Fabric
A Platform for Secure Distributed Computation and Storage

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The Web is Not Enough

- The Web: decentralized information-sharing
  - Decentralized information-sharing

- Limitations for integrating information
  - Medicine, finance, government, military, ...
  - Need security and consistency

Is there a principled way to build federated applications while guaranteeing security and consistency?
Fabric: A System and a Language

- Decentralized system for securely sharing information and computation
- All information looks like an ordinary program object
- Objects refer to each other with references
  - Any object can be referenced uniformly from anywhere
  - References can cross nodes and trust domains
  - All references look like ordinary object pointers

Compiler and runtime enforce security and consistency despite distrust
Fabric Enables Federated Sharing

HIPAA-compliant policy

General Practitioner (GP)

Different HIPAA-compliant policy

Psychiatrist
Fabric Enables Federated Sharing

General Practitioner (GP)

Psychiatrist
Fabric Enables Federated Sharing

HIPAA-compliant policy

Different HIPAA-compliant policy
Example: Filling a Prescription

- Order medication
- Verify prescription
- Get current medications
- Check for conflicts
Example: Filling a Prescription

**Security issues**
- Pharmacist shouldn’t see entire record
- Psychiatrist doesn’t fully trust pharmacist with update
  - Need secure distributed computation

**Consistency issues**
- Need atomicity
- Doctors might be accessing medical record concurrently

**Update inventory**

**Fill order**

**Mark prescription as filled**

**Must be done by pharmacist**

**Must be done by psychiatrist**
Pharmacy Example in Fabric

```java
Order orderMed(PatRec psyRec, PatRec gpRec, Prescription p) {
    if (!psyRec.hasPrescription(p)) return Order.INVALID;
    if (isDangerous(p, gpRec.getMeds())) return Order.DANGER;
}
```
Pharmacy Example in Fabric

```java
Order orderMed(PatRec psyRec, PatRec gpRec, Prescription p) {
    atomic {
        if (!psyRec.hasPrescription(p)) return Order.INVALID;
        if (isDangerous(p, gpRec.getMeds())) return Order.DANGER;

        Worker psy = psyRec.getWorker();
        psyRec.markFilled@psy(p);
        updateInventory(p);
        return Order.fill(p);
    }
}
```
A High-Level Language

Order orderMed(PatRec psyRec, PatRec gpRec, Prescription p) {
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    psyRec.markFilled@psy(p);
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    return Order.fill(p);
}

- All objects accessed uniformly regardless of location
- Objects fetched as needed
- Remote calls are explicit

Run-time system requirement:
- Secure transparent data shipping
Order orderMed(PatRec psyRec, PatRec gpRec, Prescription p) {
    atomic {
        if (!psyRec.hasPrescription(p)) return Order.INVALID;
        if (isDangerous(p, gpRec.getMeds())) return Order.DANGER;

        Worker psy = psyRec.getWorker();
        psyRec.markFilled@psy(p);
        updateInventory(p);
        return Order.fill(p);
    }
}
Order orderMed(Patient psyRec, Patient gpRec, Prescription p) {
    atomic {
        if (!psyRec.hasPrescription(p)) return Order.INVALID;
        if (isDangerous(p, gpRec.getMeds())) return Order.DANGER;
        Worker psy = psyRec.getWorker();
        psyRec.markFilled@psy(p);
        updateInventory(p);
        return Order.fill(p);
    }
}

**Federated transaction** — spans multiple nodes & trust domains

**Remote call** — pharmacist runs method at psychiatrist’s node

**Run-time system requirements:**
- Secure transparent data shipping
- Secure remote calls
- Secure federated transactions

Federated Transactions
Fabric Security Model

- Decentralized system – anyone can join
- What security guarantees can we provide?
- **Decentralized security principle:**
  You can’t be hurt by what you don’t trust
- Need notion of “you” and “trust” in system and language
  - **Principals** and acts-for

Principals and Trust in Fabric

- **Principals** represent users, nodes, groups, roles
- Trust delegated via **acts-for**
  - “Alice acts-for Bob” means “Bob trusts Alice”
  - Like “speaks-for” [LABW91]
  - Generates a **principal hierarchy**
Trust Management

- Fabric principals are objects

```java
class Principal {
    boolean delegatesTo(principal p);
    void addDelegatesTo(principal p) where caller (this);
    ...
}
```

- Explicit trust delegation via method calls

```java
// Adds “Alice acts-for Bob” to principal hierarchy
bob.addDelegatesTo(alice)
```

- Compiler and run-time ensure that caller has proper authority
Security Labels in Fabric

- Based on Jif programming language [M99]
- Decentralized label model [ML98]
  - Labels specify security policies to be enforced
    Confidentiality: Alice → Bob Alice permits Bob to read
    Integrity: Alice ← Bob Alice permits Bob to write

```java
class Prescription {
    Drug{Psy→A\text{\textsubscript{pharm}}; Psy←Psy} drug;
    Dosage{Psy→A\text{\textsubscript{pharm}}; Psy←Psy} dosage;
    ...
}
```

- Compiler and run-time system ensure that policies are satisfied
Security Labels in Fabric

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    - Confidentiality: Alice $\rightarrow$ Bob Alice permits Bob to read
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```java
class Prescription {
    Drug{Psy $\rightarrow$ A_{pharm}; Psy $\leftarrow$ Psy} drug;
    Dosage{Psy $\rightarrow$ A_{pharm}; Psy $\leftarrow$ ...
    ...
}
```

- Compiler and run-time systems satisfied

Run-time system requirements:
- Secure transparent data shipping
- Secure remote calls
- Secure federated transactions
- Enforcement of security labels
Contributions

- Language combining:
  - Remote calls
  - Nested transactions
  - Security annotations

- System with:
  - Secure transparent data shipping
  - Secure remote calls
  - Secure federated transactions
  - Enforcement of security labels

Challenge: How to provide all these in the same system?
Fabric Run-Time System

- Decentralized platform for secure, consistent sharing of information and computation
  - Nodes join freely
  - No central control over security

- Nodes are principals
  - Root of trust
  - Authentication: X.509 certificates bind hostnames to principal objects
Fabric Architecture

Worker nodes (Workers)

Dissemination nodes

Storage nodes (Stores)
Fabric Architecture

Worker nodes (Workers):

Dissemination nodes:

- **Storage nodes** securely store persistent objects.
- Each object specifies its own security policy, enforced by store.

Transaction:

Remote call:
Fabric Architecture

Worker nodes (Workers)
- **Dissemination nodes** cache signed, encrypted objects in peer-to-peer distribution network for high availability.
- **Storage nodes** securely store persistent objects.
- Each object specifies its own security policy, enforced by store.

Fabric Architecture

- **Worker nodes** compute on cached objects
- Computation may be distributed across workers in **federated transactions**

- **Dissemination nodes** cache signed, encrypted objects in peer-to-peer distribution network for high availability

- **Storage nodes** securely store persistent objects
- Each object specifies its own security policy, enforced by store

**Diagram:**
- Worker nodes compute on cached objects.
- Computation may be distributed across workers in federated transactions.
- Dissemination nodes cache signed, encrypted objects in peer-to-peer distribution network for high availability.
- Storage nodes securely store persistent objects.
- Each object specifies its own security policy, enforced by store.
Secure Transparent Data Shipping

- Illusion of access to arbitrarily large object graph
  - Workers cache objects
  - Objects fetched as pointers are followed out of cache

- Stores enforce security policies on objects
  - Worker can read (write) object only if it’s trusted to enforce confidentiality (integrity)
Secure Transparent Data Shipping

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Run-time system requirements:
- Secure transparent data shipping
- Secure remote calls
- Secure federated transactions
- Enforcement of security labels

Worker node: \( y = x.f \)

Fabric object graph (distributed)
Secure Remote Calls

Is callee trusted to see call?
• Call itself might reveal private information
• Method arguments might be private

Is caller trusted to make call?
• Caller might not have sufficient authority to make call
• Method arguments might have been tampered with by caller

Is callee trusted to execute call?
• Call result might have been tampered with by callee

Is caller trusted to see result?
• Call result might reveal private information

Confidentiality
Integrity

Static checks
Dynamic checks
Secure Federated Transactions

- Transactions can span multiple workers, cross trust domains
  - No single node trusted for entire log: distributed log structure
- Object updates propagated transparently and securely in multi-worker transactions
Also in the Paper...

• Dissemination of encrypted object groups
  – Key management to support this
• Writer maps for secure propagation of updates
• Hierarchical two-phase commit for federated transactions
• Interactions of transaction abort and information flow control
• Automatic ‘push’ of updated objects to dissemination layer
• In-memory caching of object groups at store
• Caching acts-for relationships at workers
Implementation

• Fabric prototype implemented in Java and Fabric
  – Total: 35 kLOC
  – Compiler translates Fabric into Java
    • 15 k-line extension to Jif compiler
    • Polyglot \([NCM03]\) compiler extension
  – Dissemination layer: 1.5k-line extension to FreePastry
    • Popularity-based replication (à la Beehive \([RS04]\))
  – Store uses BDB as backing store
Overheads in Fabric

• Extra overhead on object accesses at worker
  – Run-time label checking
  – Logging reads and writes
  – Cache management (introduces indirection)
  – Transaction commit

• Overhead at store for reads and commits

• Ported non-trivial web app to evaluate performance
Cornell CMS Experiment

- Used at Cornell since 2004
  - Over 2000 students in over 40 courses
- Two prior implementations:
  - J2EE/EJB2.0
    - 54k-line web app with hand-written SQL
    - Oracle database
  - Hilda [YGG+07]
    - High-level language for data-driven web apps
- Fabric implementation
Performance Results

![Bar chart showing performance results for different operations and platforms.]

- **Requests per second**
- **Operations**:
  - Course overview (read)
  - Student info (read)
  - Update grades (write)
- **Platforms**:
  - EJB
  - Hilda
  - Fabric

**Observations**:
- Fabric outperforms EJB and Hilda across all operations.
- The highest performance is observed in the Course overview (read) operation.
Scalability Results

- Language integration: easy to replicate app servers

- Reasonable speed-up with strong consistency
  - Work offloaded from store onto workers

<table>
<thead>
<tr>
<th></th>
<th>3 workers</th>
<th>5 workers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course overview</td>
<td>2.18 x</td>
<td>2.49 x</td>
</tr>
<tr>
<td>Student info</td>
<td>2.45 x</td>
<td>2.94 x</td>
</tr>
</tbody>
</table>
## Related Work

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>What Fabric Adds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federated object store</td>
<td>OceanStore/Pond</td>
<td>• Transactions&lt;br&gt;• Security policies</td>
</tr>
<tr>
<td>Secure distributed storage systems</td>
<td>Boxwood, CFS, Past</td>
<td>• Fine-grained security&lt;br&gt;• High-level programming</td>
</tr>
<tr>
<td>Distributed object systems</td>
<td>Gemstone, Mneme, ObjectStore, Sinfonia, Thor</td>
<td>• Security enforcement&lt;br&gt;• Multi-worker transactions with distrust</td>
</tr>
<tr>
<td>Distributed computation/RPC</td>
<td>Argus, Avalon, CORBA, Emerald, Live Objects, Network Objects</td>
<td>• Single-system view of persistent data&lt;br&gt;• Strong security enforcement</td>
</tr>
<tr>
<td>Distributed information flow systems</td>
<td>DStar, Jif/Split, Swift</td>
<td>• Transactions on persistent data</td>
</tr>
</tbody>
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Fabric is the first to combine information-flow security, remote calls, and transactions in a decentralized system.
Summary

• Fabric is a platform for secure and consistent federated sharing

• Prototype implementation

• Contributions:
  – High-level language integrating information flow, transactions, distributed computation
  – Transparent data shipping and remote calls while enforcing secure information flow
  – New techniques for secure federated transactions: hierarchical commits, writer maps
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