Cicada: Player-Scalable, Fault-Tolerant Secure MultiParty Computation

4th High-Performance Computing Security Workshop

Jon Berry, May, 2024

Project Team:

J. Berry (PI), G. Birch, K. Dixon (PM), A. Ganti, K. Goss, C. Mayer, U. Onunkwo, C. Phillips, J. Saia (UNM), T. Shead

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

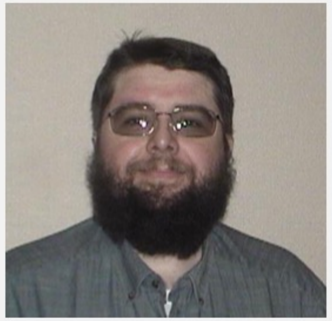
Thanks to Our Multi-Disciplinary Research Team


Jon Berry (PI)

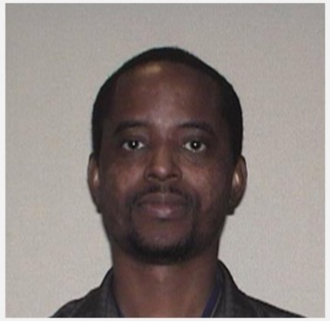

Gabe Birch


Kevin Dixon (PM)


Anand Ganti


Ken Goss


Carolyn Mayer


Uzoma Onunkwo


Cindy Phillips


Jared Saia (UNM)


Tim Shead
Cicada-mpc
main author

Outline

- Application driver: Privacy-Preserving Machine Learning
- Algorithmic case study: dense matrix multiplication
- Software overview: Cicada-mpc (Fault-tolerant, open-source)

https://github.com/cicada-mpc/cicada-mpc/
https://cicada-mpc.readthedocs.io/

https://www.youtube.com/watch?v=GM_JuKrw4Ik

Secure MultiParty Computation

Example:

Secure Multiparty Computation Goes Live. Bogetoft et al. (2009)

Related work for Machine Learning:

- *SecureML: A System for Scalable Privacy-Preserving Machine Learning.* Mohassel and Zhang. (2017).
- *ABY^3: A Mixed Protocol Framework for Machine Learning.* Mohassel and Rindal. (2018)
- Many others (e.g. FALCON) for 2, 3, or 4 players.

Size of circuit for ML using traditional MPC approaches (e.g. EMP) is prohibitive.

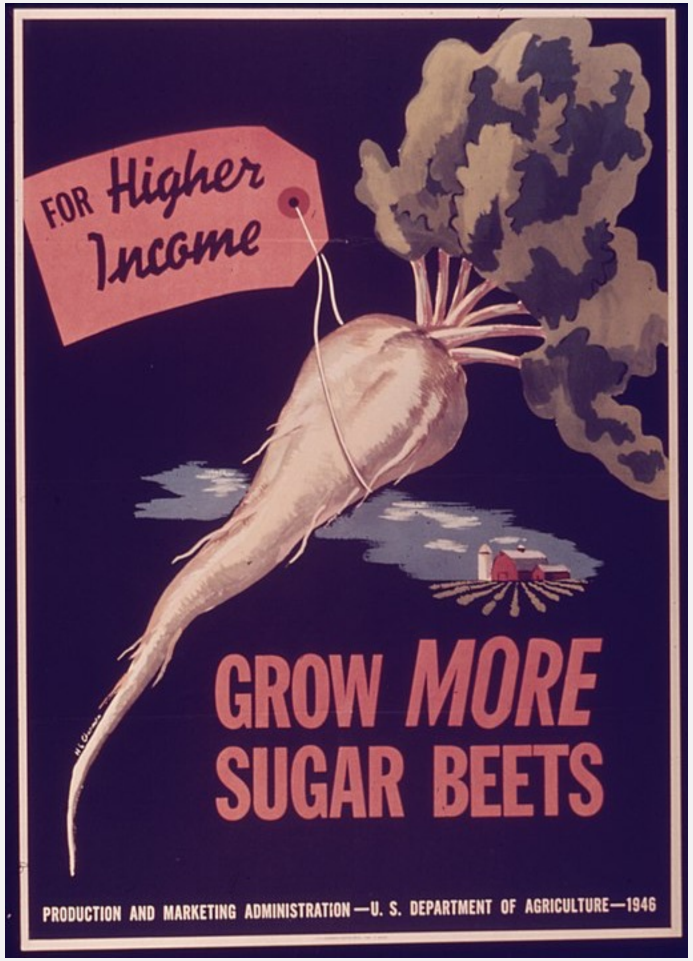


Image from National Archives. ARC Identifier: 514423

Motivation: MPC Linear Regression & Gradient Descent

Gradient descent:

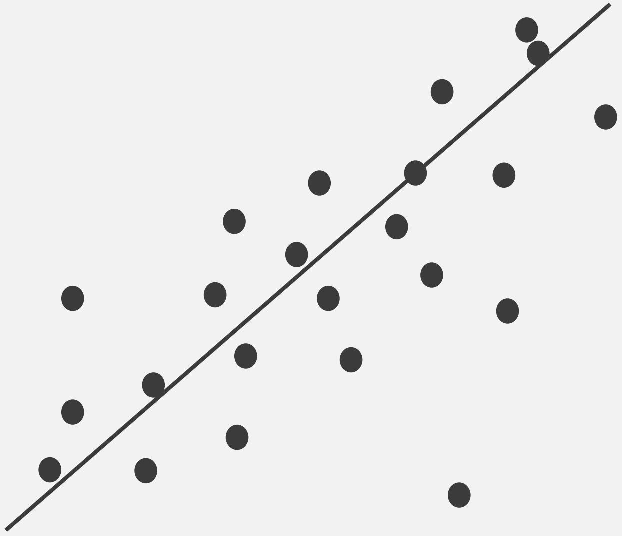
Model: vector $\boldsymbol{\beta}$.

Goal: Minimize a loss function $\boldsymbol{L}(\boldsymbol{\beta})$ by iterating $\boldsymbol{\beta}' = \boldsymbol{\beta} - \eta \nabla \boldsymbol{L}(\boldsymbol{\beta})$

for some learning rate $\boldsymbol{\eta}$.

Why linear regression?

- Single matrix-vector multiplication in each step.
- Allows for local computations.
- Hold shares of updated model locally.



$\boldsymbol{\beta} = (m, b)$

Local Gradient Matrices

Global gradient G uses all datapoints.

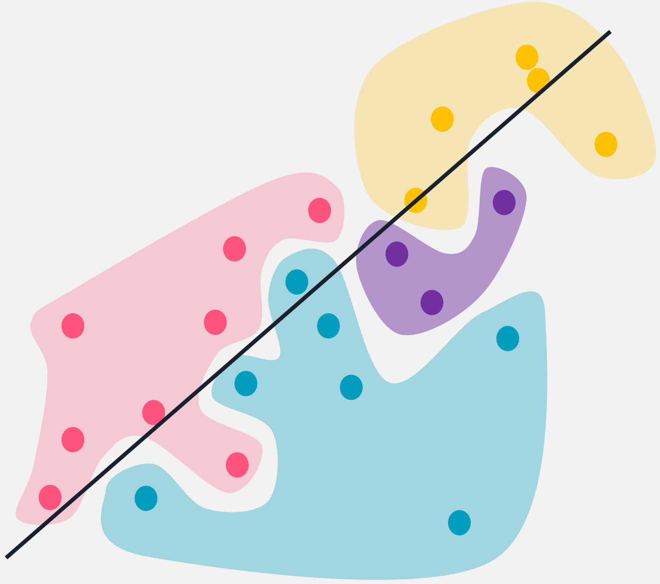
Local gradient G_p uses datapoints held by player p.

Then $G = \sum_p G_p$. Each G_p is a share of G.

Note: Players can have different amounts of data.

Note: Players' original gradient G_p is additive, *but not shareable*

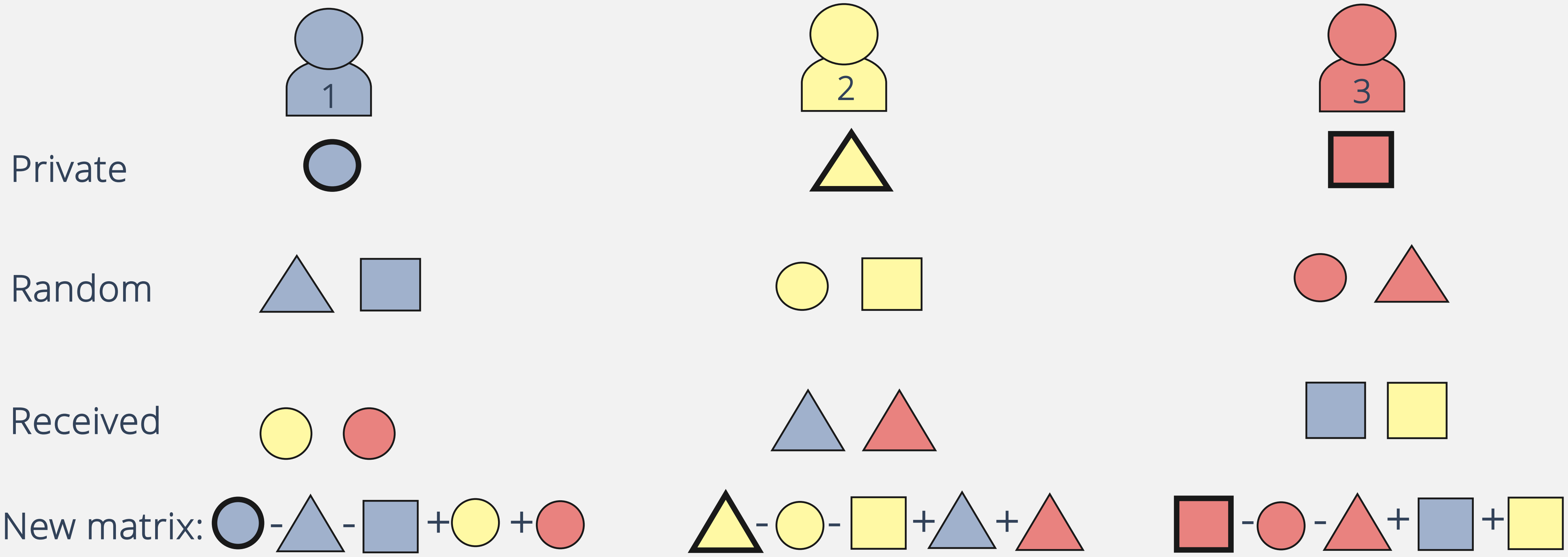
- *We create "additive secret shares" that are shareable*



$\boldsymbol{\beta} = (m, b)$

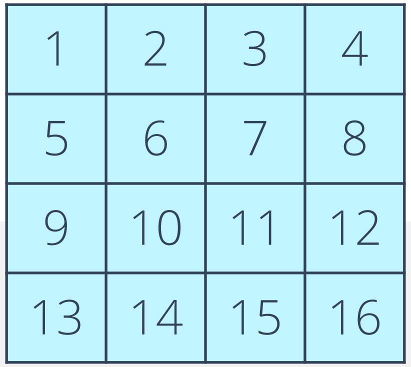
Typical MPC Computation: Resharing Matrices

Reshare to form matrices that don't individually reveal gradient information.



Private – Random + Received

MMULT(A, B)



1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

For each player p:

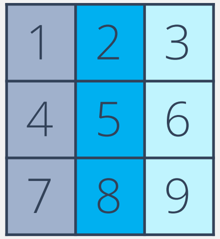
1. $A_p' \leftarrow$ AGGREGATE(A_p, C_p). # sum shares along columns
2. $B_p' \leftarrow$ AGGREGATE($B_p, \mathcal{R}_p$). # sum shares along rows
3. Return $A_p' B_p'$.

Where C_p is the column p is in and $\mathcal{R}_p$ is the row p is in.

Coalition resisted: $\sqrt{\# \, Players} - 1$

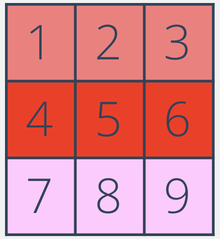
MMULT Example: 9 Players

Aggregate A in columns:



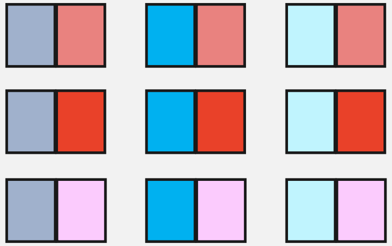
1	2	3
4	5	6
7	8	9

Aggregate B in rows:

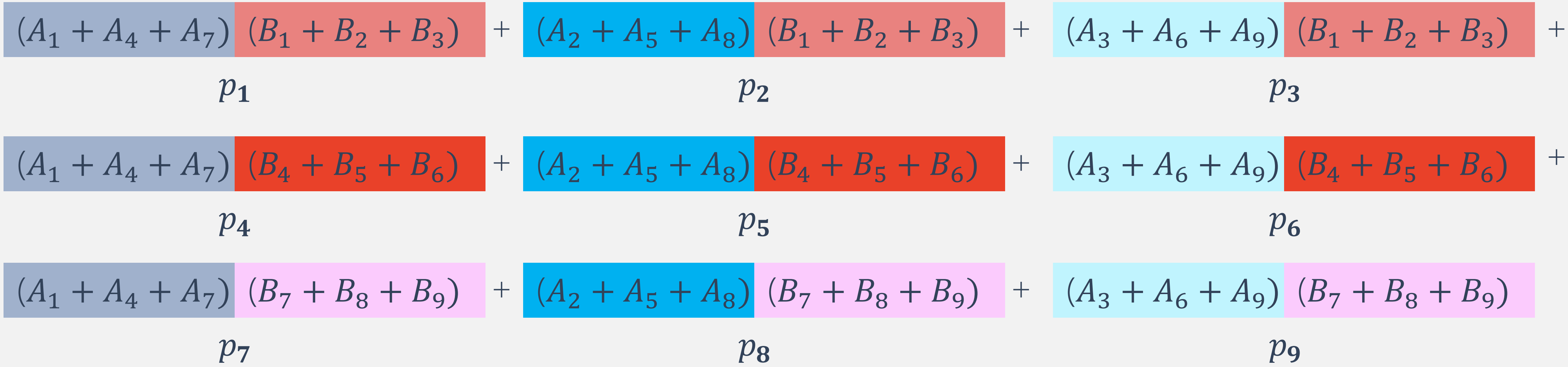


1	2	3
4	5	6
7	8	9

Local multiplications:



Global impact of MMULT:



$$\underbrace{(A_1+A_4+A_7)\,(B_1+B_2+B_3)}_{p_1} + \underbrace{(A_2+A_5+A_8)\,(B_1+B_2+B_3)}_{p_2} + \underbrace{(A_3+A_6+A_9)\,(B_1+B_2+B_3)}_{p_3} +$$

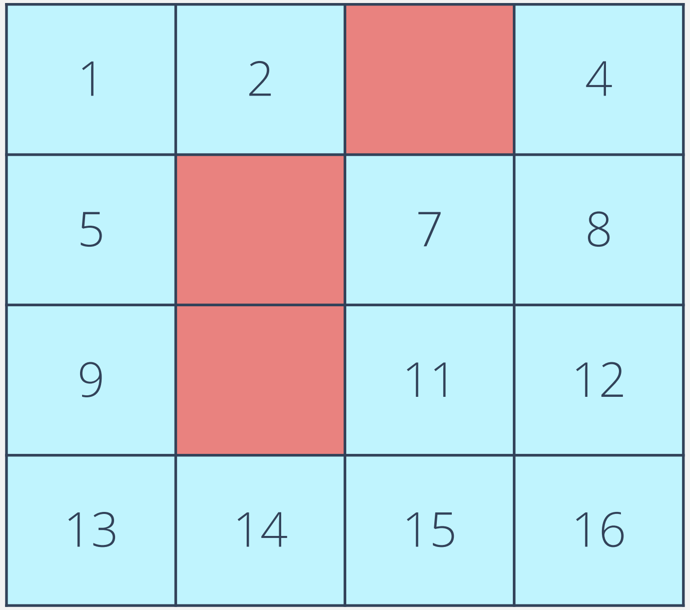
$$\underbrace{(A_1+A_4+A_7)\,(B_4+B_5+B_6)}_{p_4} + \underbrace{(A_2+A_5+A_8)\,(B_4+B_5+B_6)}_{p_5} + \underbrace{(A_3+A_6+A_9)\,(B_4+B_5+B_6)}_{p_6} +$$

$$\underbrace{(A_1+A_4+A_7)\,(B_7+B_8+B_9)}_{p_7} + \underbrace{(A_2+A_5+A_8)\,(B_7+B_8+B_9)}_{p_8} + \underbrace{(A_3+A_6+A_9)\,(B_7+B_8+B_9)}_{p_9}$$

Tolerating Fail-Stop Faults

Idea:

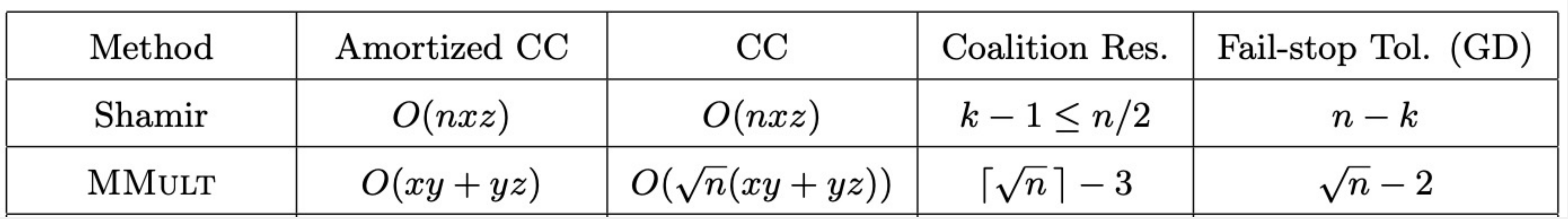
- Checkpoint row and column aggregated values.
- Use Cicada’s built-in fault tolerance and Python exception handling



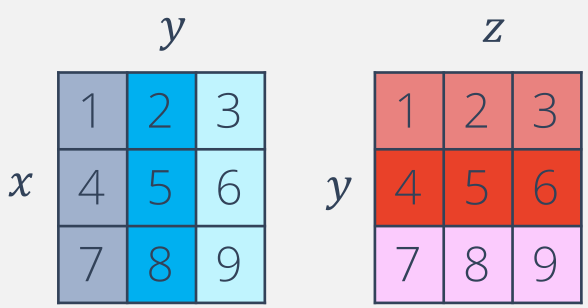
1	2	🟥	4
5	🟥	7	8
9	🟥	11	12
13	14	15	16

MMULT: Theoretical Results

The Communication Complexity (CC) of MMULT is *nearly optimal* for a single matrix multiplication, and ***optimal*** in the amortized sense for a suite of O($\sqrt{n}$) matrix multiplications (n is the number of players)



Method	Amortized CC	CC	Coalition Res.	Fail-stop Tol. (GD)
Shamir	$O(nxz)$	$O(nxz)$	$k-1 \leq n/2$	$n-k$
MMULT	$O(xy+yz)$	$O(\sqrt{n}(xy+yz))$	$\lceil\sqrt{n}\rceil - 3$	$\sqrt{n}-2$

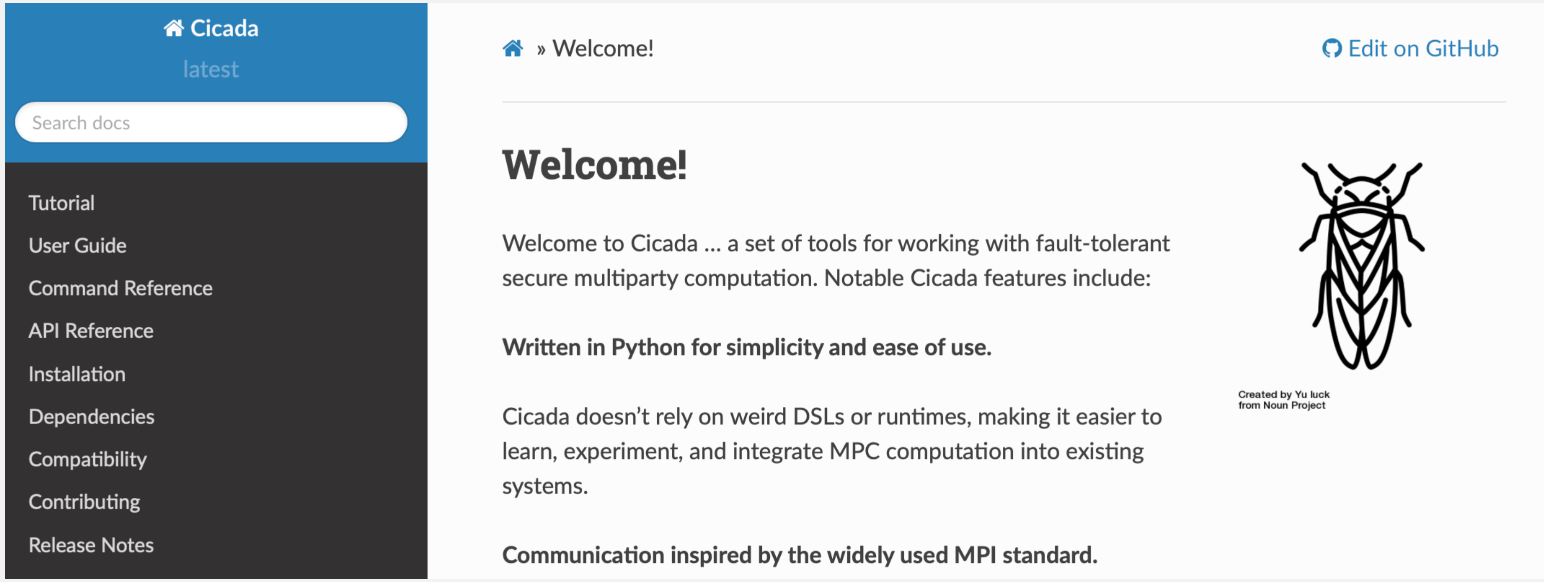


CICADA Software Framework

- MPC software toolkit tolerating dropouts
- Open-source:

  https://github.com/cicada-mpc/cicada-mpc/
  https://cicada-mpc.readthedocs.io/

CooperatIve Computing for Autonomous DAta centers



Welcome!

Welcome to Cicada ... a set of tools for working with fault-tolerant secure multiparty computation. Notable Cicada features include:

Written in Python for simplicity and ease of use.

Cicada doesn't rely on weird DSLs or runtimes, making it easier to learn, experiment, and integrate MPC computation into existing systems.

Communication inspired by the widely used MPI standard.

Written in Python, no weird DSLs or runtimes:

```python
from cicada.communicator import SocketCommunicator

with SocketCommunicator.connect() as comm:
    print(f"Hello from player {comm.rank}!")
```

```
$ cicada run hello.py
Hello from player 0!
Hello from player 2!
Hello from player 1!
```

Based on three fundamental concepts

Communicators

Network abstraction representing an unchanging group of players, and communication patterns to pass messages among them.

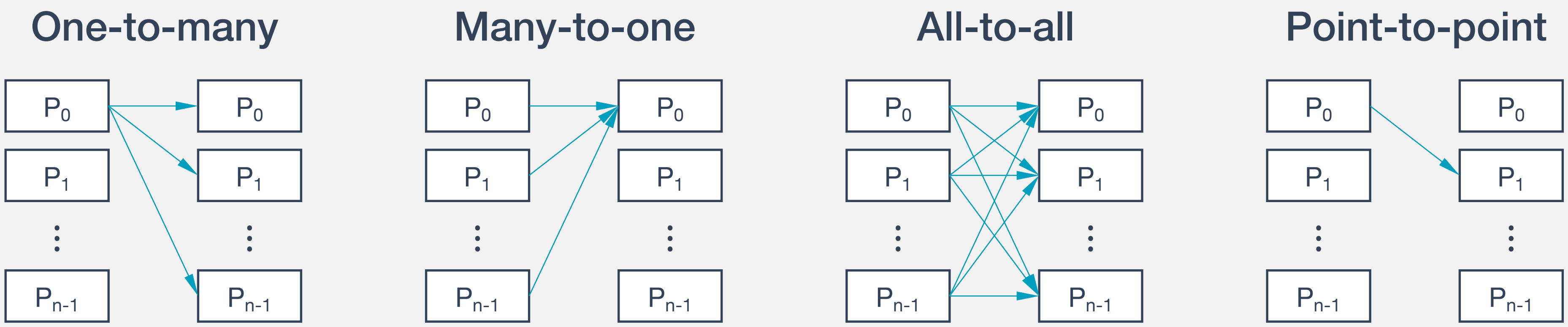
Encodings

Map between domain values and MPC-friendly integer field representations.

Protocol Suites

Use communicators and encodings to implement curated collections of privacy-preserving protocols: secret sharing, addition, multiplication, logical comparison, etc.

Communication Patterns



One-to-many

Many-to-one

All-to-all

Point-to-point

P_0

P_1

⋮

P_{n-1}

Based on three fundamental concepts:

Communicators

Network abstraction representing an unchanging group of players, and communication patterns to pass messages among them.

Encodings

Map between domain values and MPC-friendly integer field representations.

Protocol Suites

Use communicators and encodings to implement curated collections of privacy-preserving protocols: secret sharing, addition, multiplication, logical comparison, etc.

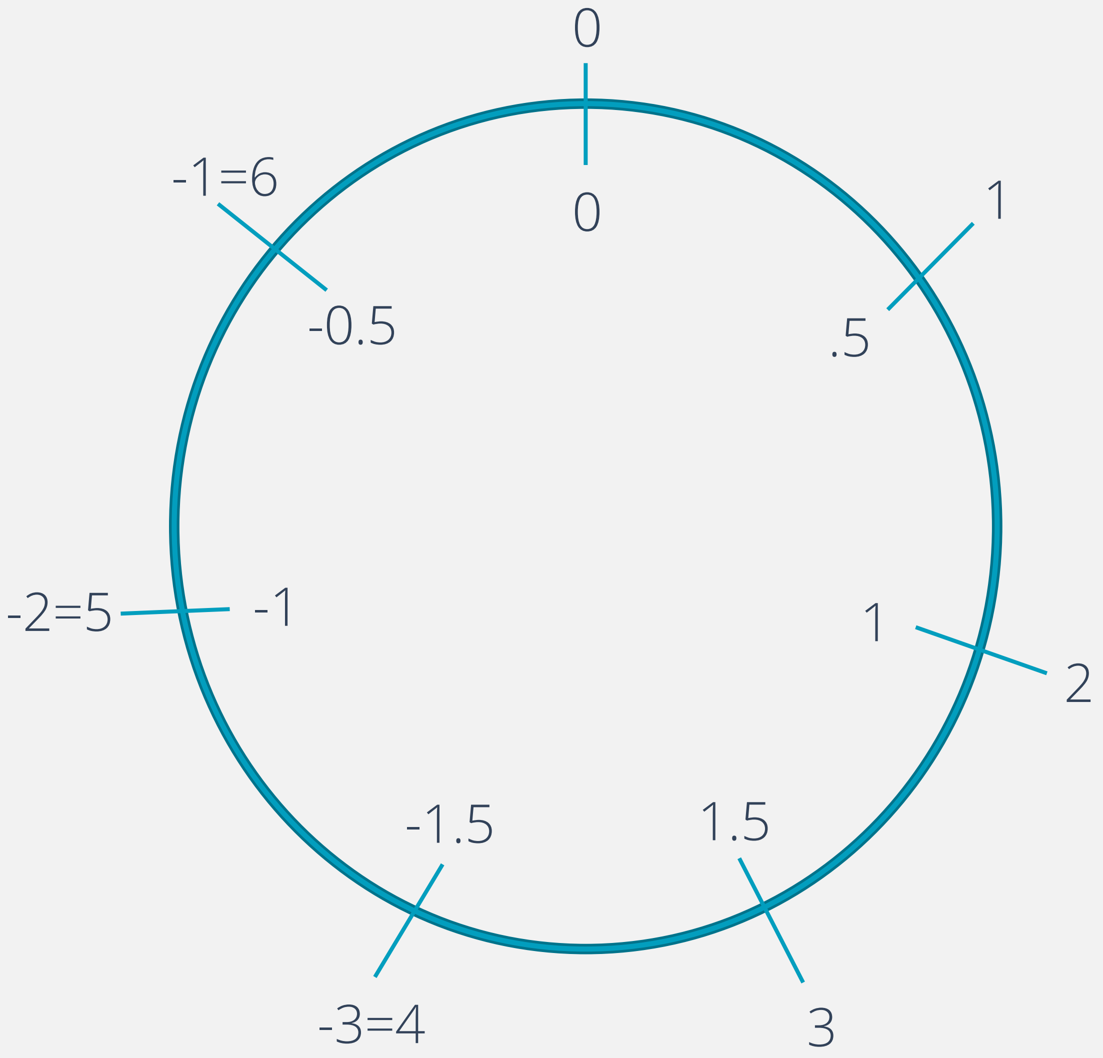
Encoding Fixed Point Arithmetic into a Field

Use fixed number of bits and two’s complement arithmetic.

Lower order bits represent fractional part.

Example: 7-element field with lowest order bit representing fractional part.

Going forward, we use fixed point arithmetic in a field $\boldsymbol{F}$ with a prime number of elements.



Based on three fundamental concepts:

Communicators

Network abstraction representing an unchanging group of players, and communication patterns to pass messages among them.

Encodings

Map between domain values and MPC-friendly integer field representations.

Protocol Suites

Use communicators and encodings to implement curated collections of privacy-preserving protocols: secret sharing, addition, multiplication, logical comparison, etc.

The Millionaires’ Dilemma in ~20 Lines of Cicada

```
import numpy

from cicada.additive import AdditiveProtocolSuite
from cicada.communicator import SocketCommunicator
from cicada.encoding import Boolean
from cicada.interactive import secret_input

with SocketCommunicator.connect(startup_timeout=300) as communicator:
    protocol = AdditiveProtocolSuite(communicator)

    winner = None
    winning_share = protocol.share(src=0, secret=numpy.array(0), shape=())

    for rank in communicator.ranks:
        prompt = f"Player {communicator.rank} fortune: "
        fortune = secret_input(communicator=communicator, src=rank, prompt=prompt)
        fortune_share = protocol.share(src=rank, secret=fortune, shape=())
        less_share = protocol.less(fortune_share, winning_share)
        less = protocol.reveal(less_share, encoding=Boolean())
        if not less:
            winner = rank
            winning_share = fortune_share

    print(f"Winner: player {winner}")
```

Communicators

```
import numpy


from cicada.additive import AdditiveProtocolSuite
from cicada.communicator import SocketCommunicator
from cicada.encoding import Boolean
from cicada.interactive import secret_input

with SocketCommunicator.connect(startup_timeout=300) as communicator:
    protocol = AdditiveProtocolSuite(communicator)

    winner = None
    winning_share = protocol.share(src=0, secret=numpy.array(0), shape=())

    for rank in communicator.ranks:
        prompt = f"Player {communicator.rank} fortune: "
        fortune = secret_input(communicator=communicator, src=rank, prompt=prompt)
        fortune_share = protocol.share(src=rank, secret=fortune, shape=())
        less_share = protocol.less(fortune_share, winning_share)
        less = protocol.reveal(less_share, encoding=Boolean())
        if not less:
            winner = rank
            winning_share = fortune_share

    print(f"Winner: player {winner}")
```

Encodings

```
import numpy

from cicada.additive import AdditiveProtocolSuite
from cicada.communicator import SocketCommunicator
from cicada.encoding import Boolean
from cicada.interactive import secret_input

with SocketCommunicator.connect(startup_timeout=300) as communicator:
    protocol = AdditiveProtocolSuite(communicator)

    winner = None
    winning_share = protocol.share(src=0, secret=numpy.array(0), shape=())

    for rank in communicator.ranks:
        prompt = f"Player {communicator.rank} fortune: "
        fortune = secret_input(communicator=communicator, src=rank, prompt=prompt)
        fortune_share = protocol.share(src=rank, secret=fortune, shape=())
        less_share = protocol.less(fortune_share, winning_share)
        less = protocol.reveal(less_share, encoding=Boolean())
        if not less:
            winner = rank
            winning_share = fortune_share

    print(f"Winner: player {winner}")
```

Protocol Suites

```python
import numpy

from cicada.additive import AdditiveProtocolSuite
from cicada.communicator import SocketCommunicator
from cicada.encoding import Boolean
from cicada.interactive import secret_input

with SocketCommunicator.connect(startup_timeout=300) as communicator:
    protocol = AdditiveProtocolSuite(communicator)

    winner = None
    winning_share = protocol.share(src=0, secret=numpy.array(0), shape=())

    for rank in communicator.ranks:
        prompt = f"Player {communicator.rank} fortune: "
        fortune = secret_input(communicator=communicator, src=rank, prompt=prompt)
        fortune_share = protocol.share(src=rank, secret=fortune, shape=())
        less_share = protocol.less(fortune_share, winning_share)
        less = protocol.reveal(less_share, encoding=Boolean())
        if not less:
            winner = rank
            winning_share = fortune_share

    print(f"Winner: player {winner}")
```

```
hostA $ cicada start --rank 0 millionaires.py

Player 0 fortune: 1230000
INFO:root:Winner: player 1
```

```
hostB $ cicada start --rank 1 millionaires.py

Player 1 fortune: 4560000
INFO:root:Winner: player 1
```

```
hostC $ cicada start --rank 2 millionaires.py

Player 2 fortune: 3400000
INFO:root:Winner: player 1
```

Fault Tolerance

Cicada is the only MPC library we're aware of with support for fault tolerance and recovery!

All communication patterns have explicit, finite timeouts ...

… so failures cannot go unnoticed.

Communicators raise exceptions when failures occur …

… this is the part where other MPC tools just die.

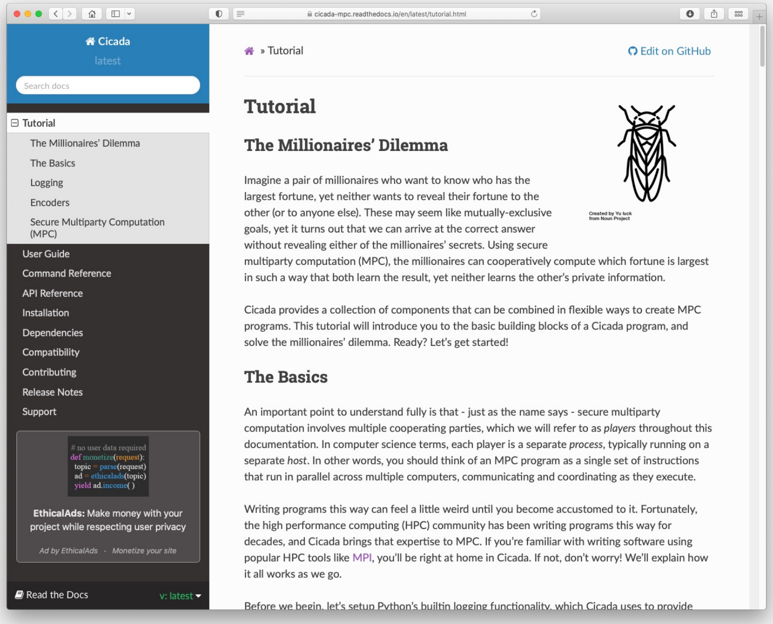
Applications can respond to exceptions in flexible ways …

… communicators can be *revoked* (preventing subsequent use by any player)

… communicators can be *shrunk* (returns a new communicator with the remaining players)

… data recovery is application specific.

Thorough Documentation



Tutorial

The Millionaires' Dilemma

Imagine a pair of millionaires who want to know who has the largest fortune, yet neither wants to reveal their fortune to the other (or to anyone else). These may seem like mutually-exclusive goals, yet it turns out that we can arrive at the correct answer without revealing either of the millionaires' secrets. Using secure multiparty computation (MPC), the millionaires can cooperatively compute which fortune is largest in such a way that both learn the result, yet neither learns the other's private information.

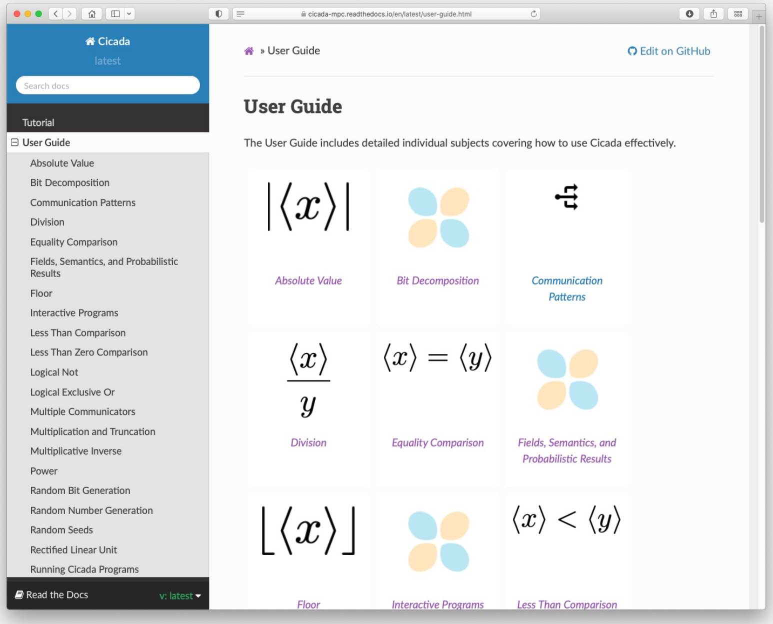
Cicada provides a collection of components that can be combined in flexible ways to create MPC programs. This tutorial will introduce you to the basic building blocks of a Cicada program, and solve the millionaires' dilemma. Ready? Let's get started!

The Basics

An important point to understand fully is that - just as the name says - secure multiparty computation involves multiple cooperating parties, which we will refer to as *players* throughout this documentation. In computer science terms, each player is a separate *process*, typically running on a separate *host*. In other words, you should think of an MPC program as a single set of instructions that run in parallel across multiple computers, communicating and coordinating as they execute.

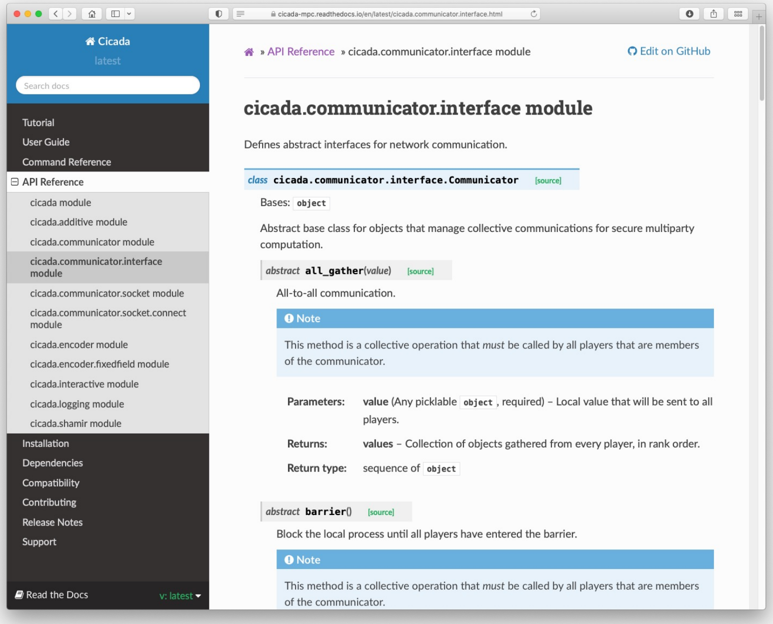
Writing programs this way can feel a little weird until you become accustomed to it. Fortunately, the high performance computing (HPC) community has been writing programs this way for decades, and Cicada brings that expertise to MPC. If you're familiar with writing software using popular HPC tools like MPI, you'll be right at home in Cicada. If not, don't worry! We'll explain how it all works as we go.

Before we begin, let's setup Python's builtin logging functionality, which Cicada uses to provide



User Guide

The User Guide includes detailed individual subjects covering how to use Cicada effectively.



cicada.communicator.interface module

Defines abstract interfaces for network communication.

class `cicada.communicator.interface.Communicator` [source]

Bases: `object`

Abstract base class for objects that manage collective communications for secure multiparty computation.

abstract `all_gather`(*value*) [source]

All-to-all communication.

Note

This method is a collective operation that *must* be called by all players that are members of the communicator.

Parameters: **value** (Any picklable `object`, required) – Local value that will be sent to all players.

Returns: **values** – Collection of objects gathered from every player, in rank order.

Return type: sequence of `object`

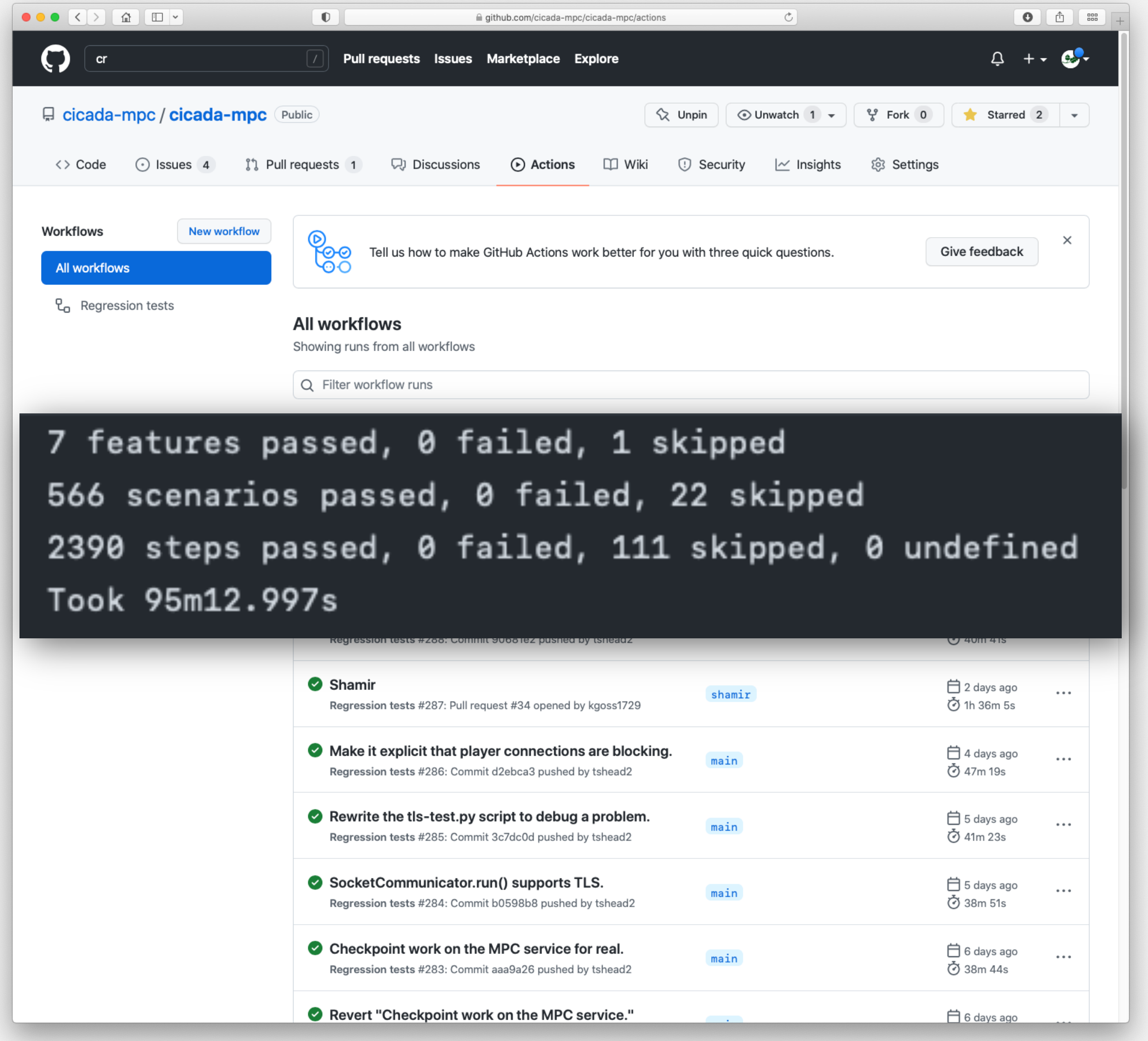
abstract `barrier`() [source]

Block the local process until all players have entered the barrier.

Note

This method is a collective operation that *must* be called by all players that are members of the communicator.

Thorough Testing and Continuous Integration



cicada-mpc / cicada-mpc Public

Workflows

- All workflows
- Regression tests

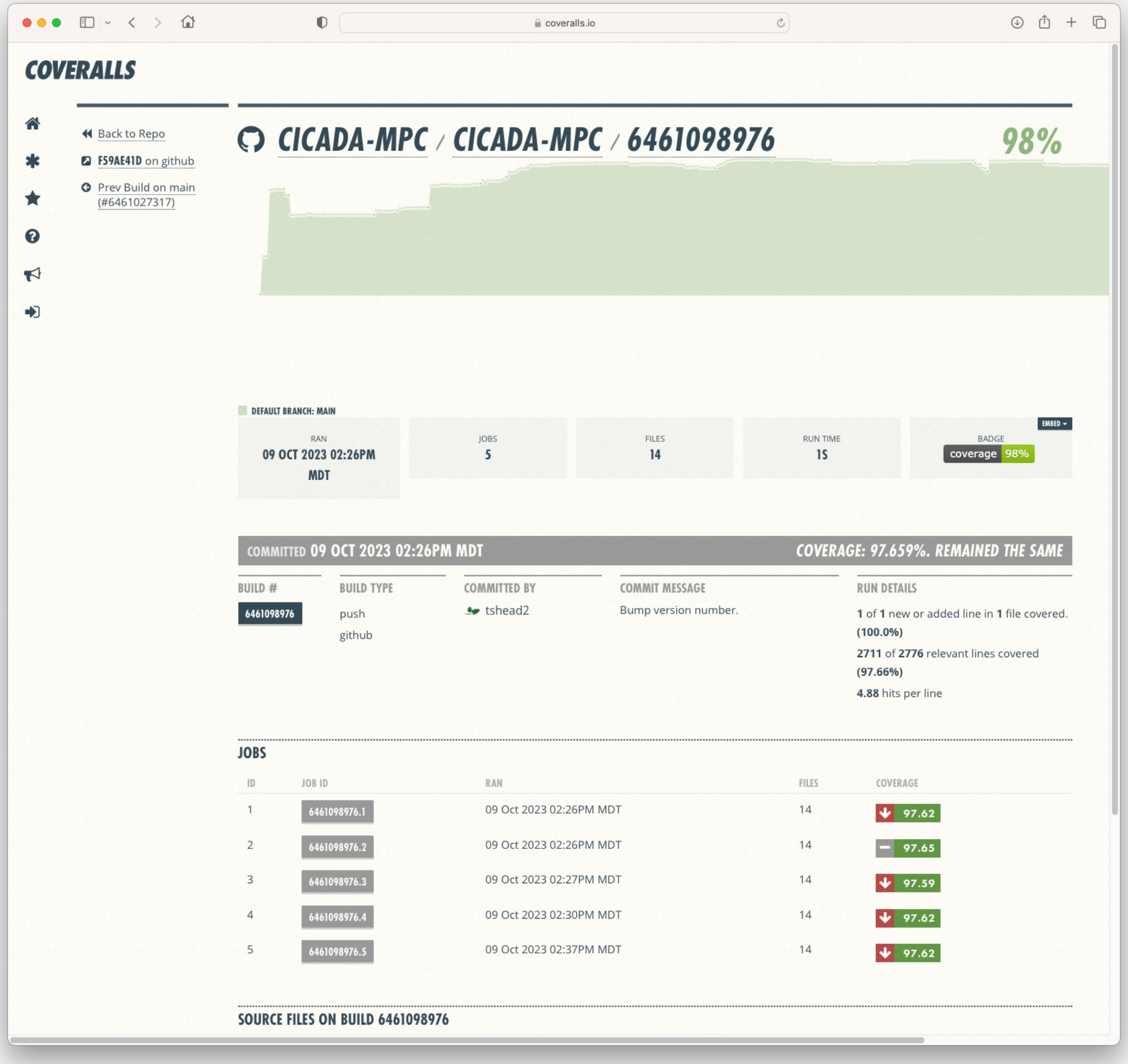
Tell us how to make GitHub Actions work better for you with three quick questions.

All workflows

Showing runs from all workflows

```
7 features passed, 0 failed, 1 skipped
566 scenarios passed, 0 failed, 22 skipped
2390 steps passed, 0 failed, 111 skipped, 0 undefined
Took 95m12.997s
```

Run	Branch	When	Duration
Shamir Regression tests #287: Pull request #34 opened by kgoss1729	shamir	2 days ago	1h 36m 5s
Make it explicit that player connections are blocking. Regression tests #286: Commit d2ebca3 pushed by tshead2	main	4 days ago	47m 19s
Rewrite the tls-test.py script to debug a problem. Regression tests #285: Commit 3c7dc0d pushed by tshead2	main	5 days ago	41m 23s
SocketCommunicator.run() supports TLS. Regression tests #284: Commit b0598b8 pushed by tshead2	main	5 days ago	38m 51s
Checkpoint work on the MPC service for real. Regression tests #283: Commit aaa9a26 pushed by tshead2	main	6 days ago	38m 44s
Revert "Checkpoint work on the MPC service."		6 days ago	



CICADA-MPC / CICADA-MPC / 6461098976 98%

DEFAULT BRANCH: MAIN

RAN	JOBS	FILES	RUN TIME	BADGE
09 OCT 2023 02:26PM MDT	5	14	1S	coverage 98%

COMMITTED 09 OCT 2023 02:26PM MDT — COVERAGE: 97.659%. REMAINED THE SAME

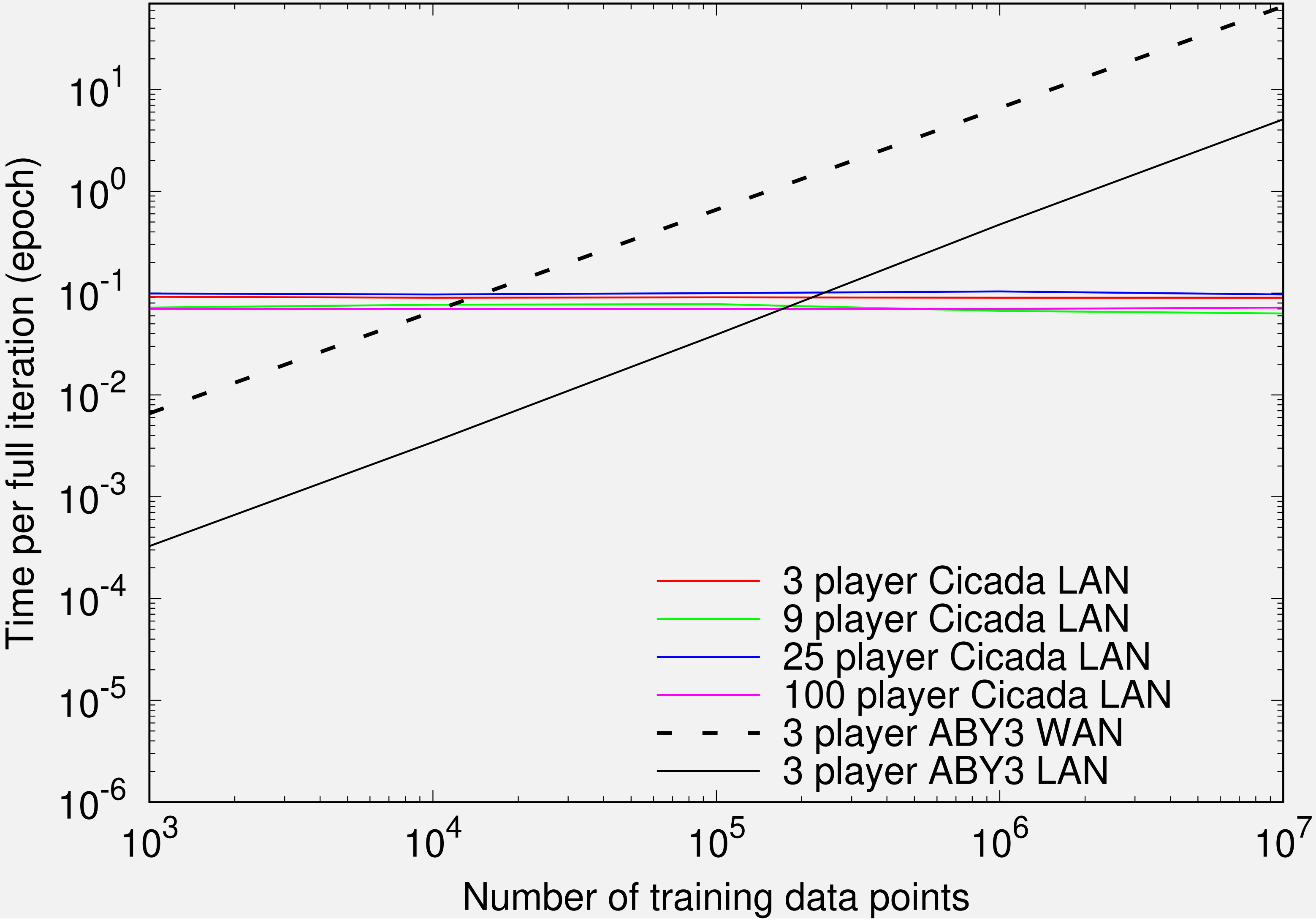
BUILD #	BUILD TYPE	COMMITTED BY	COMMIT MESSAGE	RUN DETAILS
6461098976	push github	tshead2	Bump version number.	**1** of **1** new or added line in **1** file covered. **(100.0%)** **2711** of **2776** relevant lines covered **(97.66%)** **4.88** hits per line

JOBS

ID	JOB ID	RAN	FILES	COVERAGE
1	6461098976.1	09 Oct 2023 02:26PM MDT	14	↓ 97.62
2	6461098976.2	09 Oct 2023 02:26PM MDT	14	− 97.65
3	6461098976.3	09 Oct 2023 02:27PM MDT	14	↓ 97.59
4	6461098976.4	09 Oct 2023 02:30PM MDT	14	↓ 97.62
5	6461098976.5	09 Oct 2023 02:37PM MDT	14	↓ 97.62

SOURCE FILES ON BUILD 6461098976

MPC Through 100 Players!



Conclusions, HPC Community Asks

“WHY DIDN’T WE USE MPI and USER-LEVEL FAULT MITIGATION (ULFM)?”

Three years ago, we evaluated ULFM reference implementations in MPICH and OpenMPI. We identified problems such as:

- Communicator revocation wasn’t detected by all ranks, depending on which ranks initiated the revocation.
- Some collective operations did not raise timeout errors even when some ranks were dead.
- Because ULFM hasn’t been adopted by MPI, the Python mpi4py bindings don’t support ULFM, and working with patched bindings severely limits our ability to distribute our software.

Questions?

jberry@sandia.gov