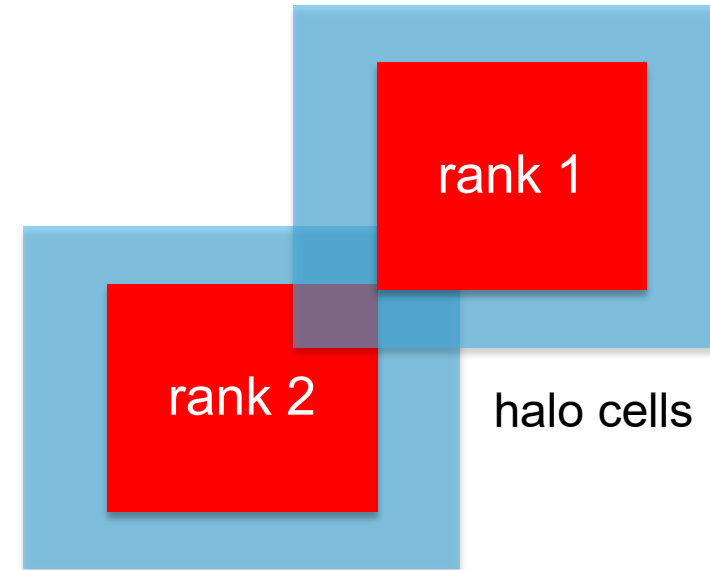
halo cells

We have another unit test

# Step 3 – Hydrodynamics

- Apply initial conditions to the mesh
  - zeroes everywhere except at the center

- Write code for the analytical expression of the distance traveled by the shock

- Do time integration

- At time **T** compare evolved solution against analytical solution

If both mesh and EOS unit test pass, then any failure is in Hydrodynamics
This is a composite unit test

This is also the idea behind scaffolding

# Step 4: AMR

- The same halo fill unit test for mesh also works for AMR

- Additional functionalities to test are:
  - Fine-coarse boundary resolution
  - Regridding

- Steps in testing
  - Run Sedov with UG
  - Run Sedov with AMR, but no dynamic refinement
    - If failed fault is in flux correction
  - Run Sedov with AMR and dynamic refinement
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All of these are examples of white box testing

# Mixed White/Black Box Testing For a Legacy Code

There may not be existing tests

- Isolate a small area of the code

- Dump a useful state snapshot

- Build a test driver
  - Start with only the files in the area
  - Link in dependencies
    - Copy if any customizations needed

- Read in the state snapshot

- Restart from the saved state

- Verify correctness
  - Always inject errors to verify that the test is working



state

driver
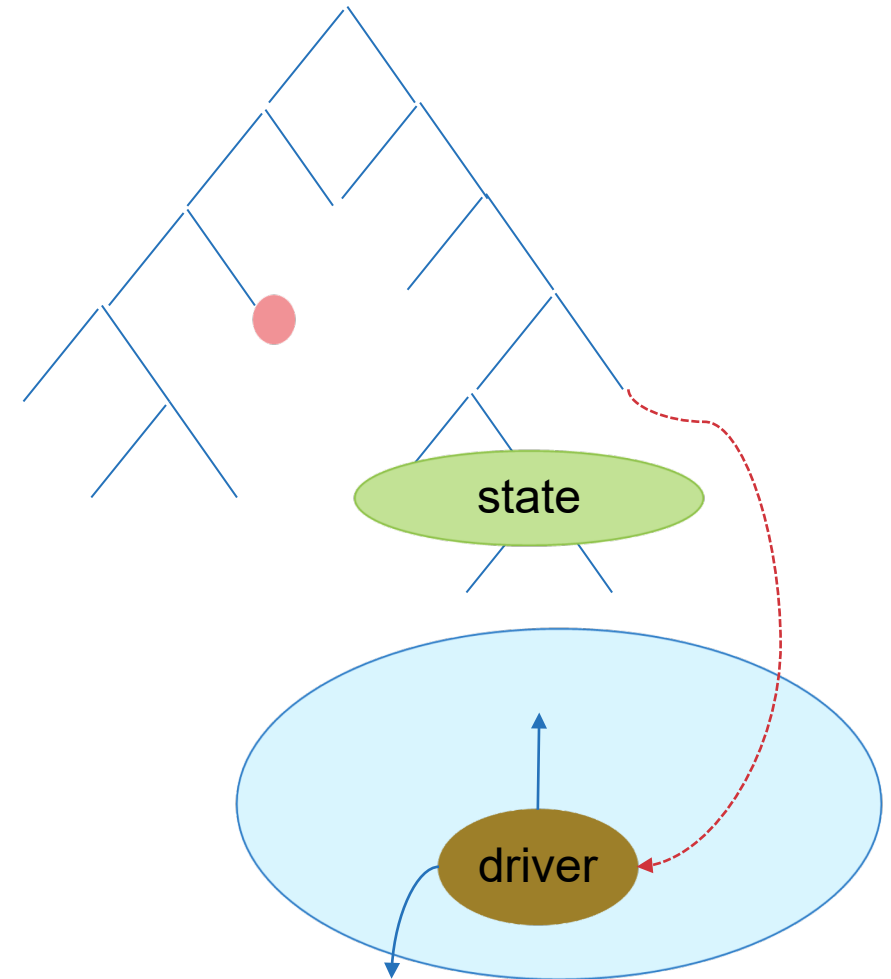
# How to build your test suite?

- A mix of different granularities works well
  - Unit tests for isolating component or sub-component level faults
  - Integration tests with simple to complex configuration and system level
  - Restart tests

- Rules of thumb
  - Simple
  - Enable quick pin-pointing

  Useful resources https://bssw.io/items?topic=testing

# How do we determine what tests are needed?

## Code coverage tools

- Expose parts of the code that aren't being tested
  - gcov - standard utility with the GNU compiler collection suite (we will use it in the next few slides)
  - Compile/link with –coverage & turn off optimization
  - Counts the number of times each statement is executed
  - Necessary for testing, but not sufficient

- gcov also works for C and Fortran
  - Other tools exist for other languages
  - JCov for Java
  - Coverage.py for python
  - Devel::Cover for perl
  - profile for MATLAB

- Lcov
  - a graphical front-end for gcov
  - available at https://github.com/linux-test-project/lcov
  - Codecov.io in CI module

- Hosted servers (e.g., coveralls, codecov)

- graphical visualization of results

- push results to server through continuous integration server

# Good Rules of Thumb

- Test your tests!
  - Make sure tests fail when they're supposed to!

- Add "regression tests"
  - Ensure that bugs aren't creeping in

- Test regularly
  - Critical when teams are adding code regularly
  - To identify and document where changes to the underlying platform change code behavior/results

- Automate regular testing
  - Inculcate the discipline of monitoring the outcome of regular testing

- Exercise third-party dependencies

- Physics/math-based strategies
  - Conserved quantities, symmetries, synthetic operators
  - Eliminate complete dependence on bitwise reproducibility

# Summary

- A testing strategy is essential for producing reliable trustworthy software
  - Invest the time needed to thoroughly test your software at all levels
  - Use automation whenever possible

- Different challenges are associated with exploratory, legacy, and composable codes
  - Adapt your strategy to fit your situation.
  - Eventually you will want to be able to verify all components in a code release.

- Don't get distracted by all the technologies out there – focus on exercising your code.
  - Scaffolding projects can help with mechanics.

# Resources

- Oberkampf, W., & Roy, C. (2010). Verification and Validation in Scientific Computing. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511760396

- Michael Feathers. 2004. Working Effectively with Legacy Code. Prentice Hall PTR, USA. ISBN: 9780131177055

- A Dubey, K Weide, D Lee, J Bachan, C Daley, S Olofin… - Ongoing Verification of a Multiphysics Community Code. Software: Practice and Experience, 2015 **https://doi.org/10.1002/spe.2220**