Using Bigraphs to Model System Architecture

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Presentation Outline

- The layered security model
- Introduction to bigraphs
- Modelling critical infrastructure with bigraphs
- Further work

Existing Systematic Models

Basic Concepts and Taxonomy of Dependable and Secure Computing
- Avizienis, Laprie, Randell and Landwehr
- Longstanding work to Classify the important aspects of dependability including security

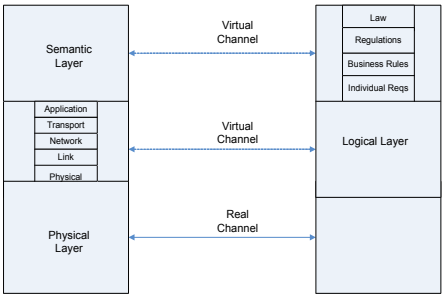
Practical Architectures for Survivable Systems and Networks
- Neumann and Parker organised systems into eight layers for security analysis
- The external environment, user, application, middleware, networking, operating system, hardware and internal environment

A Common Language for Computer Security Incidents
- Longstaff and Howard present a classification system for network security incidents
- Shows the different types of entity involved in an attack and their interrelationships

The Layered Security Model

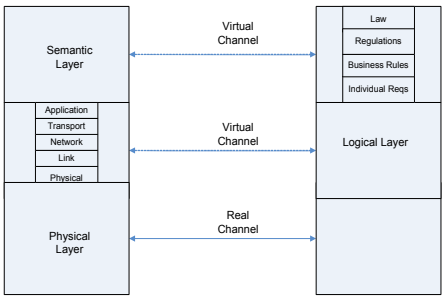
- Systems are modelled in a three-layer hierarchy
- The *semantic* or *conceptual layer* is the top layer
  - Includes people, organisations and system requirements
- The *logical layer* is the intermediate layer
  - Contains intangible entities including data and software that are stored and processed on computers
- The *physical layer* is the bottom layer
  - Represents the physical existence that all entities have in the real world
  - Includes both tangible objects and electromagnetic radiation

Three-layer model with sub-layers



- Each layer can have sub-layers for detailed analysis
- We use Tanenbaum's five-layer network model as sub-layers of our logical layer
  - The link, network and transport layers are intermediate sub-layers
  - The upper application and lower physical sub-layers interface to the social and physical layers of our model respectively

Locations and communication



- Each layer has a separate concept of location and distance between entities
- Entities at each layer have different extents, dependencies and interactions
- Entities in different locations use channels to communicate
  - Channels at higher layers are virtual, and must use a physical channel to communicate

Modelling protection requirements

- All systems have a horizontal scope at every layer
- Neumann considers four conceptual locations for compromise at every layer
- From outside, above, within and below
  - Protection from an external entity at the same layer requires horizontal controls
  - Protection from a higher layer entity requires a vertical boundary between the layers
  - Insiders should be constrained by partitioning the system with additional internal system boundaries they should not be able to breach
  - Some components that control the system must be trusted and so they should be made simple enough to assure

Conclusion - All entities, apart from unconditionally trusted entities, should be outsiders relative to one or more controls that moderate their use of the system.

Representing the 3-layer model using bigraphs

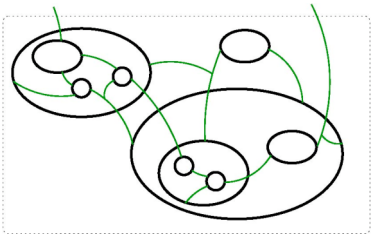
- Any system represented in our model can be transformed into a bigraph
- Use the two levels of bigraphs to represent the lower two layers of our model
  - Physical and logical layers are directly modelled
  - Locations and communication channels can be physical or logical
    - Represented by different types
  - Semantic layer is represented indirectly through lower level activities and effects
- Vulnerabilities are never removed by the application of security mechanisms, but are transformed into other vulnerabilities
  - All vulnerabilities have a physical or logical location or channel
  - The protective mechanism and the channel between the protection and the resource is vulnerable
  - Directly modelled by reaction rules in bigraphs, but not considered in most security models
    - Keys are stored in locations that must be protected with additional controls
    - Cryptographically protected resources exist in a virtual location encapsulated within special nodes that represent the protection
- Attackers have physical and logical scope and powers that can be represented by bigraphs
  - Sites represent their location
  - External names represent their potential communication
  - Rewriting rules specify their powers

Bigraph Purpose

- Bigraphs are graphs with two constituent graphs representing locality and connectivity separately
- They are an attempt at a unifying theory for program semantics
  - Have been shown to capture the semantics of the π-calculus, Petri nets and mobile ambients faithfully
- Important aid to understanding systems with both physical and logical aspects
  - Ubiquitous systems
- Understanding systems at multiple layers is essential for security

This introduction to bigraphs is based on “Axioms for bigraphical structure” by Robin Milner

Bigraph description

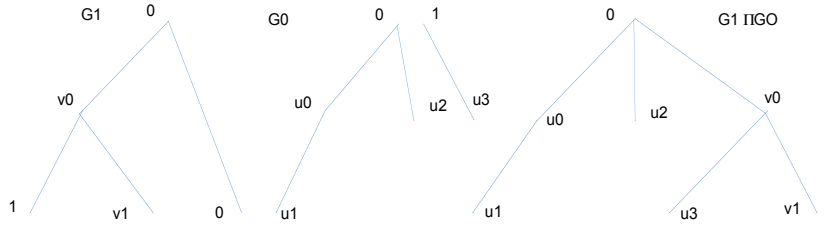


- The ovals are nodes of the bigraph, which are the common component of the underlying place and link graphs.
- Place graph edges are shown implicitly
  - The nodes are nested inside each other to represent placing one entity inside another
- Link graph edges are show explicitly
  - Each node has ports which may be linked to other nodes which models communication
- The linking and the placing of nodes is independent, shown by the way links cross node boundaries in the diagram
- Each external link (shown emerging from the top in the diagram) can be joined to some link of a host bigraph to model external communication

Place Graph

- A *place graph* G = (V, ctrl, prnt): m→n has:
  - An *inner width* m and an *outer width* n, both positive integers
  - ctrl: V→ κ represents the kind of nodes
  - A *parent map* prnt: m∪V →V∪n
- Represents n locations with a forest of n trees
- Represents m sites where other bigraphs can be placed
- The prnt map is the usual parent function for trees
  - Represents containment
- Places can be real or virtual locations
  - Keys, files and programs inhabit virtual locations

Composing Place Graphs

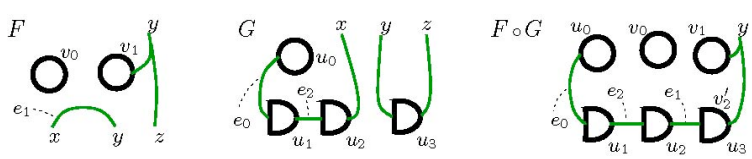


- Each root of the place graph G_0 is planted in a site of G_1
  - Identification points disappear in the composition
- If $G_i = (V_i, ctrl_i, prnt_i)$: $m_i \rightarrow m_{i+1}$ (i = 0, 1) be place graphs,
- $G_1 \circ G_0 = (V, ctrl, prnt)$ has prnt = $(Id_{V0} \cup prnt_1) \circ (prnt_0 \cup Id_{V1})$.
  - prnt(p) = $prnt_0(p)$ if $p \in m_0 \cup V_0$ and $prnt_0(p) \in V_0$
  - prnt(p) = $prnt_1(m)$ if $p \in V_0$ and $prnt_0(p) = m \in m_1$
    - new parent node in inhabitant graph
  - prnt(p) = $prnt_1(p)$ if $p \in V_1$

Link Graphs

- A link graph G = (V, E, ctrl, link): X→Y
  - Finite sets X of inner names, Y of outer names
  - Function link: X∪P → E∪Y called the link map.
    - The inner names X and ports P are the *points* of G, and the edges E and outer names Y its *links*.
    - The link map connects the attachment points to a communication channel
    - The interior link graph has a communication pattern that is enabled by the exterior link graph through the binding between interfaces
- We draw a link graph's inner names below it, and its outer names above
- Outer names can represent local or global communication
  - An outer name is an *open* link, an edge is a *closed* link
- The link graph can represent point-to-point or group communication
  - The link map is a hypergraph, so 'edges' can connect several points

Composing link graphs

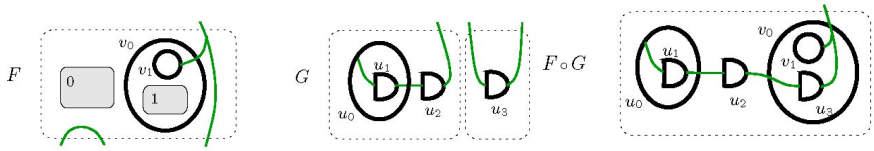


- The outer names of the interior link graph link to an exterior link graph via its corresponding inner names
- Let $G_i = (V_i, E_i, ctrl_i, link_i): X_i \rightarrow X_{i+1}$ (i = 0, 1) be two link graphs, then $G_1 \cup G_0 = (V, E, ctrl, link)$ has
- $link = (Id_{E0} \cup link_1) \circ (link_0 \cup Id_{P1})$
  - $link(p) = link_0(p)$ if $p \in X_0 \cup P_0$ and $link_0(p) \in E_0$
  - $link_1(x)$ if $p \in X_0 \cup P_0$ and $link_0(p) = x \in X$
  - outer name of G_0 links to edge, which makes it local to composed graph or to outer name of G_1, which potentially makes it global
  - $link_1(p)$ if $p \in P_1$

Bigraph Definition

- Define the composition of bigraphs in terms of the underlying operations on their constituent graphs
- An *interface* I = ⟨m, X⟩ consists of
  - A positive integer m called a *width*, representing places
  - a finite set X ⊂ ξ called a *name set*
- A *bigraph* takes the form G = (V, E, ctrl, G^P, G^L): I→J
  - The interfaces I = ⟨m, X⟩ and J = ⟨n, Y⟩ are its *inner* and *outer faces*
- The map from I to J is determined by the underlying place and link graphs
  - G^P = (V, ctrl, prnt): m→n a *place graph*
  - G^L = (V, E, ctrl, link): X→Y a *link graph*

Composing Bigraphs



- The component place and link graphs are our previous examples
- The composition of the two bigraphs are formed from the combinations of the place graphs and link graphs, which have orthogonal operations
- The sites in F indicate where the roots of an inhabitant bigraph G can be placed
- Then the outer names of G are linked to the corresponding inner names of F
- Note that G can be inserted two ways into F
- The two sites of G could represent a communication pattern that is implemented when inserted into F
  - Some of the nodes in G could be keys to protect communication over F, which could represent an insecure medium such as the Internet

Reaction Rules

- Different controls can participate in different *reaction* or *rewriting rules*
- Each rule consists of a precondition, which may be transformed into a post-condition wherever it occurs
  - Both of these conditions are bigraphs
- Atomic nodes do not have internal nodes
- Complex nodes can be active or passive
  - The control is *active* if reactions can occur inside them
  - It is *passive* if no internal reaction is allowed
    - The only method of reaction possible is when the passive nodes are destroyed

Critical Infrastructure

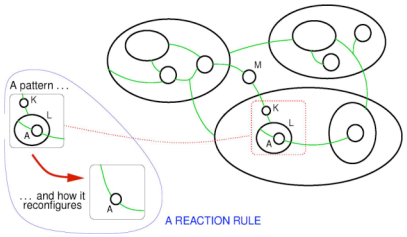
- Very complex systems that are very difficult to analyse manually
  - Large numbers of physical and computational entities and communication paths, and people with various powers
  - Large horizontal physical and logical scope
    - Allows pervasive access
  - Subject to both physical and logical attacks on resources, control systems and communication links
  - Intractable problem to avoid attacks
    - Large and unmitigated number of vulnerabilities
  - Goals of model in critical infrastructure protection
    - Finds vulnerabilities
      - Unexpected dependencies difficult to discover manually
    - Suggest remediation measures
      - Remove critical vulnerabilities
    - Continue in face of an attack
      - Avoid catastrophic failure modes
    - Helps in design of system
      - Avoid critical failure
      - Partition systems to limit damage of successful attack

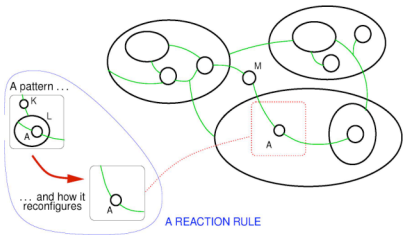
Critical Infrastructure (2)

- The bigraph representation of our three-layer model can faithfully represent critical infrastructure. It can:
  - Check objectives are satisfied
    - Can give assurance of protection of critical assets or indicate critical vulnerabilities
  - Model architectural protection using defence-in-depth
  - Model dependencies between components
  - Discover linkage between layers
    - Can discover attacks that operate and have effects at several layers
  - Handle remote effects and dependencies
    - Including transitive attacks that operate in several stages
  - Represent attackers in various locations with various powers
    - Including insider attacks
  - Model different types of network and the interaction between them
  - Model different scenarios by changes to attacker and defender

Critical infrastructure example

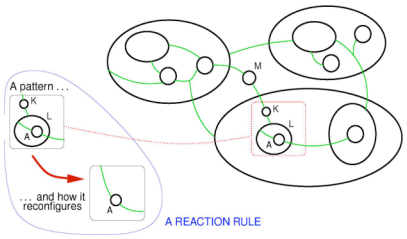
- Nodes of different types
  - Outermost ellipses are buildings
  - Circles are computers or machines
  - Intermediate size ellipses may represent rooms
- Representing requirements
  - The lower large ellipse represents a building containing a room with a telecommunication exchange or controller for an electricity substation S that can be accessed and controlled through the administrator's workstation
  - One defence goal is that there should be no path from the outside to S by either physical or logical means from unauthorised people or malware
- Cryptographic channels
  - The administrator's computer can be accessed remotely if the correct key is used for authentication, which is indicated by the graph reaction rule as shown

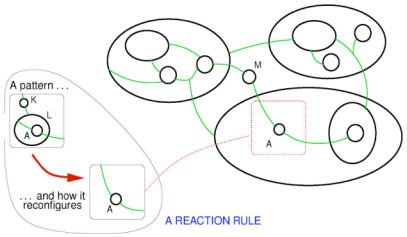




Critical Infrastructure example (2)

- A user can access the administrator's workstation remotely when he authenticates by proving he has access to the key K represented in the reaction rule
- The defence initially set up the authentication mechanism
  - Represented by the reverse of the reaction rule with the arrow in the opposite direction
- S can be accessed in multiple ways from outside
  - Logically through transitive access via the administrator's workstation A
  - Physically by entering the building and then the room
  - Via a multi-layer hybrid attack where both logical and physical accesses are combined
  - The link to the room containing S could be used to send a command having a physical effect such as cutting the power supply to S
- All these controls can be represented using bigraphs and model checking could determine if the attacker can breach any of the controls to interfere with S





Conclusion

- We demonstrated an informal three-layer model for modelling security architecture
- We formalised the model using bigraphs
- We used bigraphs to analyse a simple critical infrastructure example
- We suggested how the model unifies the treatment of insiders and outsiders
- We have used the model to represent cryptographic primitives (NSPW 2007 submission)
- We are investigating Kerberos, a complex network security protocol, that considers both physical and logical vulnerabilities

Model References

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