EINDHOVEN UNIVERSITY OF TECHNOLOGY

Secure Sessions for Ad Hoc Multiparty Computation in MPyC

Master thesis preparation phase

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Outline

Introduction

Introduction

What is Secure Multi-Party Computation?

- Joint computation of a function
- Secret inputs
- Only final result is revealed

Examples:

- Millionaire's problem
- Secret Santa
- Electronic voting
- Auctions
- Machine learning

MPC Basics

- Lagrange Interpolation
  - Set of $t + 1$ points uniquely identify a polynomial of degree $\leq t$
- Shamir's Secret Sharing
  - (t, m)-threshold secret sharing scheme based on Lagrange Interpolation
  - $\geq t + 1$ shares to reconstruct the secret S
  - Choose random polynomial $f(x)$ of degree t where $f(0) = S$
  - Share $s_i = f(i)$, for $i \in [1, m]$
- Secure Multi-Party Computation
  - m parties jointly compute a function $f(S_1, S_2, \ldots, S_m)$, from their secret inputs
  - Party i secret shares its private input S_i with the others
  - Interactive protocol to reconstruct a polynomial $g(x)$, where $g(0) = f(S_1, S_2, \ldots, S_m)$

Problem Description

MPyC:

- Python framework for MPC developed at TU/e
- No service discovery yet
- Target users of different level of expertise
  - Casual
  - Power
  - Enterprise
- MPC is Peer-to-Peer
- Local networks are tricky
  - Limited supply of IPv4 addresses
  - Slow adoption of IPv6
  - Network Address Translation (NAT)

Research Questions

How can MPyC be extended to enable casual users, power users and enterprises with limited prior knowledge of each other to discover each other and perform a secure multiparty computation under diverse networking conditions?

- deployment strategies?
- identity?
- first contact?
- connectivity?
  - security?
  - privacy?
  - performance?

Preparation Phase Scope

- Technical Survey
- Extensible Evaluation Environment (E^3) - network of host machines for MPC
  - Simple
  - Extensible
  - Cross region
  - Cross platform
  - Automated
  - Reproducible
  - Disposable
- Implementation Phase Planning

Technical Survey

Technical Survey

- Deployment tools
- Connectivity approaches

Infrastructure as Code (IaC)

Tools:

- Provisioning - Terraform, CloudFormation
- Deployment - Ansible, Puppet, Chef

Specification:

- Imperative - describes the steps to execute
- Declarative - describes the desired state

Operating Systems:

- Most Linux distributions are imperatively managed
- NixOS
  - Declarative
  - Deployment tools: NixOps, Colmena, morph, deploy-rs

Virtual Private Networks (VPNs)

- Centralized VPNs - OpenVPN, IPSec
  - Emulate a real network
  - Transparent to the other programs on the host
  - Single point of failure
  - Can be bottlenecked
- Mesh VPNs - Tailscale, Nebula, Tinc
  - Peer-to-Peer traffic
  - Discovery can happen via a public service or from a known peer

Network Address Translation (NAT)

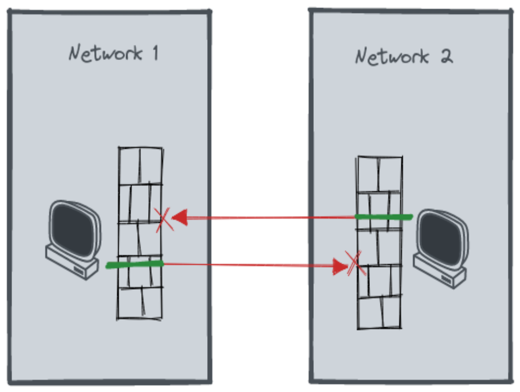

Figure 1: “Two parties behind separate NATs”

- Parties behind a NAT device (usually their router)
  - Can initiate a connection to a public endpoint
  - Cannot be discovered from the outside
  - Neither party can initiate the connection to the other

NAT Traversal

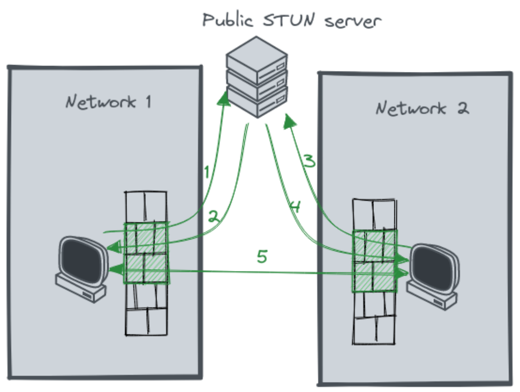

Figure 2: “NAT traversal via STUN”

- Session Traversal Utilities for NAT (STUN)
  - Parties connect to a public STUN server (can be another party)
  - The server reports the IPs it “sees” the parties at
  - User Datagram Protocol (UDP) hole punching
    - Reverse channel for the STUN server to talk back to a party
    - Appropriated by the other parties for their own traffic

Other approaches

- Decentralized identifiers (DIDs) and DIDComm
  - Lack of sessions
  - Inefficient for MPC
- The Onion Router
  - Privacy
  - Onion services
- Peer-to-peer applications
  - Bit Torrents
  - Ethereum
  - IPFS

Reference Implementation

Reference Implementation

- DigitalOcean - cloud provider
- RaspberryPi - ARM based Single Board Computer (SBC)
- NixOS - declarative Linux distribution
- Terraform - declarative provisioning
- Colmena - declarative NixOS deployment
- Tailscale - mesh VPN as a Service
- prsync - sync directories to multiple hosts over ssh
- pssh - execute commands on multiple hosts in parallel over ssh

Nix - Basic flake.nix

```nix
{
  inputs = {
    nixpkgs.url = "github:nixos/nixpkgs/nixos-unstable";
  };

  outputs = inputs@{ self, nixpkgs, ... }:
    let
      pkgs = import nixpkgs {
        system = "x86_64-linux";
      };
    in
    {
        myHello = pkgs.hello;
    };
}
```

Nix - flake.lock


```json
{
  "nodes": {
    "nixpkgs": {
      "locked": {
        "lastModified": 1666377499,
        "narHash": "sha256-dZZCGvWcxc7oGnUgFVf0UeNHsJ4VhkTM0v5JRe8EwR8=",
        "owner": "nixos",
        "repo": "nixpkgs",
        "rev": "301aada7a64812853f2e2634a530ef5d34505048",
        "type": "github"
      },
      "original": {
        "owner": "nixos",
        "ref": "nixos-unstable",
        "repo": "nixpkgs",
        "type": "github"
      }
    },
    ...
  }
}
```

Nix - Development Shell

```
devShell.x86_64-linux = pkgs.mkShell {
  shellHook = ''
    export PYTHONPATH=./
  '';

  nativeBuildInputs = [
    pkgs.curl pkgs.jq
    pkgs.colmena pkgs.pssh
    (pkgs.terraform.withPlugins
      (tp: [
        tp.digitalocean tp.null
        tp.external tp.tailscale
        tp.random
      ]))
    mpyc-demo
  ];
};
```

Nix - MPyC Package

```
{ pkgs, dir }:
(pkgs.poetry2nix.mkPoetryEnv {
    python = pkgs.python3;
    projectDir = dir;
    extraPackages = (ps: [(pkgs.python3Packages.buildPythonPackage {
          name = "mpyc";
          src = dir;
        })]);
    overrides = pkgs.poetry2nix.overrides.withDefaults (
      self: super: {
        gmpy2 = pkgs.python3Packages.gmpy2;
      }
    );
  })
```

Nix - DigitalOcean Image (1)

```nix
## flake.nix
{
  inputs = {
    nixpkgs.url = "github:nixos/nixpkgs/nixos-unstable";
  };
  outputs = inputs@{ self, nixpkgs, ... }:
    let
      mpyc-demo = (import ./nix/mpyc-demo.nix { inherit pkgs; dir = ./.; });
      pkgs = import nixpkgs {
        system = "x86_64-linux";
      };
      digitalOceanConfig = import ./nix/digitalocean/image.nix {
        inherit pkgs;
        extraPackages = [ mpyc-demo ];
      };
    in
    {
        packages.digitalOceanImage = (pkgs.nixos digitalOceanConfig).digitalOceanImage;
    };
}
```

Nix - DigitalOCean Image (2)

```nix
## nix/digitalocean/image.nix
{ pkgs, extraPackages ? [ ], ... }:
{
  imports = [ "${pkgs.path}/nixos/modules/virtualisation/digital-ocean-image.nix" ];
  system.stateVersion = "22.11";
  environment.systemPackages = with pkgs; [
    jq
  ] ++ extraPackages;

  services.tailscale.enable = true;

  networking.firewall = {
    enable = true;
    checkReversePath = "loose";
    trustedInterfaces = [ "tailscale0" ];
  };
}
```

Nix - RaspberryPi Image

```
let
  mpyc-demo = (import ./nix/mpyc-demo.nix { inherit pkgs; dir = ./.; });

  pkgs = import nixpkgs {
    system = "aarch64-linux";
  };
in
{
    packages.raspberryPi4Image = (pkgs.nixos ({ config, ... }: {
        system.stateVersion = "22.11";
        imports = [
          ("${pkgs.path}/nixos/modules/installer/sd-card/sd-image-aarch64-installer.nix")
        ];

        environment.systemPackages = [
            mpyc-demo
        ];
    })).sdImage;
};
```

Terraform - Image Import

```
resource "digitalocean_spaces_bucket_object" "nixos-image" {
  region = digitalocean_spaces_bucket.tf-state.region
  bucket = digitalocean_spaces_bucket.tf-state.name
  key    = basename(var.nixos-image-path)
  source = var.nixos-image-path
  acl    = "public-read"
  etag   = filemd5(var.nixos-image-path)
}

resource "digitalocean_custom_image" "nixos-image" {
  name    = "nixos-22.11"
  url     = "https://${digitalocean_spaces_bucket.tf-state.bucket_domain_name}/${digitalocean_spaces_bucket_object.nixos-image.key}"
  regions = local.all_regions
  tags    = ["nixos"]

  lifecycle {
    replace_triggered_by = [
      digitalocean_spaces_bucket_object.nixos-image
    ]
  }
}
```

Terraform - Hostname Generation

```
locals {
  node_definitions = var.DESTROY_NODES != "" ? [] : [
    { region = "ams3", num = 3 },
    { region = "sfo3", num = 1 },
    { region = "nyc3", num = 1 },
    { region = "sgp1", num = 1 },
  ]
  nodes_expanded = flatten([
    for node in local.node_definitions : [
      for i in range(node.num) :
      merge(node, {
        name = "mpyc-demo--${node.region}-${i}"
      })
    ]
  ])
  nodes = {
    for node in local.nodes_expanded :
    node.name => merge(node, {
      hostname = "${node.name}-${random_id.mpyc-node-hostname[node.name].hex}"
    })
  }
}
```

Terraform - DigitalOcean Droplets

```

resource "digitalocean_droplet" "mpyc-node" {
  for_each = local.nodes

  image    = digitalocean_custom_image.nixos-image.id
  name     = each.value.hostname
  region   = each.value.region
  size     = "s-1vcpu-1gb"
  ssh_keys = [for key in digitalocean_ssh_key.ssh-keys : key.fingerprint]

  provisioner "remote-exec" {
    inline = [
      "mkdir -p /var/keys/",
      "echo ${tailscale_tailnet_key.keys.key} > /var/keys/tailscale",
      "tailscale up --auth-key file:/var/keys/tailscale"
    ]
  }
}

resource "tailscale_tailnet_key" "keys" {
  ...
}
```

Colmena

```
let
  mpyc-demo = (import ./nix/mpyc-demo.nix { inherit pkgs; dir = ./.; });

  pkgs = import nixpkgs {
    system = "x86_64-linux";
  };

  digitalOceanConfig = import ./nix/digitalocean/image.nix {
    inherit pkgs;
    extraPackages = [ mpyc-demo ];
  };
in
{
  packages.colmena = {
    meta = {
      nixpkgs = pkgs;
    };
    defaults = digitalOceanConfig;
  } // builtins.fromJSON (builtins.readFile ./hosts.json);
};
```

Colmena - hosts.json

```
## hosts.json
{
  "mpyc-demo--ams3-0-15e53f39": {},
  "mpyc-demo--ams3-1-b4791c55": {},
  "mpyc-demo--ams3-2-7f09fb08": {},
  "mpyc-demo--nyc3-0-7dd0d9f6": {},
  "mpyc-demo--sfo3-0-5bffc60e": {},
  "mpyc-demo--sgp1-0-92700733": {}
}
```

Runtime

```
prsync -h hosts.pssh -zarv -p 4 ./ /root/mpyc
pssh -h hosts.pssh -iv -o ./logs/$t "cd /root/mpyc && ./prun.sh"
```

```
# assemble $args and $MY_PID from the hosts.pssh file

...


if [ $MY_PID = -1 ]
then
    echo Only $i parties are allowed. $HOSTNAME will not participate in this MPC session
else

cmd="python ./demos/secretsanta.py 3 --log-level debug \
    -I ${MY_PID} \
    ${args}"

echo $cmd
$cmd
fi
```

Demo

Demo

- Provisioning with Terraform
- Deployment with Colmena
- Running a distributed MPyC program
- Destruction of the infrastructure

Planning

Planning - connectivity implementations

- Headscale
- Nebula - IP allocation, Certificate authority, Certificate distribution
- Mesh VPN with alternative identity management
  - MPC based CA
  - Decentralized Identifiers
- DIDComm
  - sessions
  - NAT traversal
- TOR, Ethereum, IPFS
- Carbyne stack

Planning - analysis

Compare the implementations in terms of:

- Security
- Performance
- Ease of use
- Privacy