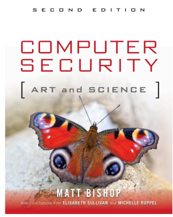
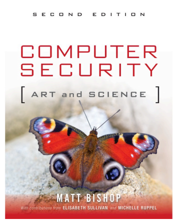


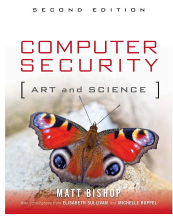
Formal Methods

Chapter 21



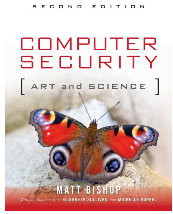
Outline

- Formal verification techniques
- Design verification languages
- Bell-LaPadula and SPECIAL
- Current verification systems
- Functional programming languages
- Formally verified products



Formal Verification Techniques

- Formal specification languages for specifying requirements and systems
  - Well-defined semantics, syntax
  - Based on mathematical logic systems
- Mathematically-based automated formal methods for proving properties of specifications and programs
  - Inductive verification techniques
  - Model checking techniques



Inductive Verification vs. Model Checking

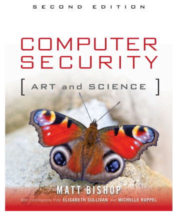
Classification criteria:

- *Proof-based vs. model-based techniques*:
  - *premises* embody system description
  - *conclusion* represents properties to be proved
  - Proof-based: derive intermediate formulae that go from premises to conclusion
  - Model-based: establish that premises, conclusion have same truth table values
- *Degree of automation*: fully manual to fully automatic, with everything in between

Inductive Verification vs. Model Checking

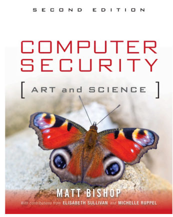
Classification criteria:

- *Full vs. property verification*:
    - System specification may describe entire system or part of system
    - Property specification may be single property or many properties
- *Predevelopment vs. postdevelopment*: may be design aid or for verification after system design is complete
- *Intended domain of application*: hardware or software, sequential or concurrent, non-terminating (like an operating system) or terminating, and so forth



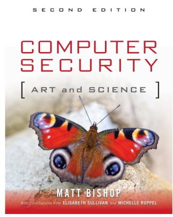
Example: HDM

- Developed at SRI
- Began as proof-based formal verification methodology
  - Covers design through implementation
  - Automated, general-purpose methodology
  - Used specification languages, implementation languages
- Provided model checking with its multilevel security tool
  - Input is formal specification in language SPECIAL
  - Theorem prover uses proof-based technique; fully automated property-oriented verification system



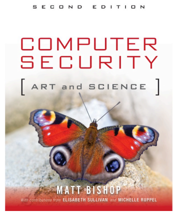
Example: HDM

- Tool uses SRI model (interpretation of Bell-LaPadula model)
  - Given a SPECIAL specification
  - Verification condition generator creates formulae that assert specification correctly implements SRI model
  - Boyer-Moore theorem prover processes these formulae
  - Output is list of the formulae that were satisfied and those that were not



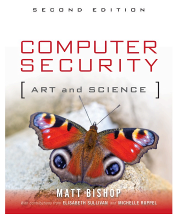
Formal Specification

- A specification written in a formal language with restricted syntax, well-defined semantics, based on well-established mathematical concepts
    - Precise semantics avoids ambiguity
    - Languages support exact descriptions of system function behavior
    - Generally eliminate implementation details
- Automated tools support verification of syntax, semantics



Example Language: SPECIAL

- First-order logic-based language
  - Nonprocedural, strongly typed
- Specification in SPECIAL represents module
  - Specifier defines module scope
  - Systems described in terms of modules
- Function representation in modules
  - VFUN: describe variable data
  - OFUN: describe state transitions
  - OVFUN: describe state transitions and changes in VFUN values



Bell-LaPadula Model and SPECIAL

MODULE Bell_LaPadula_Model give-access

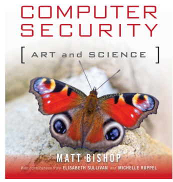
TYPES

Subject_ID: **DESIGNATOR**;

Object_ID: **DESIGNATOR**;

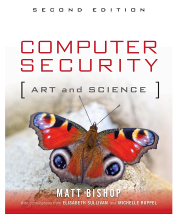
Access_Mode: {OBSERVE_ONLY, ALTER_ONLY, OBSERVE_AND_ALTER};

Access: **STRUCT_OF**(Subject_ID subject;
Object_ID object;
Access_Mode mode);



Comments

- Subject_ID, Object_ID types described at lower level of abstraction
    - The DESIGNATOR indicates this
- Access_Mode types have 3 possible values
- Access type is structure with 3 fields of types shown



Bell-LaPadula Model and SPECIAL

FUNCTIONS

VFUN active (Object_ID object) -> **BOOLEAN** active:

HIDDEN;

INITIALLY

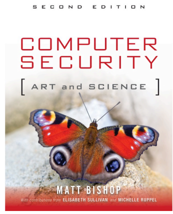
        TRUE;

VFUN access_matrix () -> Access accesses:

HIDDEN;

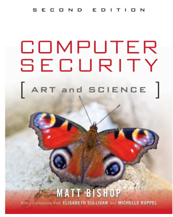
INITIALLY

        FORALL Access a: a **INSET** accesses => active(a.object);



Comments

- VFUN *active*(*object*) defines the state variable *active* for the *object* and sets it to **TRUE** initially
  - So state variable for that object is true if the object exists
- VFUN access_matrix() defines the state variable *access_matrix* to be set of triples (*subject*, *object*, *right*)
  - This is simply the current set of access rights in the system



Bell-LaPadula Model and SPECIAL

OFUN give-access(Subject_ID giver; Access access);

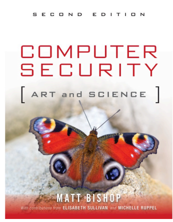
ASSERTIONS

    active(access.object) = **TRUE**;

EFFECTS

access_matrix() = access_matrix() **UNION** (access);

END_MODULE



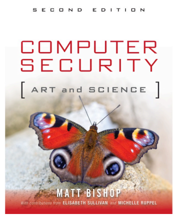
Comments

- OFUN *access_matrix*() defines state transition when new object added to matrix
- State variable *active* for object must be true
    - See in the **ASSERTIONS** sections
- Value of state variable *access_matrix* after transition is value before transition and additional access rights for the new object

Hierarchical Development Methodology (HDM)

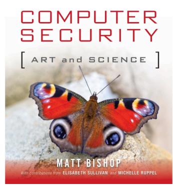
- General-purpose methodology for design, implementation
  - Goal was to automate and formalize development process
- System design specification is hierarchy of a series of abstract machines at increasing level of detail

Requirements	Analyze, accept requirements
↓	
Model	Model proven internally consistent, used as basis for verifying lower AMs
↓	
External Interfaces AM 1	First AM is usually external interface, called Formal Top Level Specification
↓	
Abstract Machine AM 1	Each AM mapped to next lower AM, which represents lower levels of system specification
⋮	
Primitive Machine AM *n*	Some combination of hardware and software that runs verified system



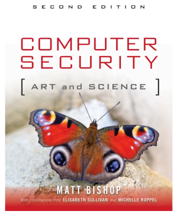
Specifications

- *Hierarchical* specification identifies abstract machines (AMs) making up hierarchy
- Each AM a set of modules written in SPECIAL
  - Modules could be reused in more than one AM
- *Mapping specifications* define functions of one AM in terms of next higher AM
- Hierarchy consistency checker: ensured consistency among hierarchy specs, associated module specs for AMs, mapping specs between AMs



Design Hierarchy

- Look at each pair of consecutive AMs, mappings between them
- For each function in higher AM, write programs to show how it was implemented in terms of lower-level AM
  - Written in high-order language
  - Translator mapped program into common internal form that HDM tools used
  - Specs mapped into intermediate language; this and common internal form generated verification conditions
    - Sent to Boyer-Moore theorem prover
  - If lower-level AM correct, then higher-level AM verified to work correctly

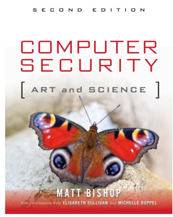


Verification in HDM

- Approach: prove the FTLS correctly implemented predefined properties within a model
- Used to verify design of a multi-level security (MLS) tool implementing a version of Bell-LaPadula model (called *SRI model*)

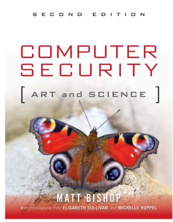
SRI Model

- Some SRI model entities had no corresponding Bell-LaPadula features
  - Visible function references and results (VFUN, OVFUN)
  - Defined subjects implicitly (function callers)
  - *-property addresses downward flow of information
- Bell-LaPadula model had features SRI model did not
  - Discretionary access control, current access triples
  - Defined subjects explicitly
  - *-property addressed allowable downward access



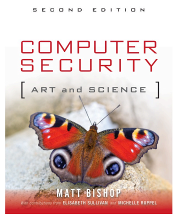
Properties of SRI Model in MLS Tool

- Information returned by specific function invocation to subject can depend only on information with security levels no greater than subject
- Information flowing into state variable (ie, VFUN) can depend only on other state variables with security levels no greater than that of first state variable
- If value of state variable modified, only function invocation with security level no greater than level of state variable can do the modification



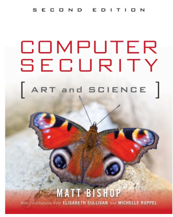
MLS Tool

- Processed SPECIAL specification describing external interfaces to SPECIAL model
  - One AM represented, so no mappings
  - Could be multiple modules in specification; each module had to be verified, and then the set verified using hierarchy consistency tool



MLS Tool

- To verify properties:
  - MLS tool generated formulae claiming correctness of properties
  - Property 1 correctness: formulae generated from exceptions from visible functions and VFUN, OVFUN return values
  - Properties 2, 3 correctness: formulae generated for each new value assignment to state variables
- Formulae (*verification conditions*) submitted to theorem prover
- Theorem prover reported the verification conditions that passes, failed, could not be proven

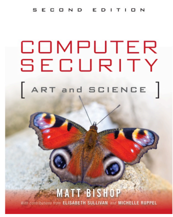


Boyer-Moore Theorem Prover

- User provides theorems, lemmata, axions, assertions needed for proof
  - For example, rules of reflexivity, associativity, transitivity among partial ordering relations
  - Provided in a LISP-like notation
  - Maintained list of previously proven theorems, axioms for future proofs
- Used extended propositional calculus
- Heuristics organized to find proof in most efficient manner
  - Used a series of steps on formula in search of proof

Boyer-Moore Steps

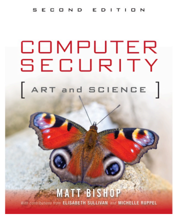
- *Simplify*: apply axioms, lemmata, function definitions, and other techniques
- *Reformulate*: replace terms by equivalent terms easier to process
- *Substitute equalities*: replace equal expressions with appropriate substitutions to eliminate equality expressions
- *Generalize*: introduce variables for terms that are no longer used
- *Eliminate* irrelevant terms
- *Use induction* to prove theorems when needed



Boyer-Moore Evaluation

1. Iterated between simplify, reformulate steps until formula proved or disproved, or formula did not change
2. Substitute equalities, and if any changes then go back to step 1
3. Generalize, and if any changes then go back to step 1
4. Eliminate, and if any changes then go back to step 1
5. Apply induction, and if any changes then go back to step 1

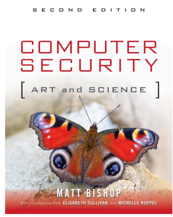
If formula reduced to **TRUE** or **FALSE**, done; otherwise formula could not be proven



Enhanced HDM (EHDM)

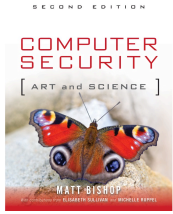
EHDM addressed difficulties with HDM

1. SPECIAL not defined in terms Boyer-Moore theorem prover could use readily
    - Missing specific constructs that theorem prover needed
    - EHDM used new language, similar to SPECIAL but with the missing constructs, such as concepts of AXIONM, THEOREM, LEMMA
2. HDM theorem prover not interactive
    - EHDM theorem prover based on Boyer-Moore theorem prover, but was interactive



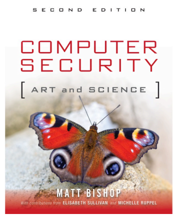
Gypsy Verification Environment

- Gypsy Verification Environment (GVE) focused on implementation proofs
  - Verification system tried to show correspondence between specifications, their implementation
  - Verification system could also prove properties of Gypsy specifications
- Set of tools including a Gypsy language parser, verification condition generator, theorem prover



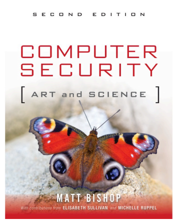
Gypsy Language

- Combined specification language constructs with programming language (Pascal base)
- Limitations on Pascal base
  - Could not nest routines, but could group them together in named ”scope”
  - No global variables; only constants, types, functions, procedures visible between routines
  - Parameters all constant and passed only by reference
  - No pointers
  - New data structures sets, sequences, mappings, buffers; new operations of addition, deletion, moving component



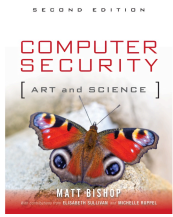
Gypsy Language Specifications

- Gypsy program made up of small, verifiable units
  - Functions, procedures, lemmata, types, constants
  - Proof of unit depended only on external specifications of referenced units
- Specification constructs
  - *Entry*: conditions assumed to be true when routine activated
  - *Exit*: conditions that must have been true if routine exited
  - *Block*: conditions that must have been true if routine blocked waiting on access to shared memory
  - *Assert*: conditions that had to be true at specific point of execution
  - *Keep*: conditions that had to remain true throughout execution of routine



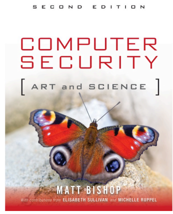
Gypsy Language Specifications

- Gypsy supported execution of *lemmata* as separate units
  - Lemmata defined relation among functions, global constraints
  - *hold* specification defined constraint on values of abstract data type
- Expressive level
  - Existential quantifier *some*
  - Universal quantifier *all*
  - Mechanism to distinguish old, new values
  - *Validation directive* says when to prove condition: during verification, validated at runtime, or both



Bledsoe Theorem Prover

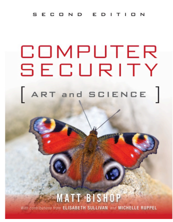
- Interactive natural deduction system using extended first-order logic
  - Allowed subgoaling, matching, rewriting
- Every loop had to be broken by at least one *assert* specification
- Each verification condition was theorem corresponding to single path of execution
  - Due to *asserts*, finite number of execution paths
  - Condition stated that specification at beginning of path implies specification at end of path
- Analyst could guide the prover, or it could be told to choose next step



Current Verification Systems

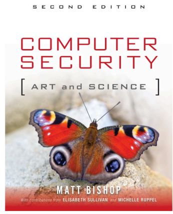
- Prototype Verification System (PVS)
- Symbolic Model Verifier (SMV)
- Naval Research Laboratory Protocol Analyzer (NPA)

(as of the publication date of this book)



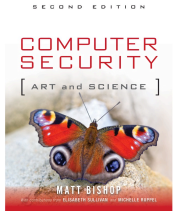
PVS

- Builds on prior work at SRI, especially EHDM
- HDM, EHDM focused on proving programs correct and the full life cycle of software development
- PVS focuses on mechanically checked specifications, readable proofs
  - It does *not* provide a full software development environment
  - No notion of layers of abstraction, mapping between levels
- Components:
  - Specification language integrated with theorem prover
  - Theorem prover highly interactive (a “proof checker”)
  - Other tools like syntax and type checkers, parsers



PVS Specification Language

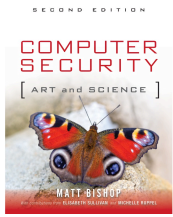
- Strongly typed, based on first-order logic, nonprocedural
- Supports defining theories
  - Statements called *declarations* identifying types, constants, variables, axioms, formulae
  - Theories reusable, some incorporated into PVS and are called *preludes*
  - Preludes provide definitions, theorems of set theory, functions, relations, ordering, properties of numbers
  - External libraries provide finite sets, coalgebras, real analysis, graphs, lambda calculus, temporal logics



Example PVS Specification

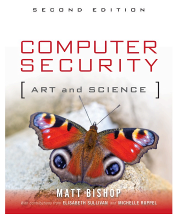
- Built-in theory; beginning of theory of rational numbers

```
rats: THEORY
BEGIN
      rat: TYPE
      zero: rat

      nonzero : TYPE {x | x ≠ zero}
      / : [rat, nonzero -> rat]
      * : [rat, rat -> rat]
      x, y : VAR

      left_cancellation : AXIOM zero ≠  x IMPLIES x * (y/x) = y
      zero_times : AXIOM zero * x = zero
END rats
```



Example PVS Specification

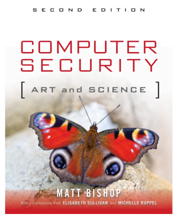
- Types *rat*, *nonzero*
  - *nonzero* subtype of *rat* (as all members of *nonzero* are elements of *rat*, but not vice versa)
- Constant *zero* of type *rat*
- Multiplication , division functions take 2 arguments, return value of type *rat*
  - Note second argument of division must have type *nonzero*



Example PVS Specification

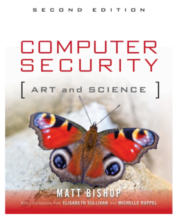
- Type checker checks types for an occurrence of "/" in left cancellation'
  - It generates a *type correctness condition*
  - It adds this to the specification
  - TCCs must be proved in order to show theory type correct (hence called *obligations*)
- For example, here is added declaration:

```
left_cancellation _TCC1: OBLIGATION
    (FORALL (x: rat): zero ≠ x IMPLIES x ≠ zero)
```



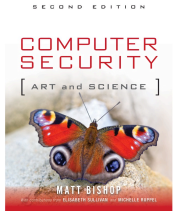
PVS Proof Checker

- Proceeds in 4 phase:
    1. *Exploratory phase*: developer tests specification proofs, revises high-level proof ideas as needed
    2. *Development phase*: developer constructs proof in larger steps, works on making it efficient
    3. *Presentation phase*: proof is sharpened, polished, checked
    4. *Generalization phase*: developer analyzes proof, lessons learned, for future proofs
- Uses goal-directed proof search
    - So it starts from the conclusion, infers subgoals
    - Process repeats until subgoals obvious to prove



PVS Proof Checker

- Inferencing applies inference rules
  - Starts with small set of rules
  - Applies mechanism to compose rules into proof strategies
- Types of rules and some examples:
  - *Propositional rules*: cut rule for introducing case splits, another rule for raising *if* conditionals to top level of formula, another for deleting formulae from goal
  - *Quantifier rules*: rules for instantiating existentially quantified variables with terms
  - *Equality rules*: replace one side of an equality premise with another
- Proof strategies: frequently used proof patterns collapsed into one step
  - Examples: propositional simplification, rewriting with a definition of lemma



Experiences with PVS

- Applied in many areas beyond computer security:
  - Used by NASA to analyze requirements for several spacecraft projects, avionics control
  - Used to verify microarchitectures, complex circuits, algorithms, protocols in hardware devices
  - Used to analyze fault-tolerant and distributed algorithms

SMV

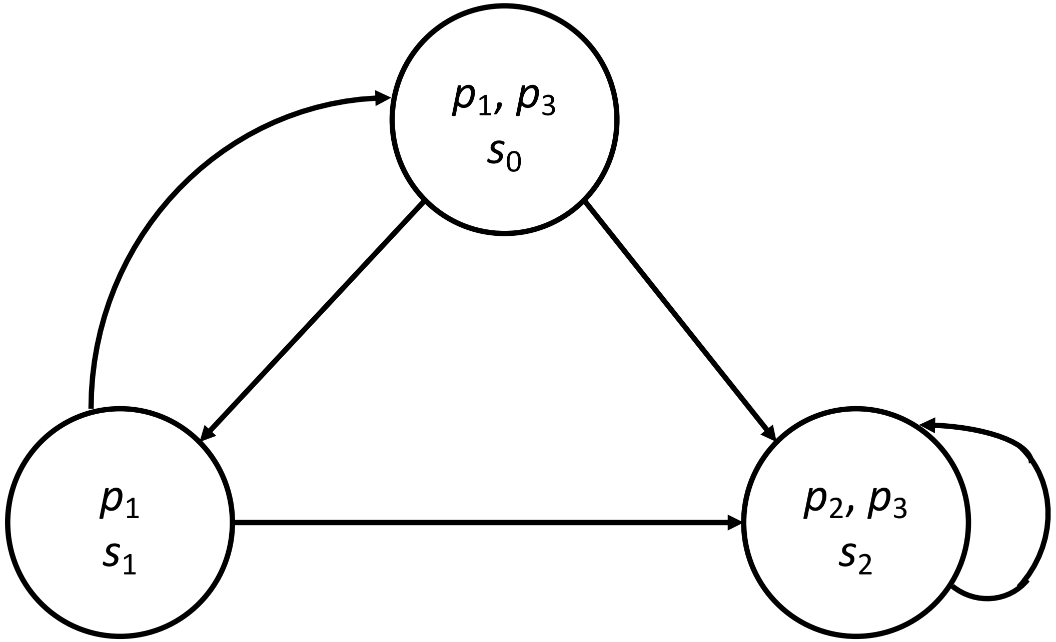
- Based on Control Tree Logic that uses 2 letters for connectives:
  - First letter: "A" (along all paths), "E" (along at least 1 path)
  - Second letter: "F" (some future state), "G" (all future states), "U" (until), "X" (next state)
  - Examples: "AX" (along all possible paths to the next states), "EX" (along at least 1 path to the next states)
- Represent model in CTL as a digraph
  - Nodes represent states
  - Propositional atoms holding in a state represented by node annotations
  - Edges show possible state transitions

Example

- Model M specifies system with states s_0, s_1, s_2 and propositional atoms p_1, p_2, p_3
- Possible state transitions:

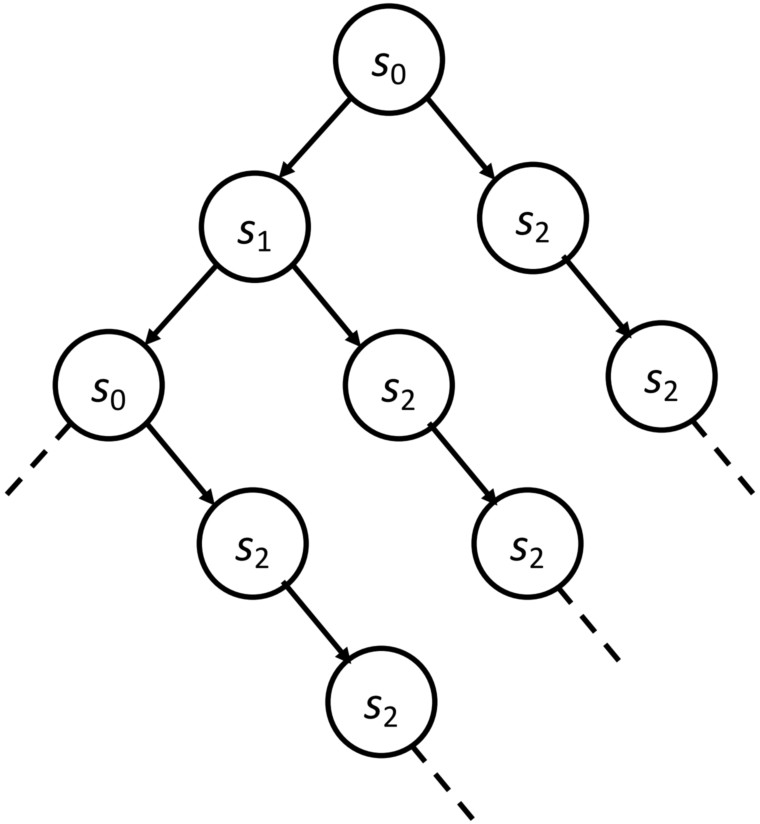
$$s_0 \rightarrow s_1,\ s_0 \rightarrow s_2,\ s_1 \rightarrow s_0,$$
$$s_1 \rightarrow s_2,\ s_2 \rightarrow s_2$$

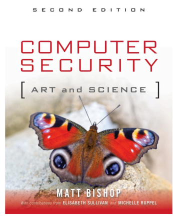
- Suppose p_1 true in s_0 and s_1, p_2 true in s_2, p_3 true in s_0, s_2



Example

- Unwind the graph to create a tree of all computational paths beginning at s_0



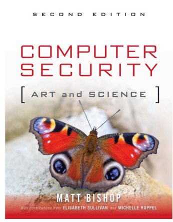


SMV Language

- Program specifies system, properties to be verified
- SMV tool returns *true* (specs hold for all initial states), or a trail of actions showing how it fails
- Module *min* identifies modules of program, forms root of model hierarchy
  - Individual module specifications describe set of variables
  - May be parameterized, contain instances of other modules; can be reused as needed

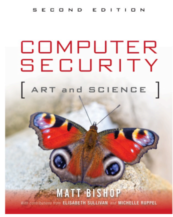
SMV Language

- VAR: defines variable, identifies type of variable
  - SMV supports boolean, scalar, fixed array, structured data types
- ASSIGN: assigns initial, next values to variables
  - Next values defined in terms of current values of variables
- DEFINE: assigns values to variables in terms of other variables, constants, logical and arithmetic operators, case and set operators
- INVAR: invariant of state transition system
- SPEC: CTL specification to be proved about module
- Other features:
  - Fairness contraints to rule our infinite executions



Example

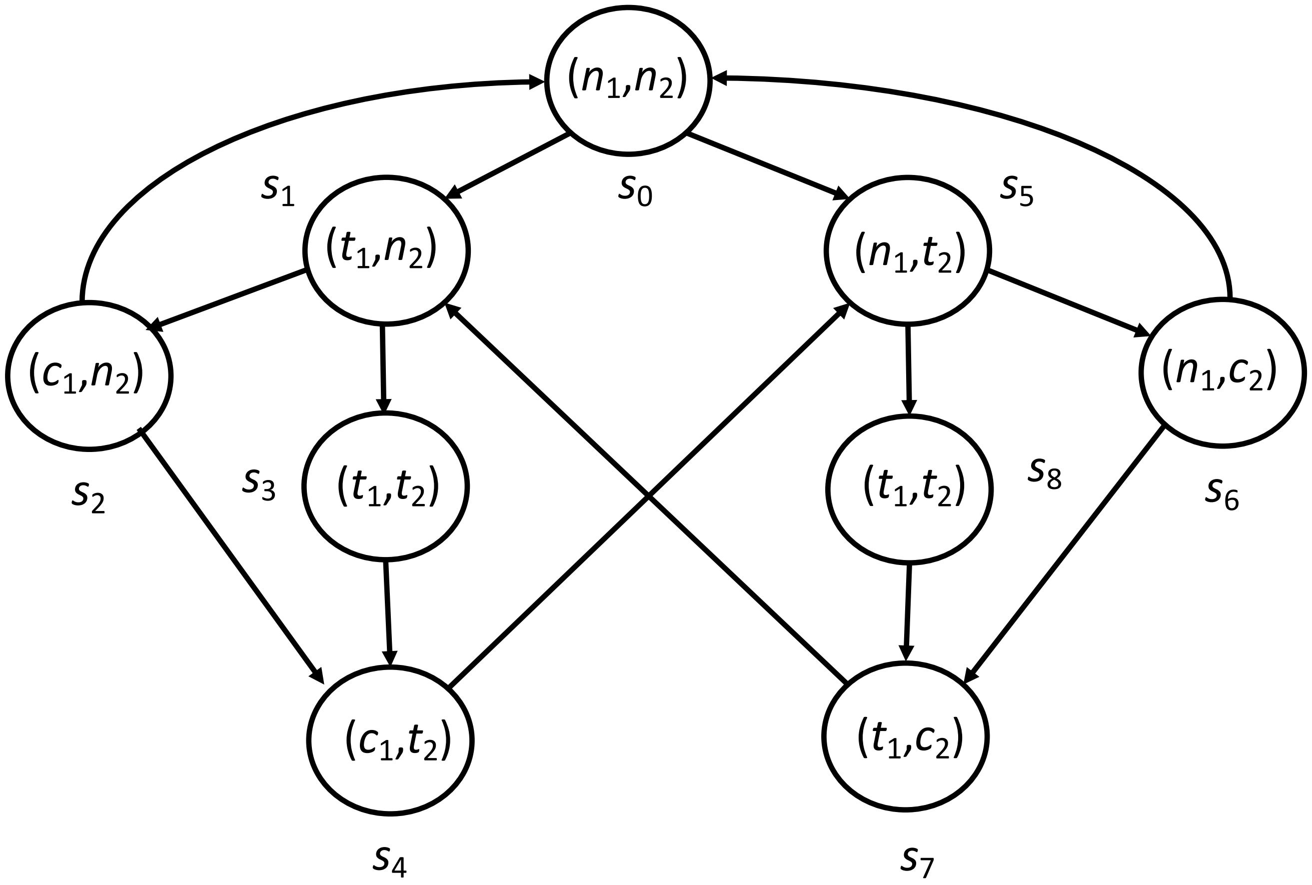
- 2 concurrent processes share mutually exclusive resource
  - Define critical section of process' code, and protocol for entry
- Model M: processes p_1, p_2
- States for each process:
  - n_i: process not attempting entry
  - t_i: process trying to enter
  - c_i: process in critical section
- Allowed states: (n_1, n_2), (n_1, t_2), (n_1, c_2), (t_1, n_2), (t_1, t_2), (t_1, c_2), (c_1, n_2), (c_1, t_2)
- Omit (c_1, c_2) as both processes cannot be in critical section at the same time



Building the model

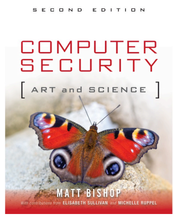
- (t_1, t_2) occurs 2 times – one with the next state (c_1, t_2) and the other with the next state (t_1, c_2)
  - That is, first case is when p_1 gets into the critical section, and the second when p_2 gets into the critical section

Graph of the Model



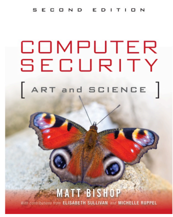
What to Show

- *Safety*: only 1 process at a time can be in the critical section
- *Liveness*: a process trying to enter the critical section will eventually do so
- *Nonblocking*: a process can always request to enter its critical section



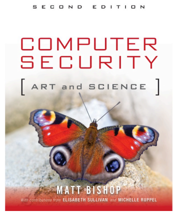
From the Model . . .

- *Safety* requires that, for all paths, c_1 and c_2 cannot be true simultaneously; in CTL, $AG\neg(c_1 \land c_2)$.
  - State (c_1, c_2) not defined in model, so trivially true
- *Liveness* requires that for all paths, if t_i is true, then there is some future state on the same path in which c_i is true; in CTL, $AG(t_i \rightarrow AFc_i)$
  - Inspection of graph shows this is true
- *Nonblocking* requires that, for every path, every state n_i has a successor state t_i; that is, in CTL, $AG(n_i \text{ -> } EXt_i)$
  - Inspection of graph shows this is true



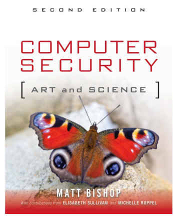
Use of SVM

- Used to verify sequential circuit designs
- Used to verify IEEE Futurebus+ Logical Protocol Specification
- Also used to verify security protocols, finite state real-time systems, concurrent systems



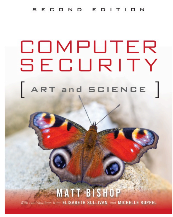
NPA

- Verification system for cryptographic protocols
  - Written in Prolog
- Based on Dolev-Yao model of rewriting terms
  - Underlying assumption: adversary can read, modify, destroy any message, and can do any operation (encryption, decryption) that a legitimate user can do
  - Also assumes adversary does *not* know specific words (keys, messages)
  - Goal: learn those specific words
- Approach based on interactions among a set of state machines
  - User specifies nonsecure states and tries to prove they are unreachable



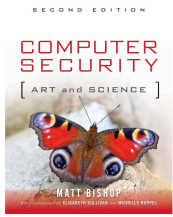
NPA Languages

- NPA Temporal Requirements Language (NPATRL) expresses generic requirements of key distribution, agreement protocols
- Common Authentication Protocol Specification Language (CAPSL)
  - High-level language for cryptographic authentication, key distribution protocols
  - Idea is to specify in this language, and then translators can translate it into languages for various protocol verification systems
  - NPA has CAPSL interface



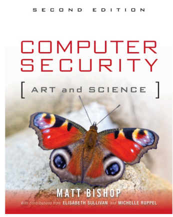
CAPSL Language

- *Protocol specification* defines protocol
- *Types specification* describes encryption, decryption operations
- *Environment specification* provides specific details about the scenario in which the protocol is to be used to help in finding a proof



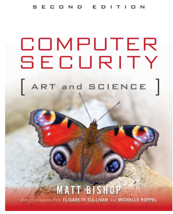
Use of NPA

- Used to test and verify many protocols
  - Internet Key Exchange protocol
  - Needham-Schroeder public key protocol



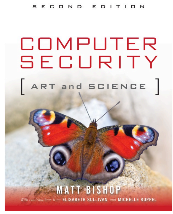
Functional Programming Languages

- These languages use mathematical expressions that are evaluated
  - Expressions only depend on inputs, so results (outputs, effects) not dependent on global variables, local state
  - Functions treated like any other value, so can be modified, used as input, output parameters
- These languages are well-defined, well-0typed leading to simpler analyses than programs unimplemented using nonfunctional programming languages



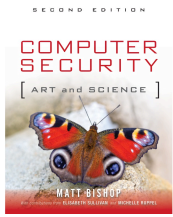
Examples

- OCaml: programs verified by compiler prior to execution
  - Reduces programming errors
  - Used where speed, error-free functionality is critical
- Haskell: offers built-in memory management
  - Strongly typed
  - Programs tend to be shorter, leading to a program that is easier to verify
- Rust: combines speed of C programming language with functional programming language characteristics
  - Provides thread safety, prevents segmentation faults
  - Formally proved that unsafe implementations are safely encapsulated



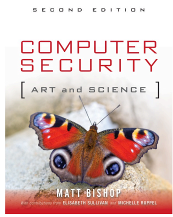
Formally Verified Products

- As computing power increases and formal verification methods become more scalable, formally verifying products becomes more feasible
- Example: open-source seL4 microkernel
  - Designed using high assurance techniques
  - Formally verified against its own specification, including ability to enforce security properties
- Usually done by embedding hypotheses about program in the program
  - When one is encountered, it is checked; on failure, appropriate action taken



Example: SOAAP

- Security-Oriented Analysis of Application Programs uses annotations
  - Based on compartmentalization of execution
  - Describe what parts of program should be in sandbox, how they communicate
- Example: function to decipher file, put cleartext into second file
  - Annotated functions compiled into intermediate representation
  - All such file linked
  - SOAAP performs both static, dynamic control, data flow analysis to identify violations
  - Also warns if overhead added by checking causes program not to meet performance requirements



Example

```
__soaap_var_read("decipher")
int  retval;

__soaap_sandbox_persistent("decipher")
void  decipher(fdes in, fdes out)
{
        char key[128] __soaap_private;
        if (getkey("Key:", key) < 0)
                retval = -1;
        while ((n = read(buf, 1023, in)) > 0)
                decrypt(buf, key);
                if (write(buf, n, out) != n)
                        retval = -1;
        retval = 0;
}
```

Example

- *decipher* to be run in sandbox:

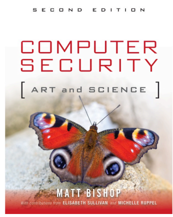
```
__soaap_sandbox_persistent(“decipher”)
```

- *key* value should not be visible outside this function

```
__soaap_private
```

- *retval* used to communicate success (0) or failure (–1), so *decipher* must be able to modify its value even though it is outside scope of sandbox

```
__soaap_var_read(“decipher”)
```



Key Points

- Formal verification based on formal specifications
- HDM, EHDM use hierarchy of abstract machines and mappings between each layer
- Gypsy focused on proving properties of implementations
- PVS provides system to prove theorems about specifications using interactive theorem prover
- SMV is a model-checking tool
- NRL Protocol Analyzer verifies protocols, can identify potential attacks