Unified Configuration Modeling Infrastructure

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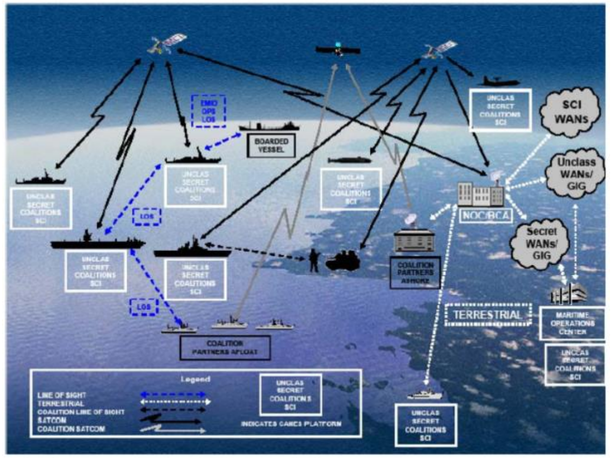
Modern Systems and Their Configuration

- Built from COTS / open-source components
  - General purpose components: support diverse usage scenarios
  - Must be properly configured to interoperate and provide desired functionality

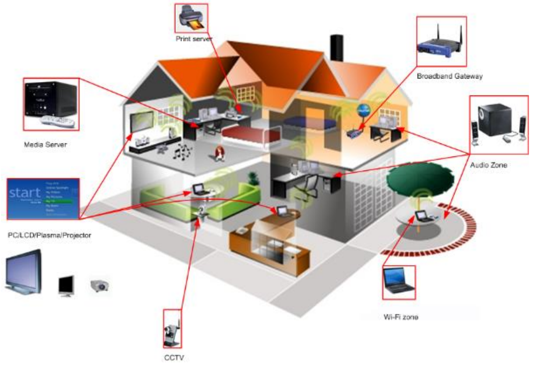
DoD Systems

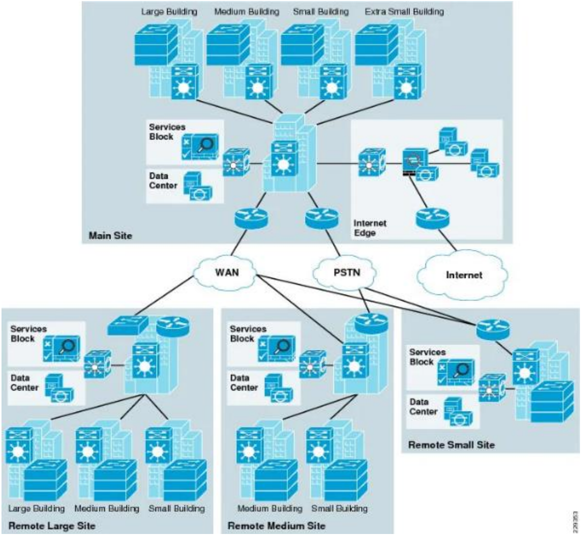
CONSOLIDATED AFLOAT NETWORKS
CANES
AND ENTERPRISE SERVICES

PEO C4I



Home Networks





Enterprise Systems

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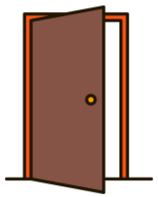
The Importance of Proper Configuration

- Misconfiguration constitutes a significant security threat
  - Easier to exploit than conventional vulnerabilities
  - Extend attack surface



vs.

Misconfiguration

Conventional Vulnerability

- Verizon's Data Breach Investigations Report (DBIR) Report, 2021
  - Overall, around 8% of breaches are due to misconfiguration
  - http://verizon.com/dbir/

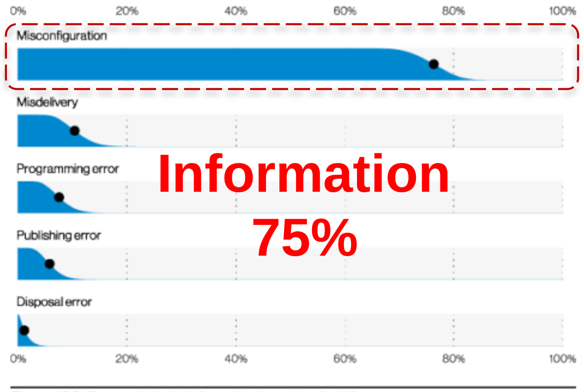


Figure 106. Error varieties in Information breaches (n=111)

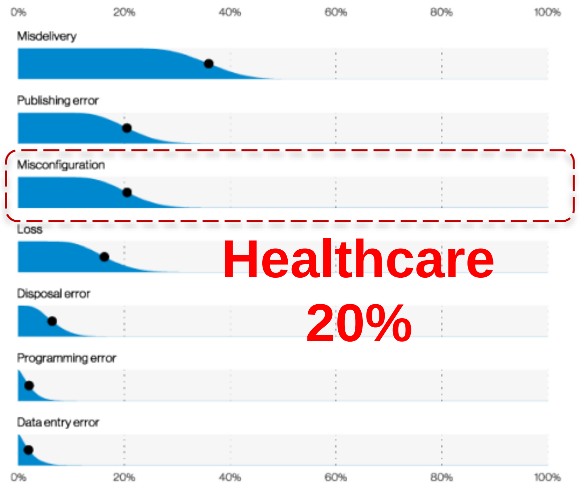


Figure 105. Error varieties in Healthcare breaches (n=70)

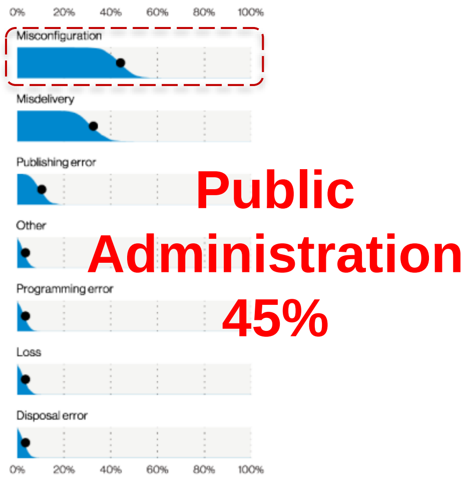


Figure 118. Top Error varieties in Public Administration breaches (n=86)

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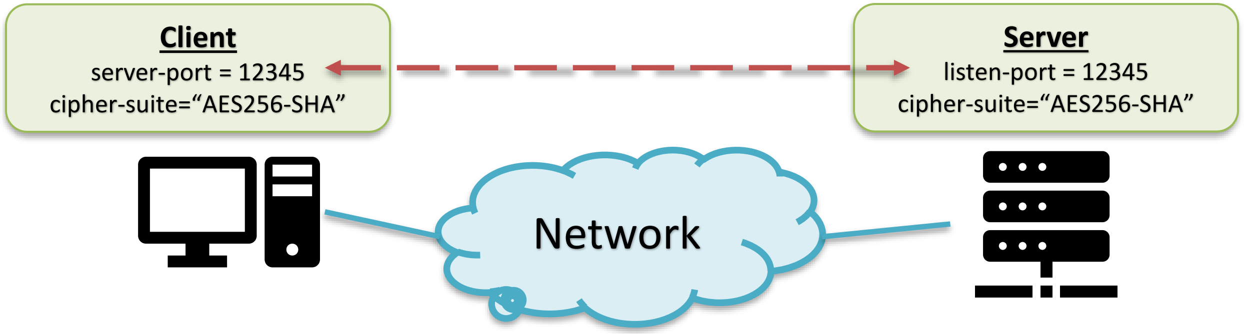
Why is Configuration Tricky?

- **Global relationships among configuration parameters**
  - Configuration must agree for the communication end-points
  - Local policies (e.g., STIGs), while useful, often fail system-wide constraints



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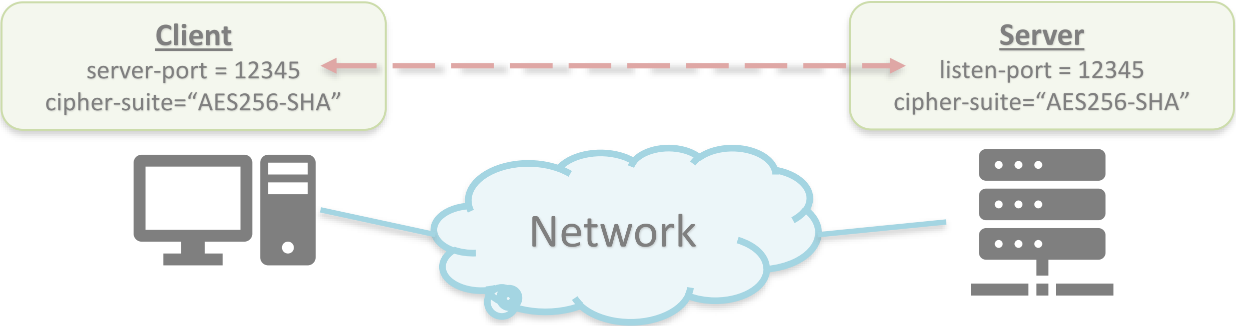
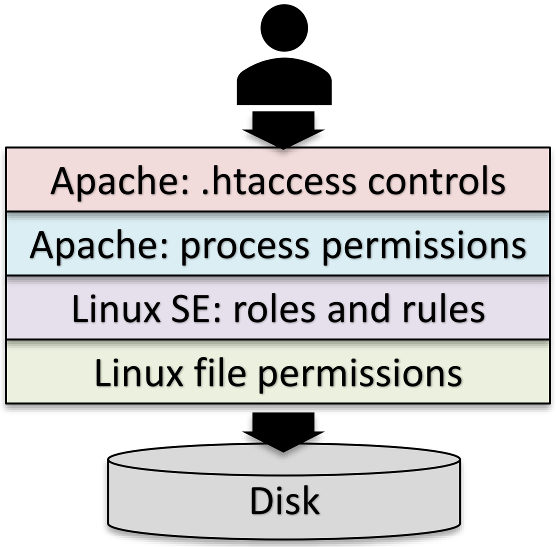


- **Configuration stacking for multi-layer systems**
  - Each layer is configured independently
  - Layer configurations are combined
  - *Overall end-to-end effect is hard to perceive*



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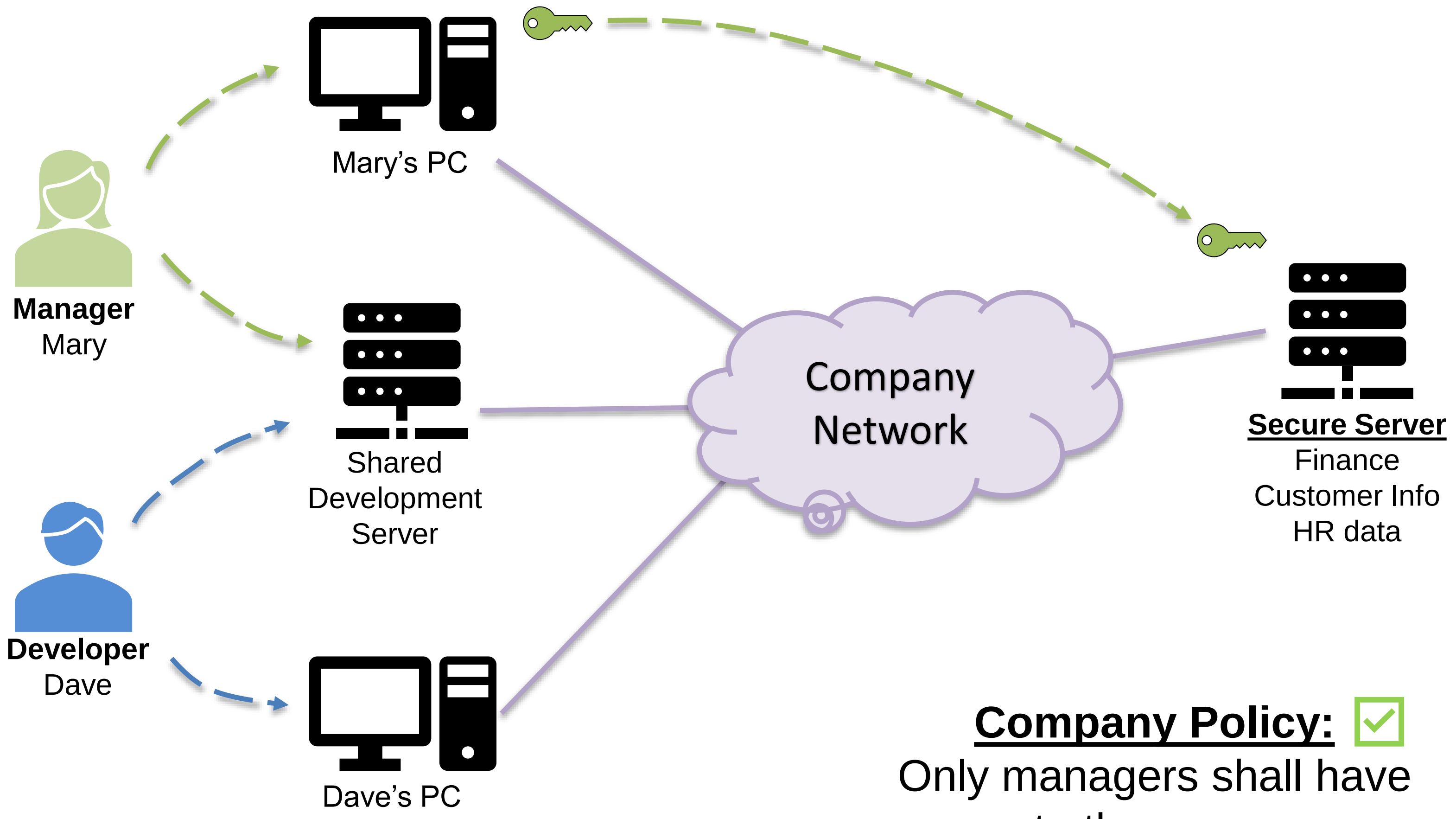
Misconfiguration: Security Breach Scenario



Human Actors:

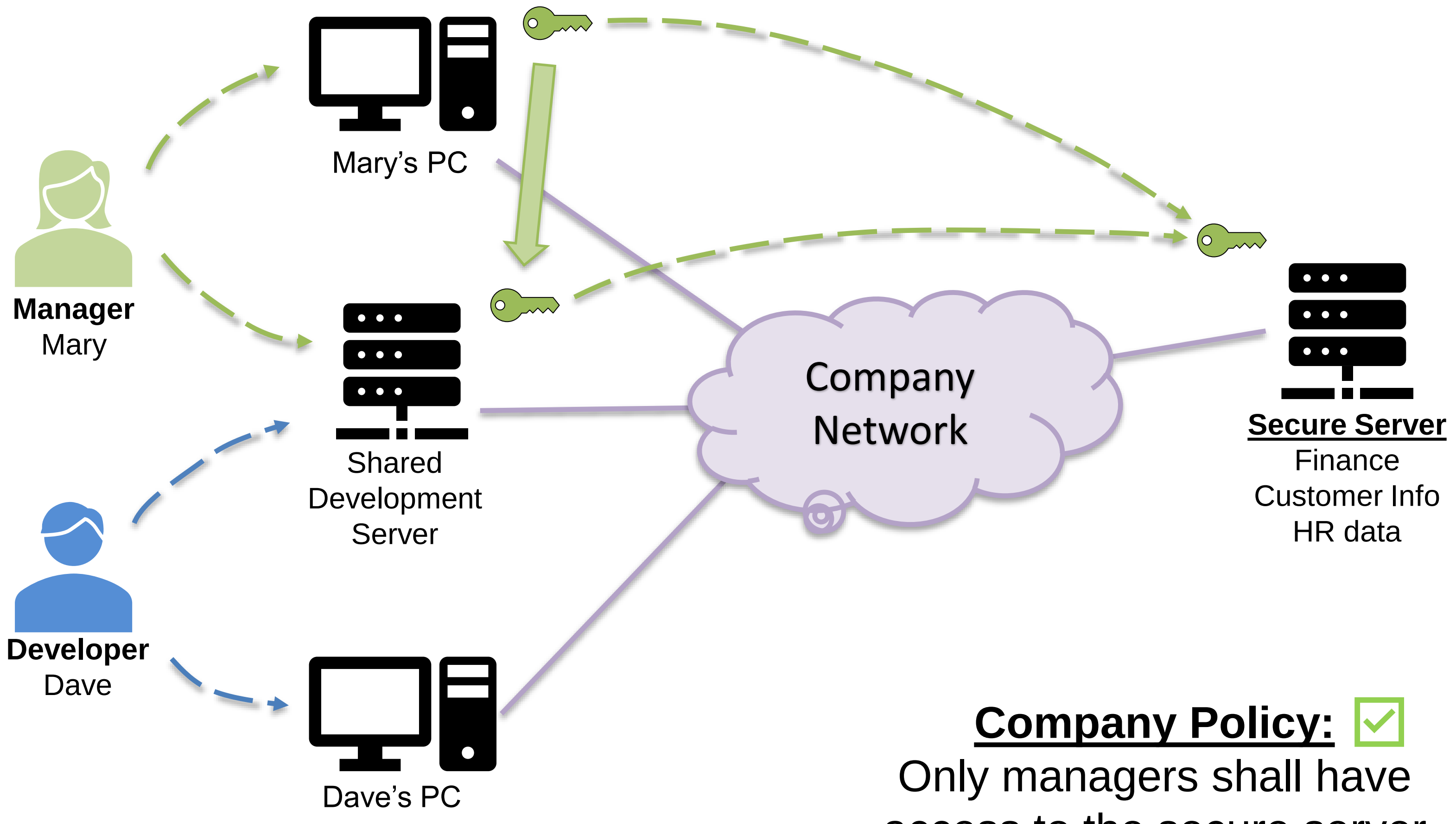
- Mary: manager
- Dave: developer

System Access:

- Both Mary and Dave:
  - Respective PCs
  - Development server
- Mary only:
  - Secure server via PKI

Company Policy: ☑
Only managers shall have access to the secure server

Misconfiguration: Security Breach Scenario



Mary:

- Wants to access the secure server from the development server
- Copies her private key (or sets up a new one)

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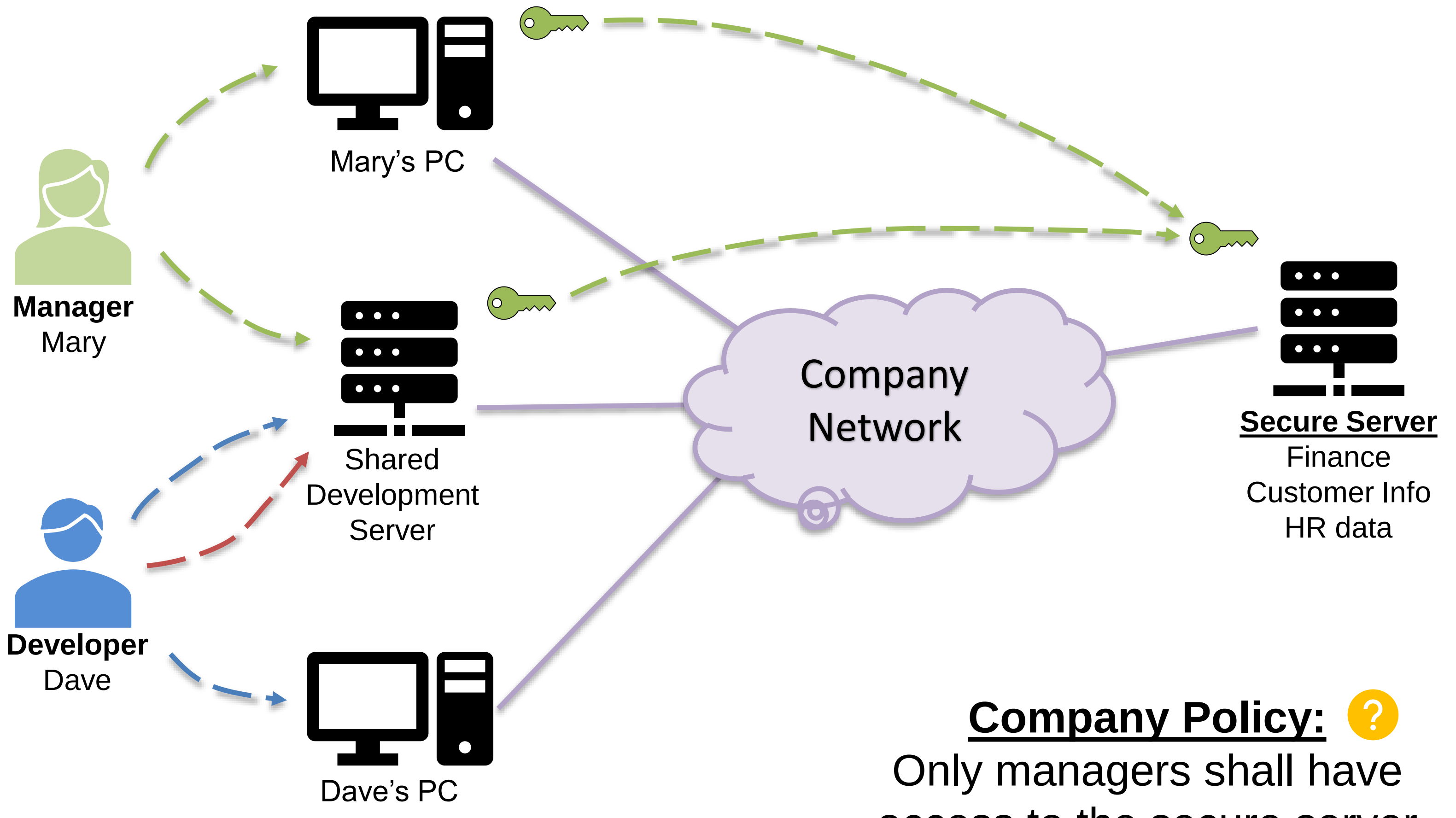
Misconfiguration: Security Breach Scenario



Company Policy: ?
Only managers shall have access to the secure server

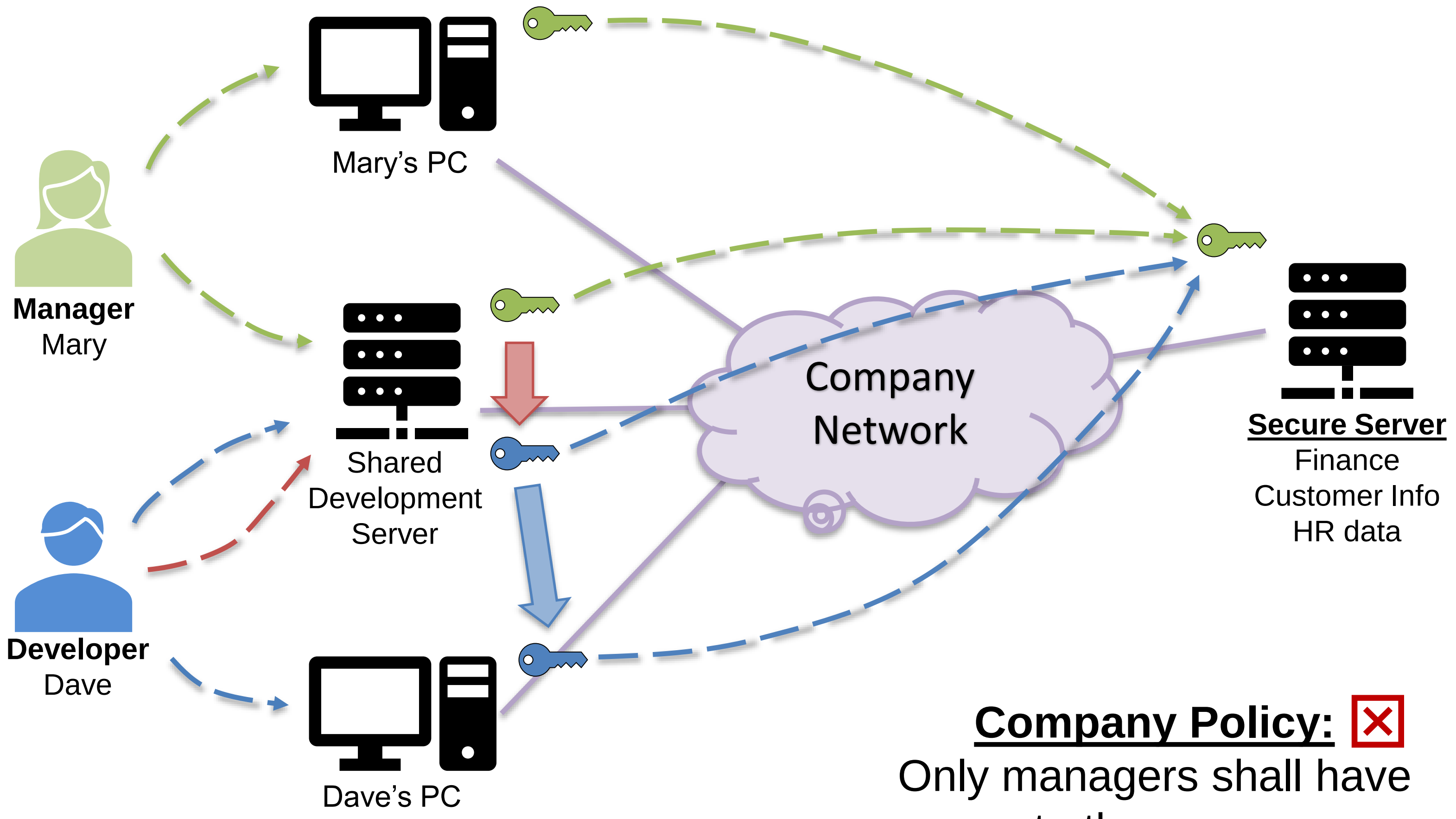
Mary:

- Wants to access the secure server from the development server
- Copies her private key (or sets up a new one)

Dave:

- Wants extra privileges (to install new software)
- Admin gives him root-level access (using naïve "sudo" configuration)

Misconfiguration: Security Breach Scenario

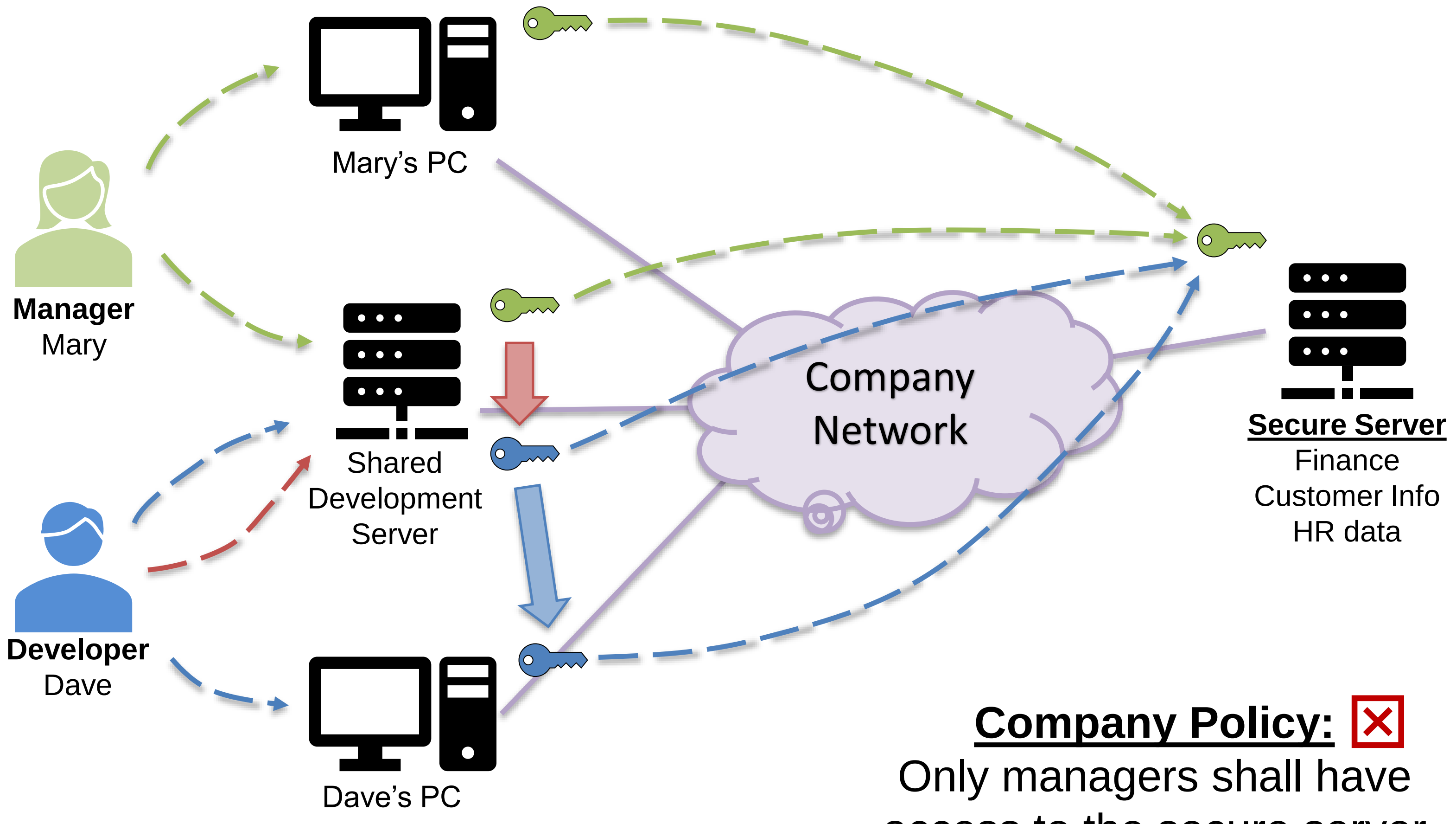


Company Policy: ☒
Only managers shall have access to the secure server

Security Breach:

- Dave copies (steals) Mary's private key using his root-level access privileges
- Gets access to the secure server by impersonating Mary
- ***Policy is violated!***

Misconfiguration: Security Breach Scenario



Company Policy: ☒
Only managers shall have access to the secure server

Observations:

- Local configuration changes may have global effect that is hard to predict / anticipate
- Fixes (e.g., implementing a more fine-grained sudo policy for Dave) further increase configuration complexity

Formal Reasoning to the Rescue

- System configuration modeling
  - Formal, self-contained description of the system
  - Logically links system behavior to the values of its configuration parameters
  - **Abstract:** reduces the complexity of the actual system
  - **Functional:** provides an effective way to query system properties
  - **Initial focus:** *access-control properties*

Can a system user with certain level of physical access and certain knowledge perform a certain operation on certain resource?

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Dave's PC

Dave's Credentials

Can a system user with certain level of physical access and certain knowledge perform a certain operation on certain resource?

Log into

Secure Server

Configuration Modeling: Practical Applications

- Automated configuration synthesis:
  - Find config that enables system functionality while minimizing attack surface
  - Formal modeling enables setting this up as ***an optimization problem***
  - Initial motivation for the research
- Symbolic configuration analysis:
  - Check non-trivial security and functionality properties
  - Assess how local configuration changes affect system-wide behavior
  - ***Example:*** validate that refined "sudo" configuration
    - Allows Dave to perform necessary development server maintenance
    - Respects relevant company's security policies

Configuration Modeling: Practical Applications

- Penetration testing and red teaming:
  - Can an outsider with minimal knowledge gain access to system's sensitive data?
  - If so, how? Can we get a sequence of operations to execute?
- Internal threat minimization:
  - Find system users with privileges that are not required for system functionality
  - Ensure access privileges are properly revoked
- Forensic analysis:
  - The system is breached!
  - What is the breach perimeter? What system data can we still trust?

Configuration Modeling: Overview

- Supports essential programming-language features
  - *Modular:* define and hierarchically compose modules
  - *High-level datatypes:* enums, records, collections, variants
  - *Strict static typing:* catch and debug errors

- *Current status:* language is bytecode / IR like
  - Aimed for machine consumption, rather than for human use
  - Working on a more human-friendly front-end language

Modeling Language

Declarative; supports modularity, high-level data types

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Configuration Modeling: Overview

Primitives:
- Network interfaces
- Linux users, groups
- Linux files, directories, symlinks
- Services (e.g., sshd, httpd)
- Public / private keys
- SSL certificates
- ….

Concepts:
- Network access
- Service access
- Local and remote host access
- Local and remote file access
- ….

Predicate Library

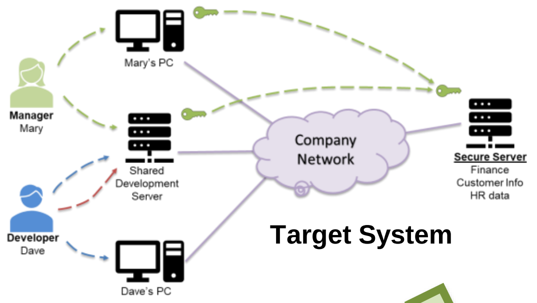
Logical definitions that describe generic system-building primitives and concepts

Definitions express semantics in terms of configuration parameters (*free model variables*)

Modeling Language

Declarative; supports modularity, high-level data types

Configuration Modeling: Overview



Target System

Predicate Library

Logical definitions that describe generic system-building primitives and concepts

Behavior

Instantiates predicates to capture system topology and device setup

Configuration

Assigns values to configuration parameters (*model variables*)

Modeling Language

Declarative; supports modularity, high-level data types

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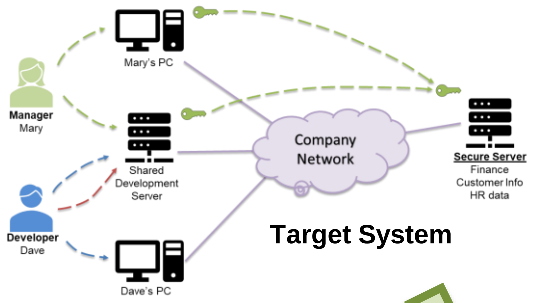
Configuration Modeling: Overview



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Assigns values to configuration parameters (*model variables*)

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Declarative; supports modularity, high-level data types

Querying System Properties

Compile into Prolog program and use off-the-shelf interpreter (better alternatives are possible)

Deductive Database

Facts and Rules

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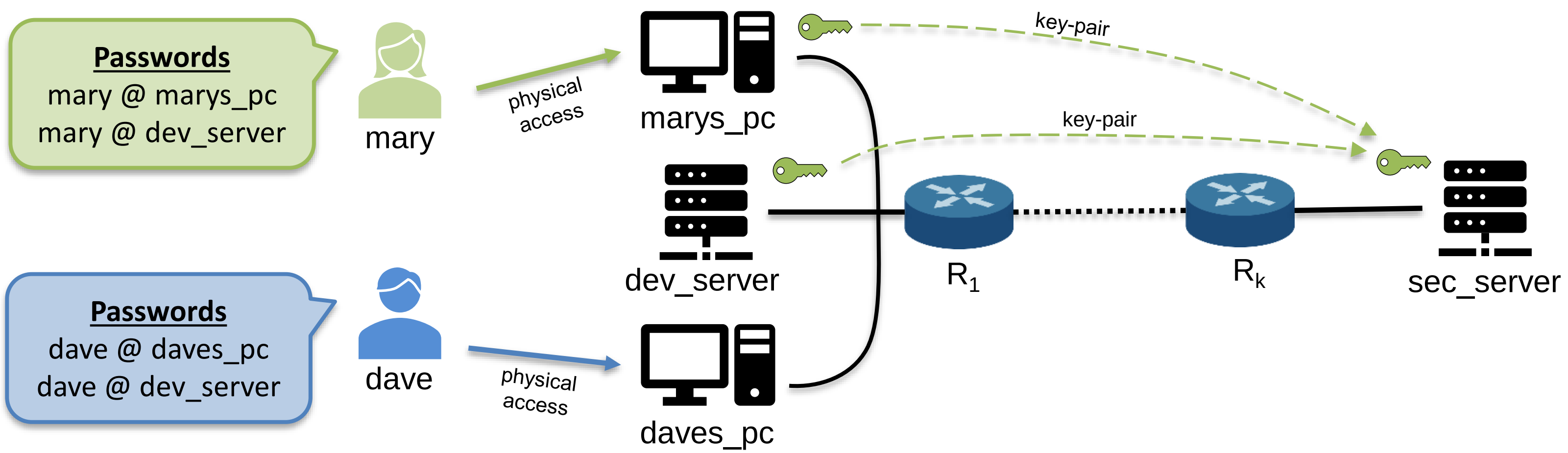
Configuration Modeling: Deep(er) Dive

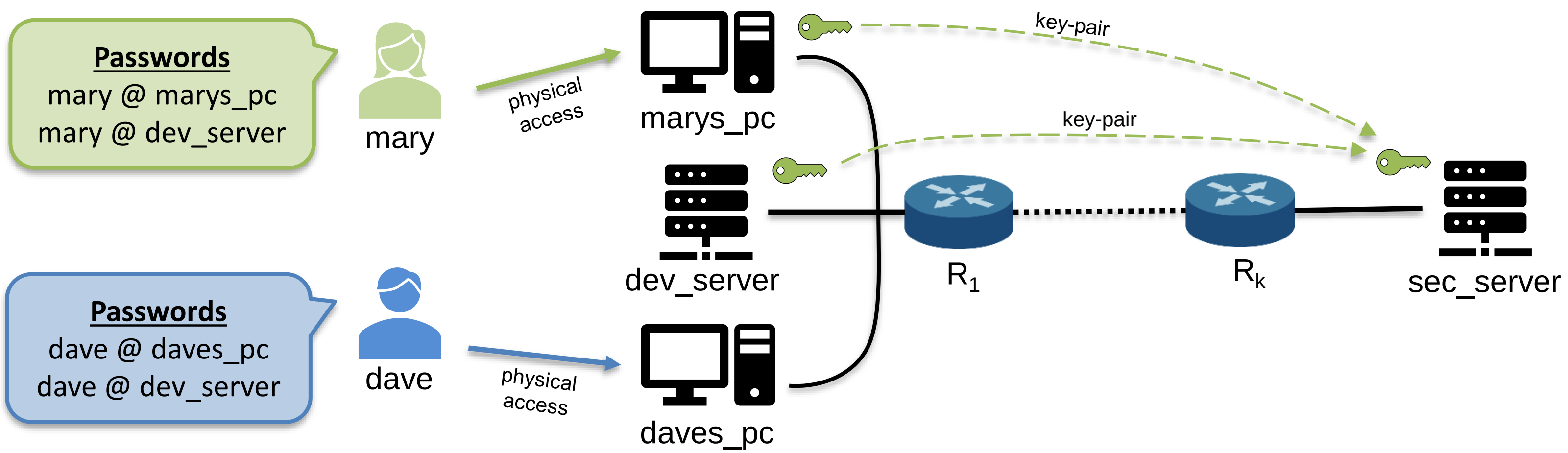



```
actorAccess(dave, sec_server, User).
```

***Query:** What user can Dave login as to the secure server?*

***Note:** User is a free variable; a value will be assigned to it if the query is satisfiable*

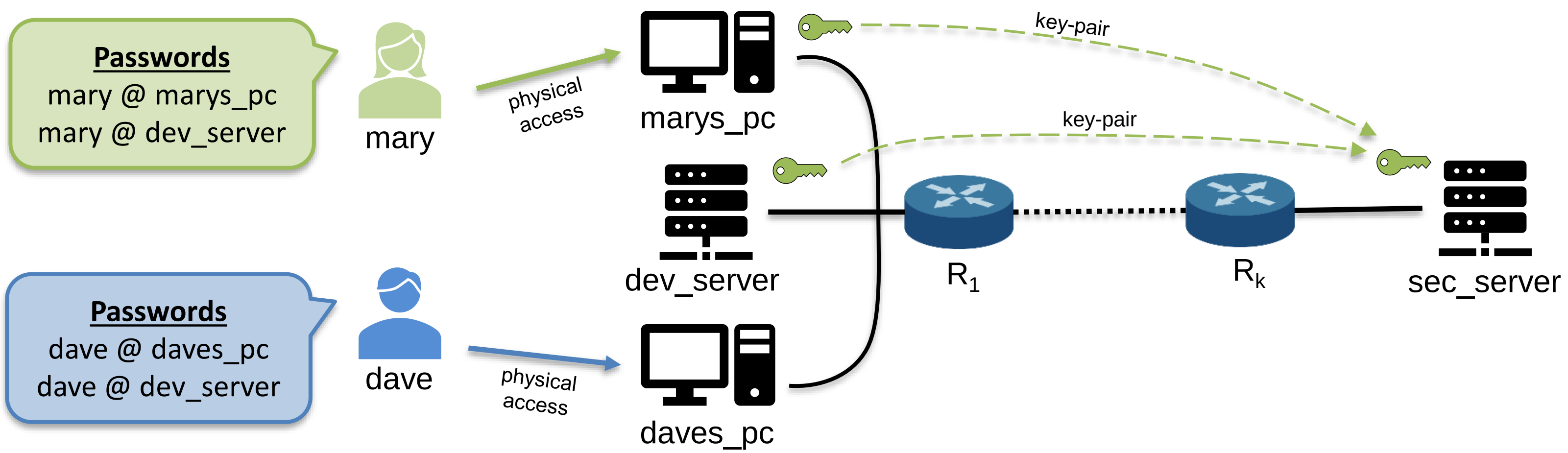
Configuration Modeling: Deep(er) Dive




```
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, Host),
```

What computers can Dave physically access?

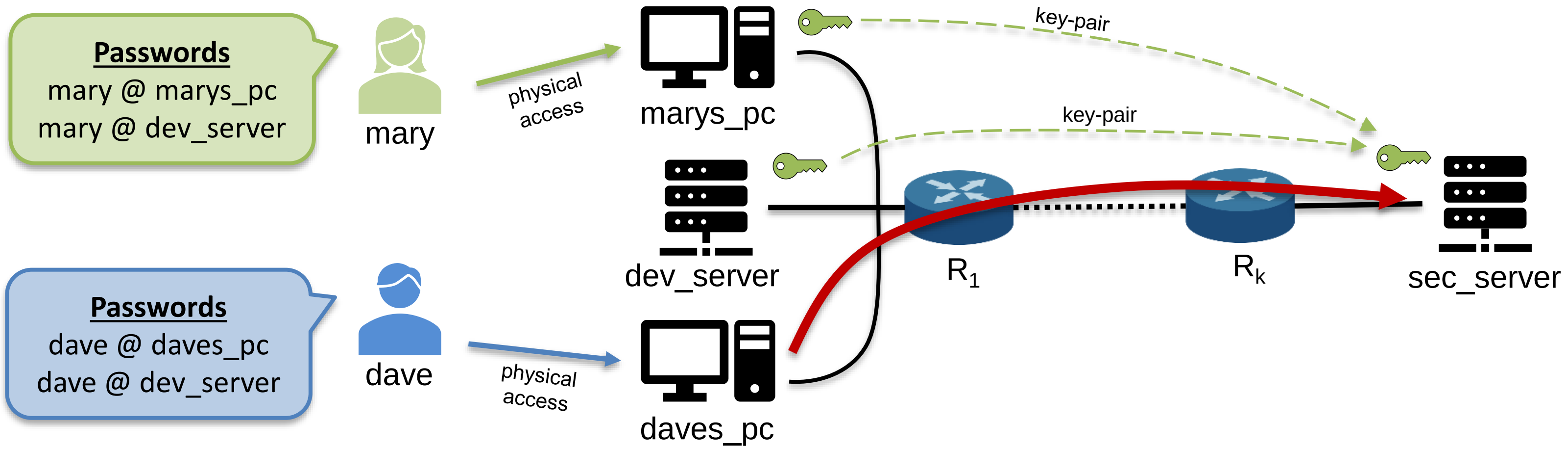
Configuration Modeling: Deep(er) Dive




```
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, daves_pc), ☑
```

What computers can Dave physically access?
(derived trivially from the actor set up)

Configuration Modeling: Deep(er) Dive



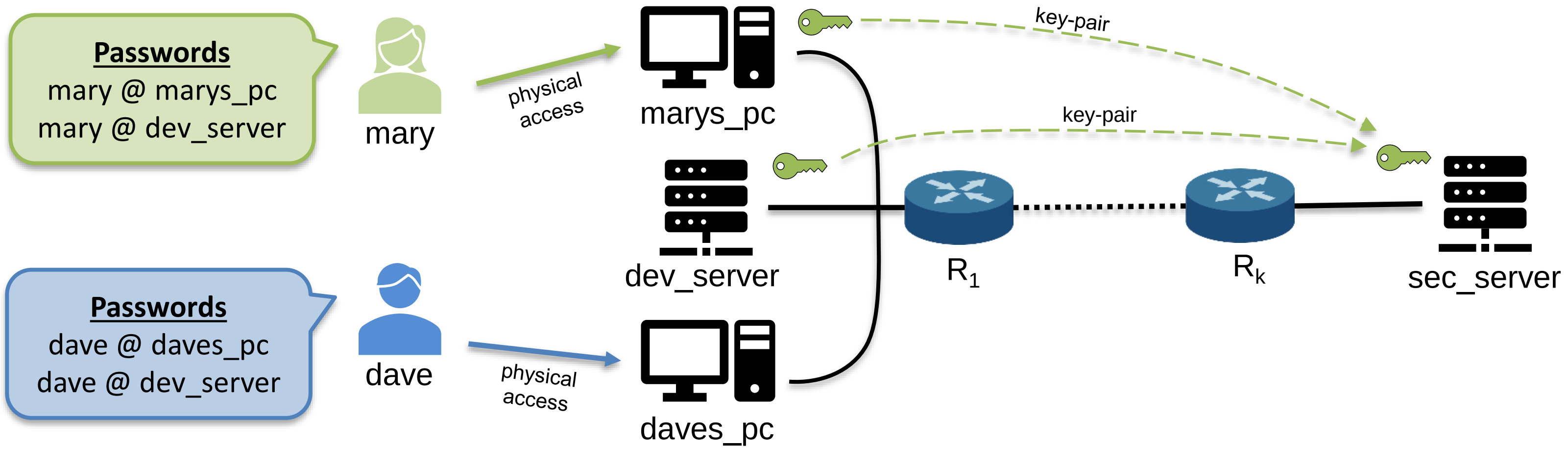

```
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, daves_pc),
   netAccess(daves_pc, sec_server, 22, tcp), ☑
```

Is there network connectivity between Dave's PC and secure server to support an SSH session?

Relevant configs: *routing, firewall configuration for routers R_1 through R_k*

For brevity: we assume it is possible, and will not expand netAccess definition

Configuration Modeling: Deep(er) Dive




```
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, daves_pc),
   netAccess(daves_pc, sec_server, 22, tcp),
   remoteLogin(dave, sec_server, User).
```

Can Dave login into the secure server?

Relevant configs: *SSH configuration, user configuration (i.e., /etc/passwd, /etc/shadow contents) on the secure server.*

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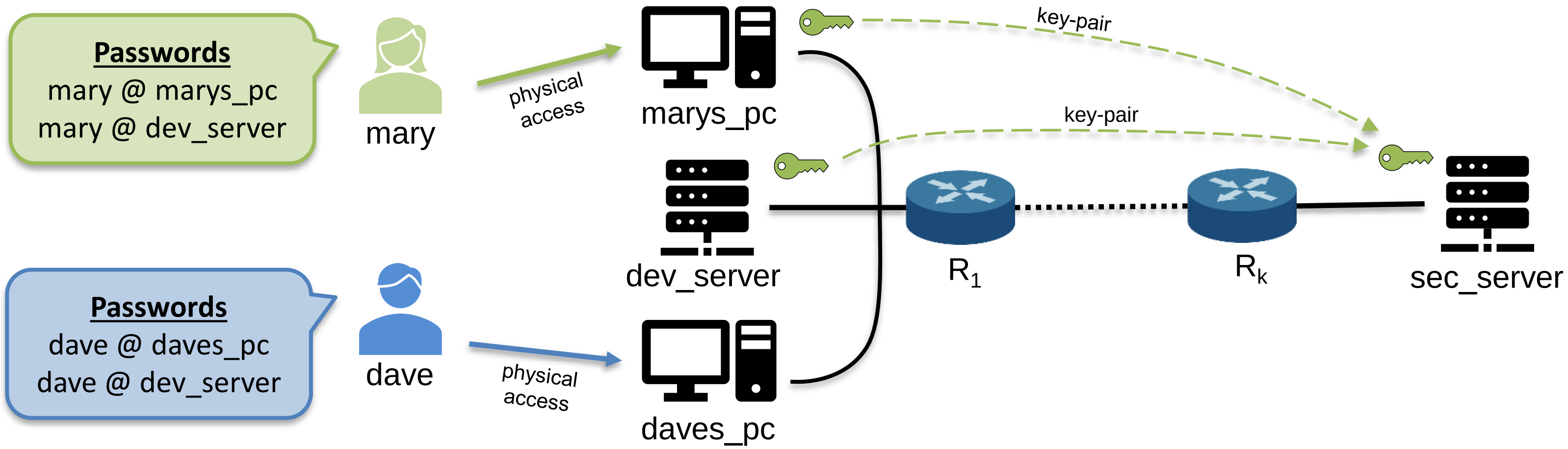
Configuration Modeling: Deep(er) Dive

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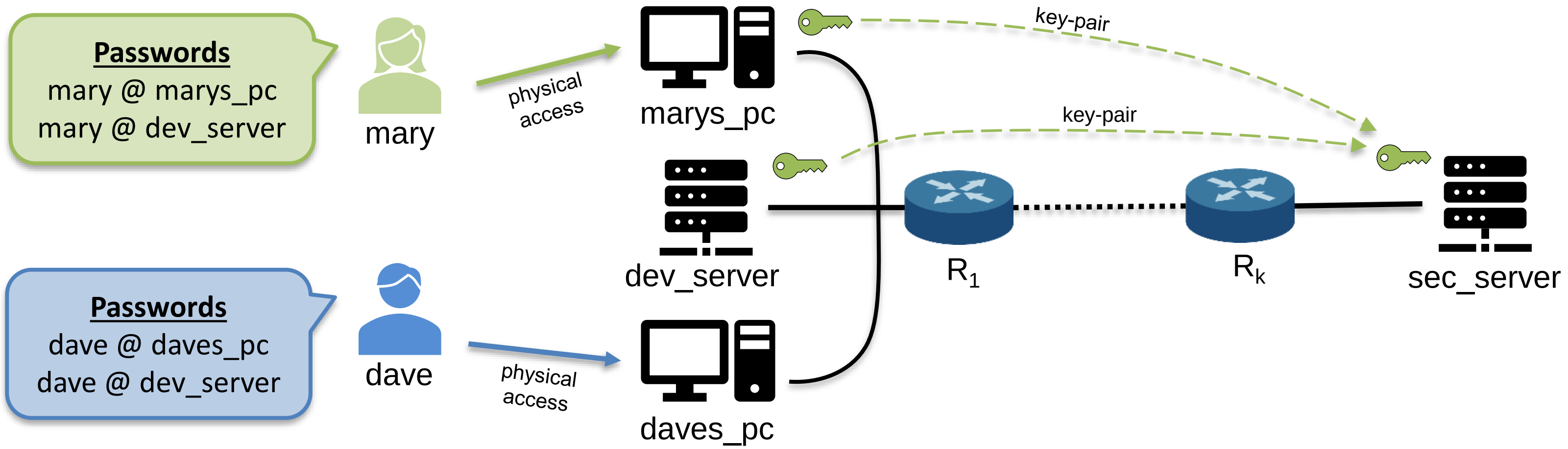
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, daves_pc),
   netAccess(daves_pc, sec_server, 22, tcp),
   remoteLogin(dave, sec_server, User) :-
      runsServiceSSH(sec_server, Service),
      sshPasswordAuthentication(Service),
      userPasswd(User, Passwd),
      actorKnowsPassword(dave, Passwd).
```

Does the secure server run SSH service ***and***

Does SSH support password-based login ***and***

Does Dave know the password for a sec_server user?

Configuration Modeling: Deep(er) Dive

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      runsServiceSSH(sec_server, Service),
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      userPasswd(User, Passwd),
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```

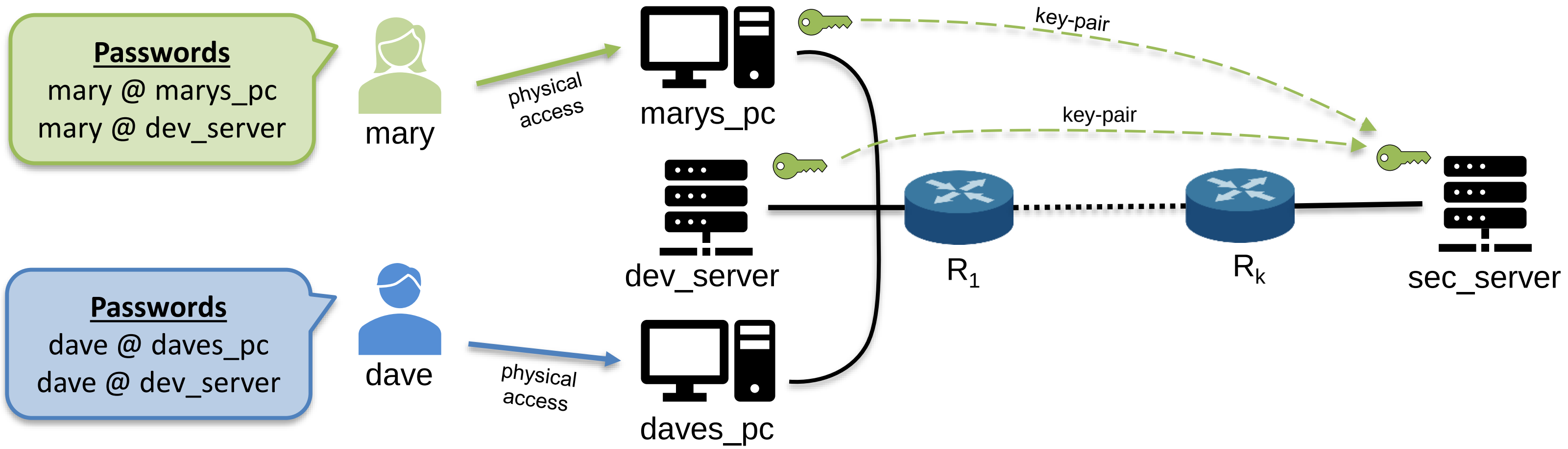
*Does the secure server run SSH service **and***

*Does SSH support password-based login **and***

Does Dave know the password for a sec_server user?

***Fails:** Dave does not know any relevant passwords*

Configuration Modeling: Deep(er) Dive

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   hasPhysicalAccess(dave, daves_pc),
   netAccess(daves_pc, sec_server, 22, tcp),
   remoteLogin(dave, sec_server, User) :-
      runsServiceSSH(sec_server, Service),
      sshPubkeyAuthentication(Service),
      sshPubkeyAccess(Service, User, PublicKey),
      keyPair(PublicKey, PrivateKey),
      fileContains(Host, Path, PrivateKey),
      actorFileRead(dave, Host, Path).
```

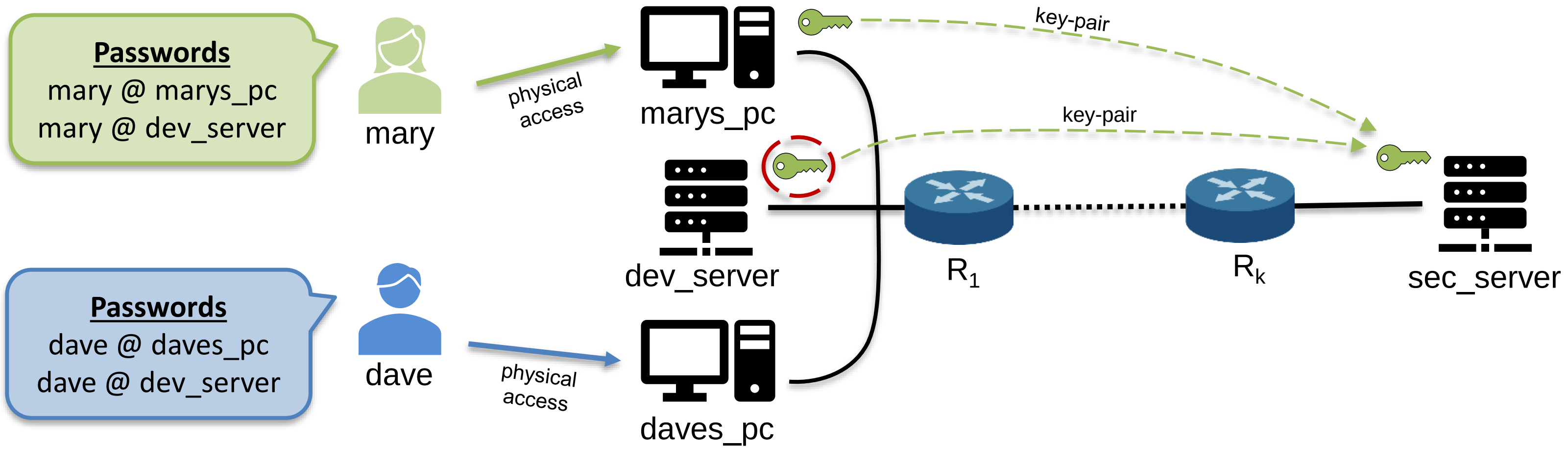
Alternative: PKI Authentication

*Does SSH support public-key-based login **and***

Can Dave get a private key needed for access

(e.g., can Dave read a file that stores a private key)?

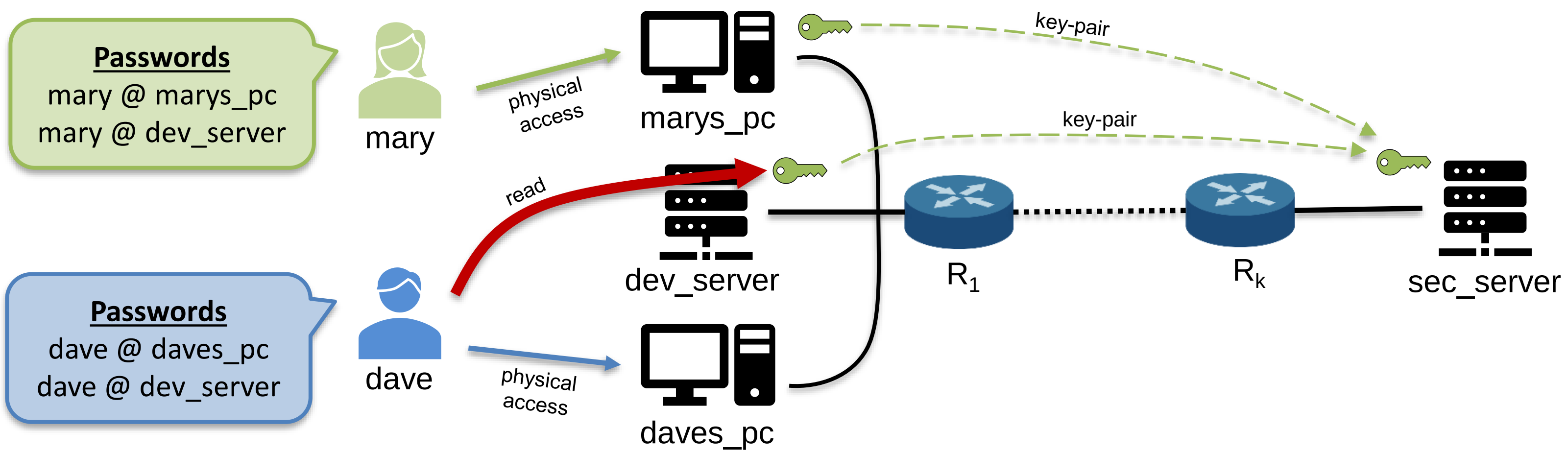
Configuration Modeling: Deep(er) Dive



Focus on Mary's private key stored on the development server:

```
actorAccess(dave, sec_server, User) :-
   hasPhysicalAccess(dave, daves_pc),
   netAccess(daves_pc, sec_server, 22, tcp),
   remoteLogin(dave, sec_server, User) :-
      ...,
      actorFileRead(dave, dev_server, "/home/mary/.ssh/id_rsa").
```

Configuration Modeling: Deep(er) Dive

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   remoteLogin(dave, sec_server, User) :-
      ...,
      actorFileRead(dave, dev_server, "/home/mary/.ssh/id_rsa") :-
         actorAccess(dave, dev_server, dave@dev_server), ☑
         userSwitch(dave, dave@dev_server, root@dev_server), ☑
         localFileRead(
            dev_server, root@dev_server, "/home/mary/.ssh/id_rsa"). ☑
```

Focus on Mary's private key stored on the development server:

Dave can access dev_server
(recursive actorAccess definition)

Dave can elevate privileges to root
(due to weak sudo config)

Root can read Mary's files

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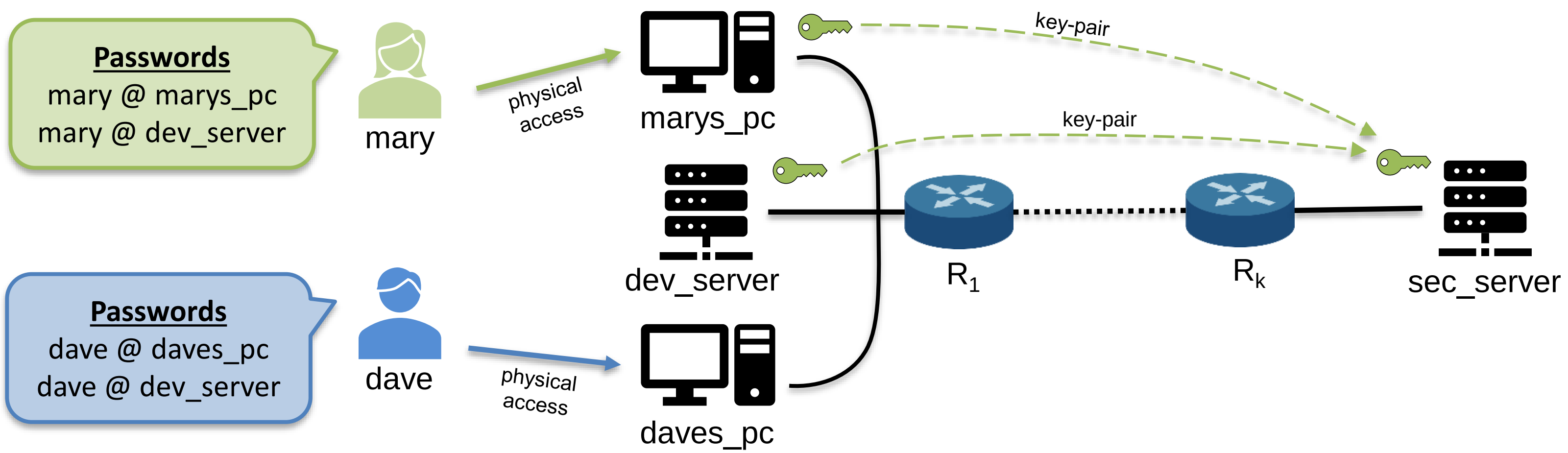
Configuration Modeling: Deep(er) Dive



`actorAccess(dave, sec_server, mary@sec_server).` ☑

***Result:** Dave can log into Mary's account on the secure server*

(violation of the security policy)

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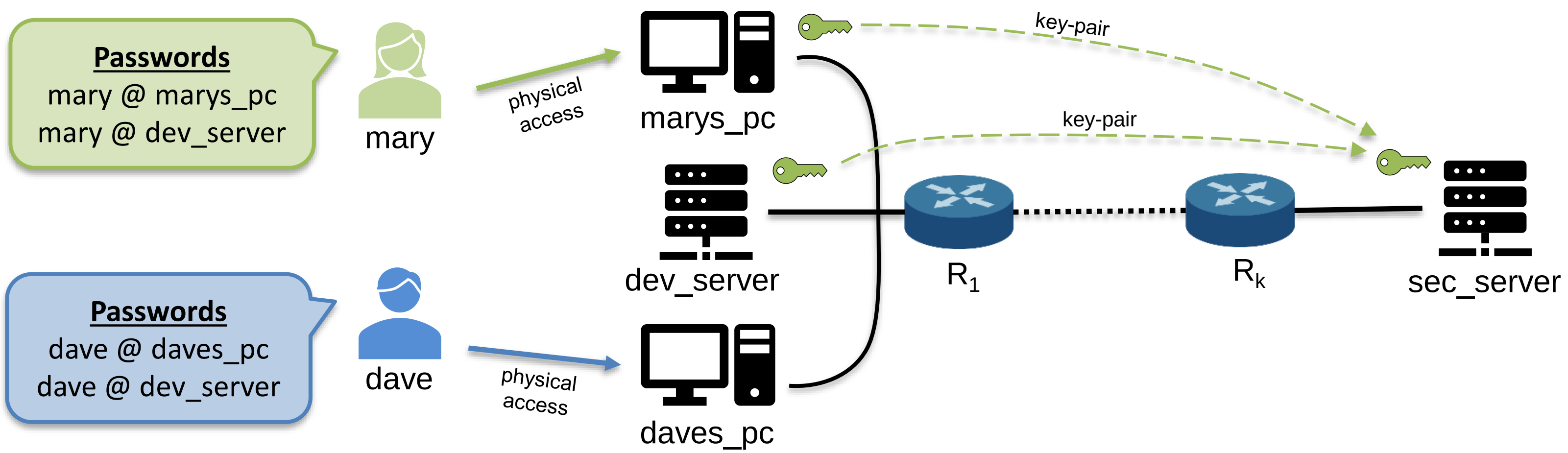

`actorAccess(dave, sec_server, mary@sec_server).` ☑

Result: *Dave can log into Mary's account on the secure server*
(violation of the security policy)

- Configuration modeling:
  - Systematically captures possible resource-access mechanisms
  - Supports parametric queries, not just Boolean ones
  - Tracks derivation to construct the sequence of steps for accessing the resource

NAWC Capture The Flag (CTF) System for Cyber Training

- Modeled CTF subset:
  - 20 devices connected to 6 or so subnets
- Resulting model stats:
  - 2K configuration parameters:
    - Firewall rule lists (for routers)
    - User to group mapping
    - Ownership and permissions for selected files
    - Subsets of options for ssh, tomcat, docker services
  - 4K facts and 200 rules
- Performance of Prolog-based solver:
  - 10K queries in under 2 minutes

<u>Sample Functional Requirements:</u>

- Web administrators shall be able to edit tomcat configuration files on the web server.
- Web developers shall be able to inspect tomcat logs.
- …

<u>Security Requirements</u>

- The principle of least privilege.

Configuration Modeling: Vision

- ***Challenge:*** diversity
  - Multitude of existing (and future) platforms, services, configuration surfaces

- ***Inspiration:*** re-targetable binary analyses
  - The use of uniform micro-code to specify semantics for various ISAs

- <u>Design principles:</u>
  - General formalisms for capturing semantics of diverse platforms / services
  - Semantic encoding that is agnostic to specific target analyses / backend solvers
  - Semantic encoding that enables diverse querying mechanisms
  - Extensible library of reusable modules

Further Research

- ***Automation:*** streamline library-extension efforts
  - Generate models for services, software (semi-)automatically
- ***Validation:*** boost modeling accuracy
  - Validate component models against real-world behavior
  - *Possible approaches:* testing, runtime monitoring, formal verification
- ***Scope:*** model properties beyond access control
  - *Privacy:* e.g., track which system data is encrypted and how
  - *Trust:* e.g., track how SSL certificates are set up and used
  - *More:* social engineering, service response times, user convenience?

Conclusion & Acknowledgements

- System Configuration Modeling Approach
  - ***Unified:*** uniform representation of various system-configuration aspects
  - ***Formal:*** well-understood systematic logical encoding (deductive database)
  - ***Modular:*** models are built from reusable building blocks
  - ***Extensible:*** formalisms and methodology for effective library extension

- ***Acknowledgements***
  - Research funded by DARPA under "Configuration Security" (ConSec) program

    The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.
  - Special thanks to other ConSec performers: STR, Peraton Labs, Siemens, PARC, Radiance, and Lockheed Martin for productive discussions and feedback!

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