CSCI 234

Design of Internet Protocols: PROMELA and SPIN

George Blankenship

Outline

- Verification and Validation
- History and motivation
- Spin
- Promela language
- Promela model

Verification vs. Validation

- Software verification is often confused with software validation
- Software verification is a verification of conformance to the specification
- Software validation is a validation of the compliance with the requirements

Common Design Flaws

- Deadlock
- Livelock
- Underspecification
- Overspecification
- Violations of constraints
- Assumptions about speed

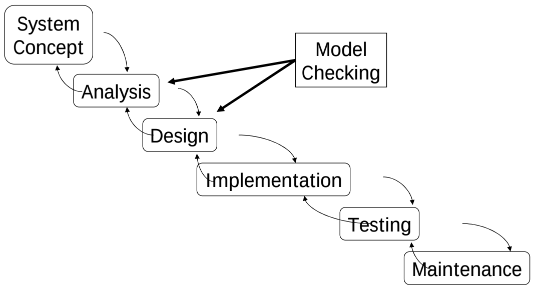
Diagnosing Design Flaws

- Complexity makes design flaws difficult to uncover.
- Engineers often use simplified models (prototypes) for design verification.
- Abstract models can also be used to verify concurrent systems.

What is Model Checking?

- Use a simplified model of our system.
- Verify the system exhaustively.
- Automatically check that given properties hold in all possible states.

System Development



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System State Based Analysis

- Complete state space must be represented
- State space defined by significant variables
- Each integer variable has 2^{32} distinct possibilities. Two such variables have 2^{64} possibilities.
- In concurrent protocols, the number of states usually grows exponentially with the number of processes.

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State Space Capture

- System is the asynchronous composition of processes
- For each state the successor states are enumerated using the transition relation of each process

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Reducing Complexity

- Problem: state space explosion!
- Automatic state space compression and reduction by SPIN.
- Manual reduction techniques by the designer.
  - We need to find the smallest sufficient model of our system.
  - Biggest challenge!

If it is so constrained, is it of any use?

- Many protocols are finite state.
- Many programs or procedure are finite state in nature. Can use abstraction techniques.
- Sometimes possible to decompose a program, and prove part of it by model checking and part by theorem proving.
- Many techniques to reduce the state space explosion (Partial Order Reduction).

Alternating Bit Protocol

```
mtype = {MSG, ACK};
chan toS = [2] of {mtype, bit};
chan toR = [2] of {mtype, bit};
proctype sender(chan in, chan out)
{
   bit sendbit, recvbit;
   do
   :: out!MSG, sendbit ->
        in?ACK, recvbit
        if
        :: recvbit == sendbit ->
           sendbit = 1-sendbit
        :: else
        fi
   od
}
```

```
proctype receiver(chan in, chan out)
{
   bit recvbit;
   do
   :: in?MSG, recvbit ->
        out!ACK, recvbit
   od
}

init
{
   run sender(toS, toR);
   run receiver(toR, toS);
}
```

What is this all about?

- SPIN
  - On-the-fly verifier developed at Bell-labs by Gerard Holzmann and others
- Promela
  - Modeling language for SPIN
  - Targeted at asynchronous systems

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"First Computer Bug"

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History

- Work leading to SPIN started in 1980
  - First bug found on Nov 21, 1980 by Pan
  - One-pass verifier for safety properties
- Succeeded by
  - Pandora (82)
  - Trace (83)
  - SuperTrace (84)
  - SdlValid (88)
  - SPIN (89)

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SPIN

- SPIN (Simple PROMELA Interpreter)
  - Tool for analyzing the logical consistency of concurrent systems.
  - Takes a PROMELA model as input.
- Model-checker.
- Based on automata theory.
- Allows LTL or automata specification
- Efficient (on-the-fly model checking, partial order reduction).
- Developed in Bell Laboratories.

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SPIN Features

- "press on the button" verification (model checker)
- efficient implementation
- graphical user interface (Xspin)
- used for research and industry
- contains more than two decades research on advanced computer aided verification (many optimization algorithms)

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The language of SPIN

- Called Promela
- The expressions are from C.
- The communication is from CSP.
- The constructs are from Guarded Command.

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Command Line Tools

- Spin
  - Generates the Promela code for the LTL formula
  - Generates the C source code
- Pan (Process Analyzer)
  - Performs the verification
    - Has many compile time options to enable different features
    - Optimized for performance

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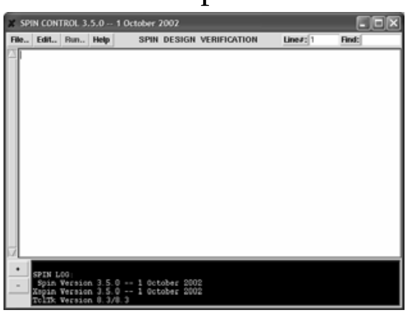
Xspin



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Simulator

- Spin can also be used as a simulator
  - Simulated the Promela program
- It is used as a simulator when a counterexample is generated
  - Steps through the trace
  - The trace itself is not “readable”
- Can be used for random and manually guided simulation as well

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XSpin Features

- Graphical front-end to the SPIN model checker.
- Features:
  - Editor
  - Syntax checking
  - Simulation
  - Verification
  - Requirements specification

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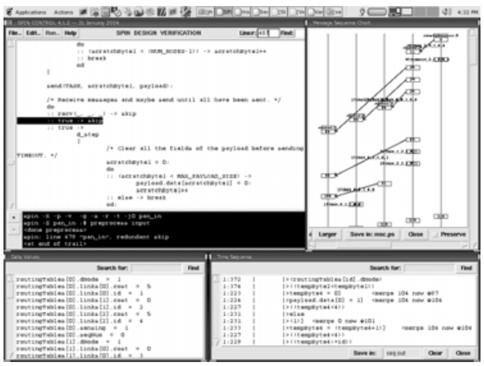
XSpin Screenshot



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Types of Properties

- Invalid end-states (deadlock)
- Assertion violations
- Unreachable code
- Liveness properties
  - Non-progress cycles
  - Acceptance cycles
- Linear Temporal Logic (LTL) formulae

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Spin capabilities

- Interactive simulation
  - For a particular path
  - For a random path
- Exhaustive verification
  - Generate C code for verifier
  - Compile the verifier and execute
  - Returns counter-example
- Lots of options for fine-tuning

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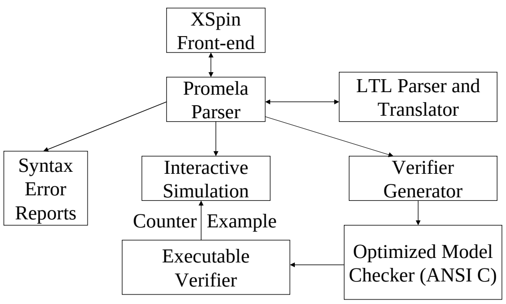
Spin overall structure



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PROMELA

- PROMELA (Process/Protocol Meta Language)
  - Specification language to model finite-state systems.
  - Dynamic creation of concurrent processes.
  - Communication via synchronous or asynchronous message channels.
  - Non-deterministic (you'll see!).
- Language for asynchronous programs
  - Dynamic process creation
  - Processes execute asynchronously
  - Communicate via shared variables and message channels
    - Races must be explicitly avoided
    - Channels can be queued or rendezvous
  - Very C like

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Finite Systems Only!

- No unbounded data.
- No unbounded message channels.
- No unbounded processes.
- No unbounded process creation.

Variables and Types

- Five different (integer) basic types.
- Arrays
- Records (structs)
- Type conflicts are detected at runtime
- Default initial value of basic variables (local and global) is 0.

Variables

- Variables should be declared
- Variables can be given a value by:
  - assignment
  - argument passing
  - message passing
- Variables can be used in expressions
- Most arithmetic, relational, and logical operators of C/Java are supported

Data Types

- Basic : bit/bool, byte, short, int, chan
- Arrays: fixed size
  - byte state[20];
  - state[0] = state[3 * i] + 5 * state[7/j];
- Symbolic constants
  - Usually used for message types
  - mtype = {SEND, RECV};

Basic Types (integer)

Declarations	Value range
bit turn=1;	[0..1]
bool flag;	[0..1]
byte counter;	[0..255]
short s1, s2;	[-2^{16}-1.. 2^{16}–1]
int msg;	[-2^{32}-1.. 2^{32}–1]

Arrays

- <type> <array name>[<array size];
- byte a[27]; // array a can hold 27 bytes
- bit flags[4]; // array flags can hold 4 bits
- Same as C/C++
- Array index starts at 0
- Array index ends at size-1

Expressions

- Arithmetic: +, -, *, /, %
- Comparison: >, >=, <, <=, ==, !=
- Boolean: &&, ||, !
- Assignment: =
- Increment/decrement: ++, --

Records

- Type definition defines records (structure)

```
typedef MyRecord {
short f1; byte  f2;
}
```

- Variable declaration defines variable

```
MyRecord rr;
```

- Values are reference field by field

```
rr.f1 = …
rr.f2 = …
byte a = rr.f2;
```


Message types and channels

- Message type is enumeration declaration <type name>={<value list>}
- mtype = {OK, READY, ACK, ERROR}
  - #define OK = 1;
  - #define READY=2;
  - #define ACK=3
  - #define ERROR=4
- mtype Mvar = ACK

Channels

- Channel defines queue that is used to pass messages between processes
  chan <name>=[<size>] of {<message record>}
- chan Ng=[2] of {mtype, byte, byte},
  Next=[0] of {byte}
- Enqueue a message – blocks if channel has no space
  <name>!<record fields>
- Dequeue a message – blocks if channel is empty
  <name>?<variables to receive fields>
- Ng!OK(5,4); /* send message type OK with data 5 and 4
  Ng!OK,5,4; /* same as OK(5,4)
- Ng?OK(byte0,byte1); /* store data if type is OK

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Delimiters

- Semi-colon is used a statement separator not a statement terminator
- Last statement does not need semi-colon
- Often replaced by **->** to indicate causality between two successive statements

(a == b); c = c + 1
(a == b) -> c = c + 1

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Statements

- The body of a process consists of a sequence of statements
- A statement is either
  - executable: the statement can be executed immediately
  - blocked: the statement cannot be executed
- Executable/blocked depend on the global state of the system.

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Executable Statements

- An assignment is always executable
- An expression is also a statement; it is executable if it evaluates to non-zero
  - 2 < 3 always executable
  - x < 27 only executable if value of x is smaller 27
  - 3 + x executable if x is not equal to –3

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Executability

- The body of a process consists of a series of statements.
- Statements are either executable or blocked.
- No difference between conditions and statements
  - Execution of every statement is conditional on its executability
  - Executability is the basic means of synchronization
- Declarations and assignments always executable
- Conditionals are executable when they hold
- The following are the same

```
while (a != b) skip
(a == b)
```

```
(x < y)

i = 3

ch!MSG

ch?msg
```

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Statements

- The skip statement is always executable
- A run statement is only executable if a new process can be created (the number of processes is bounded)
- A printf statement is always executable
- Statements in a sequence are separated by a semi-colon: “;”
- A given statement in a sequence isn’t executable until previous statement executed

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Sample

```
int x;
proctype A( ) {
  int y=1;
  skip;
  run N( );
  x=2;
  x>2 && y==0;
  skip;
}
```

Executable if N can be created... (points to: run N( );)

Can only become executable if some other process makes x greater than 2 (points to: x>2 && y==0;)

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assert(<expression>);

- The assert statement is always executable
- If <expr> evaluates to zero, SPIN will exit with an error, as the <expr>“has been violated”
- The assert statement is often used to check whether certain properties are valid in a state
- proctype monitor() { assert(n <= 3); }
- proctype receiver() { ...
  toReceiver ? msg;
  assert(msg !=ERROR);
  ... }

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if-statement

if :: choice$_1$ -> stat$_{1.1}$; stat$_{1.2}$; stat$_{1.3}$; ...
:: choice$_2$ -> stat$_{2.1}$; stat$_{2.2}$; stat$_{2.3}$; ...
:: ...
:: choice$_n$ -> stat$_{n.1}$; stat$_{n.2}$; stat$_{n.3}$; ...
fi;

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if-statement

- If there is at least one $choice_i$ (guard) executable, the if statement is executable and SPIN non-deterministically chooses
- If no $choice_i$ is executable, the if-statement is blocked
- The operator "->"is equivalent to ";"
- The else guard is always executable
- Guard need not be exhaustive or mutually exclusive

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do-loops

do
:: $choice_1$ -> $stat_{1.1}$; $stat_{1.2}$; $stat_{1.3}$; ...
:: $choice_2$ -> $stat_{2.1}$; $stat_{2.2}$; $stat_{2.3}$; ...
:: ...
:: $choice_n$ -> $stat_{n.1}$; $stat_{n.2}$; $stat_{n.3}$; ...
od;

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do-loops

- With respect to the choices, a do statement behaves in the same way as an if statement
- However, instead of ending the statement at the end of the chosen list of statements, a do-statement repeats the choice selection
- The (always executable) break statement exits a do-loop statement and transfers control to the end of the loop

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goto-statement

- Transfer control to a non-sequential statement
  goto <label >;
- Transfers execution to label
- Each Promela statement might be labeled
- Quite useful in modeling communication protocols

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Interleaving Semantics

- Promela processes execute concurrently
- Non-deterministic scheduling of the processes
- Processes are interleaved
- All statements are atomic; each statement is executed without interleaving with other processes
- Each process may have several different possible actions enabled at each point of execution

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atomic-statement

- Groups statements into an atomic sequence
  atomic{ st_1; st_2; ... st_n }
- all statements are executed in a single step (no interleaving with statements of other processes)
- is executable if st_1 is executable
- if a st_i is blocked, the “atomicity token” is (temporarily) lost and other processes may do a step

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PROMELA Model Basics

- Promela model consists of:
  - type declarations
  - channel declarations
  - variable declarations
  - process declarations

```
mtype = {MSG, ACK};
chan toS;
chan toR;
bool flag;

proctype sender()
{
  …
}
proctype receiver()
{
  …
}
```

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Promela Code

```
mtype = {MSG, ACK};
chan toS = ...
chan toR = ...
bool flag;
proctype Sender() {
 ...
}
proctype Receiver() {
...
}
init {
 ...
 }
```

process body

creates processes

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Promela Model Syntax

- Type declarations
  - mtype, typedefs, constants
- Channel declarations
  - chan ch= [dim] of {type, ...}
  - asynchronous: dim> 0
  - rendez-vous: dim== 0
- Global variable declarations
  - can be accessed by all processes
- Process declarations
  - behaviourof the processes
  - local variables + statements
- [initprocess]
  - initializes variables and starts processes

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Processes

- A process is defined by a proctype definition
- A process executes concurrently with all other processes, independent of speed of behavior
- A process communicates with other processes
  - using global (shared) variables
  - using channels
- There may be several processes of the same type
- Each process has its own local state

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Process

name

```
proctype Sender(chan in; chan out) {
    bit sndB, rcvB;
    do
    :: out ! MSG, sndB ->
            in ? ACK, rcvB;
            if
            :: sndB == rcvB -> sndB = 1-sndB
            :: else -> skip
            fi
    od
}
```

body

formal parameters

local variables

The body consist of a sequence of statements

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Process Example

byte state = 2;

proctype A() { (state == 1) -> state = 3 }

proctype B() { state = state – 1 }

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Process Instantiation

byte state = 2;
proctype A() { (state == 1) -> state = 3 }
proctype B() { state = state – 1 }
init { *run* A(); *run* B() }

- *run* can be used anywhere

Parameter passing

proctype A(byte x; short foo) {
(state == 1) -> state = foo
}
init { run A(1,3); }

- Data arrays or processes cannot be passed

Variable scoping

- Global scope variables are known throughout the model
- Process local scope variables are only known within the process
- Parameters are only known within the process and initialized to passed value

- byte foo, bar, baz;
  proctype A(byte foo) {
  byte bar;
  baz = foo + bar;
}

Races and deadlock

```
byte state = 1;
proctype A() {
   (state == 1) -> state = state + 1
}
proctype B() {
   (state == 1) -> state = state – 1
}
init { run A(); run B() }
```


Atomic Sequence

```
byte state = 1;
proctype A() { atomic {
   (state == 1) -> state = state + 1
}  }
proctype B() { atomic {
   (state == 1) -> state = state – 1
}  }
init() { run A(); run B() }
```


Message Passing

- Convention: first message field often specifies message type (constant)
  - Alternatively send message type followed by list of message fields in braces
  - qname!expr1(expr2,expr3)
  - qname?var1(var2,var3)
- Channel declaration
  - chan qname = [16] of {short}
  - chan qname = [5] of {byte,int,chan,short}
- Sending messages
  - qname!expr
  - qname!expr1,expr2,expr3
- Receiving messages
  - qname?var
  - qname?var1,var2,var3

Message Passing Mismatch

- More parameters sent
  - Extra parameters dropped
- More parameters received
  - Extra parameters undefined
- Fewer parameters sent
  - Extra parameters undefined
- Fewer parameters received
  - Extra parameters dropped

Message Passing Example

```
chan x = [1] of {bool, bool};
chan y = [1] of {bool};

proctype A(bool p, bool q) { x!p,q ; y?p }

proctype B(bool p, bool q) { x?p,q ; y!q }

init { run A(1,2); run B(3,4) }
```


Executability

- Send is executable only when the channel is not full
- Receive is executable only when the channel is not empty
- A channel size reflects the ability of a channel to “store” a message for a future consumer
- len(qname) returns the number of messages currently stored in qname
- If used as a statement it will be unexecutable if the channel is empty

Rendezvous

- Channel of size 0 defines a rendezvous port
- Can be used by two processed for a synchronous handshake
- No queueing
- The first process blocks
- Handshake occurs after the second process arrives

Procedures and Recursion

- Procedures can be modeled as processes
- Even recursive ones
- Return values can be passed back to the calling process via a global variable or a message

Timeouts

```
Proctype watchdog() {
    do
    :: timeout -> guard!reset
    od
}
```

- timeout is a predefined global boolean that is set true when the entire system is deadlocked
- No absolute timing considerations

Processes

- Process are created using the run statement (which returns the process id)
- Processes can be created at any point in the execution (within any process)
- Processes start executing after the run statement.
- Processes can also be created by adding active in front of the proctype declaration
  - Parameters will be initialized to 0

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Processes

- There may be several processes of the same proctype
- Each process has its own local state:
  - process counter(location within the proctype) – contents of the local variables

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Hello World!

```
active proctype Hello( ) {
   printf("Hello process, my pid is: %d\n",_pid);
}
init{
   int lastpid;
   printf("init process, my pidis: %d\n", _pid);
   lastpid= run Hello();
   printf("last pid was: %d\n",lastpid);
 }
```

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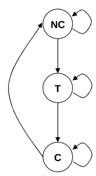
Concurrent Processes

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```



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Message Type Definition

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```

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XSpin Directive (show)

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```

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Process Definition

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```

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Start Execution

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```

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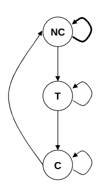
Execution

```
mtype = { NONCRITICAL, TRYING, CRITICAL};
show mtype state[2];
proctype process(int id) {
   beginning:
   noncritical:
        state[id] = NONCRITICAL;
        if
                :: goto noncritical;
                :: true;
        fi;
   trying:
        state[id] = TRYING;
        if
                :: goto trying;
                :: true;
        fi;
   critical:
        state[id] = CRITICAL;
        if
                :: goto critical;
                :: true;
        fi;
        goto beginning;}
init { run process(0); run process(1); }
```



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Enabled Statements

- A statement needs to be enabled for the process to be scheduled.

```
bool a, b;
proctype p1(){
  a = true;
  a & b;
  a = false;
}
proctype p2(){
  b = false;
  a & b;
  b = true;
}
init { a = false; b = false; run p1(); run p2(); }
```

These statements are enabled only if both ***a*** and ***b*** are true.

This statements can never be enabled since *b* is always false.

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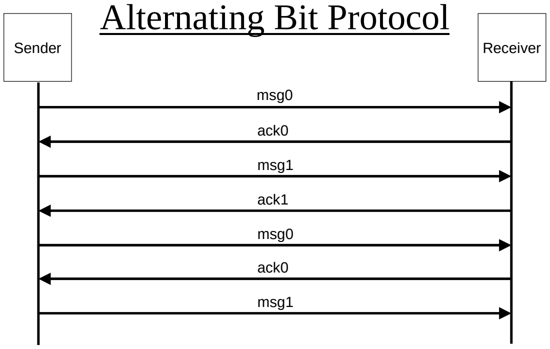
Alternating Bit Protocol



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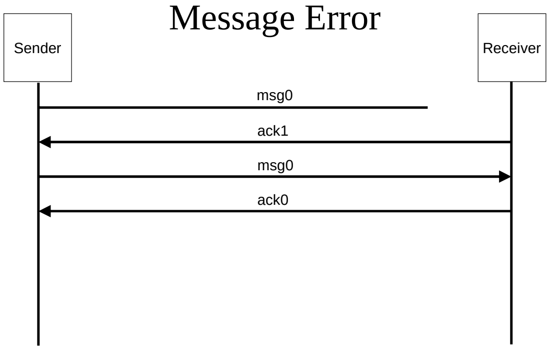
Message Error



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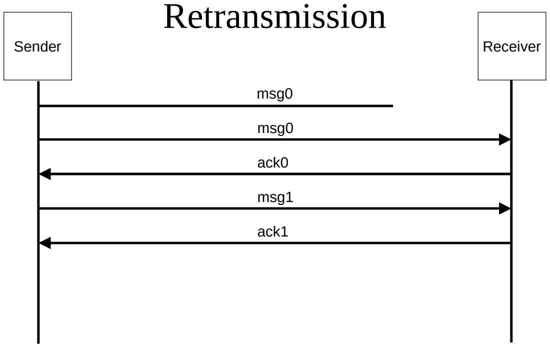
Retransmission



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Message and Channel Definitions

```
mtype = { msg0, msg1, ack0, ack1 }
chan sender = [1] of { mtype };
chan receiver = [1] of { mtype };
```

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Sender Process

```
active proctype Sender(){
  do
  ::
    if
    :: receiver?msg0;
    :: skip
    fi;
    do
    :: sender?ack0 -> break
    :: sender?ack1
    :: timeout ->
        if
        :: receiver!msg0;
        :: skip
        fi;
    od;
```

```
  ::
    if
    :: receiver?msg1;
    :: skip
    fi;
    do
    :: sender?ack1 -> break
    :: sender?ack0
    :: timeout ->
        if
        :: receiver!msg1;
        :: skip
        fi;
    od;
  od;
}
```

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Receiver Process

```
active proctype Receiver(){
  do
  ::
    do
    :: receiver?msg0 -> sender!ack0; break;
    :: receiver?msg1 -> sender!ack1
    od

    do
    :: receiver?msg1 -> sender!ack1; break;
    :: receiver?msg0 -> sender!ack0
    od
  od
}
```

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Lynch's Protocol

- … a reasonable looking but inadequate scheme …
- Full duplex operation on two channels
- If previous reception was error-free, the next message on reverse channel contains ACK, otherwise NAK
- If previous reception carried NAK or was in error, retransmit, other wise send new message

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Lynch's Protocol Problems

- Cannot send ACK/NAK without data – need to send fill
- Startup not defined – send error to start process
- Receiver cannot tell whether transmission is retransmission of properly received data or new data

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