University of Glasgow | School of Computing Science

Message Passing (2)

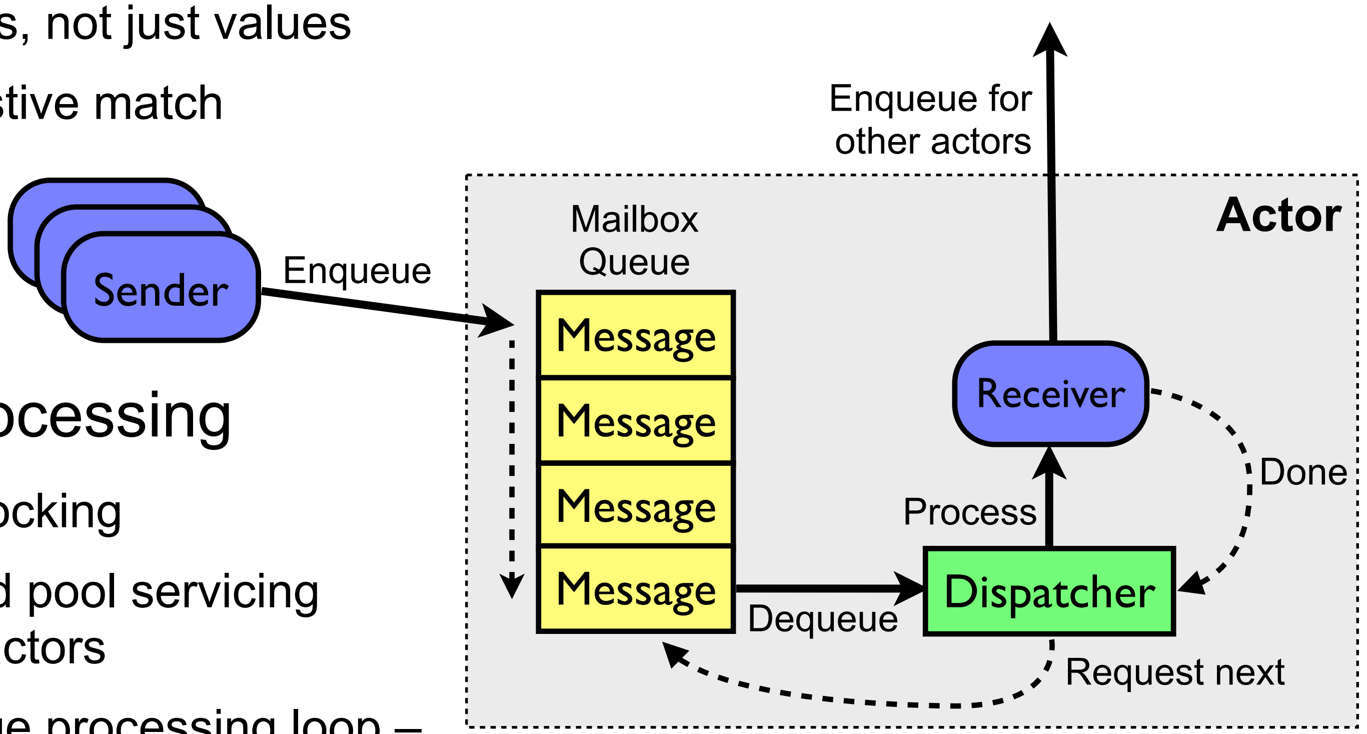
Advanced Operating Systems
Lecture 12

Lecture Outline

- Message handling
- Pattern matching and state machines
- Remote actors
- System upgrade and evolution
- Error handling in message passing systems

Message Handling

- Receivers pattern match against messages
  - Match against message types, not just values
  - Type system ensures exhaustive match



- Messages queued for processing
  - Enqueue operation is non-blocking
  - Dispatcher manages a thread pool servicing receiver components of the actors
  - Receivers operate in message processing loop – single-threaded, with no concern for concurrency
  - Sent messages enqueued for processing by other actors

Use Immutable Messages

- Runtime ensures a receiver processes messages sequentially, but it is part of a concurrent system
  - Sending and receiving actors may run concurrently
  - Message data is shared between sender and receiver
- Important to ensure message data is immutable
  - Or, at least, never mutated once the message has been sent
  - Erlang ensures this in the language → races due to shared message data not possible
  - Scala+Akka requires programmer discipline → potential race conditions if message data modified after message sent

Ownership Transfer – Linear Types

- Alternative to immutability: type system ensures ownership of message data is transferred
- A variable with *linear* type may be used only once; it goes out of scope after use
- Potentially useful when sharing mutable data between threads
  - Implement sharing via a `sendMessage` function that takes a linear type for the data to be shared
  - Message data consumed by the `sendMessage` function and the receiver, and so can't be used by the sender once the message has been sent
  - Data doesn't need to be locked, since it can only be used by one thread at once
- The compiler enforces that linear data is not shared between threads

```
linear int x = 5;
int y = x;
int z = x + 1; // error
```

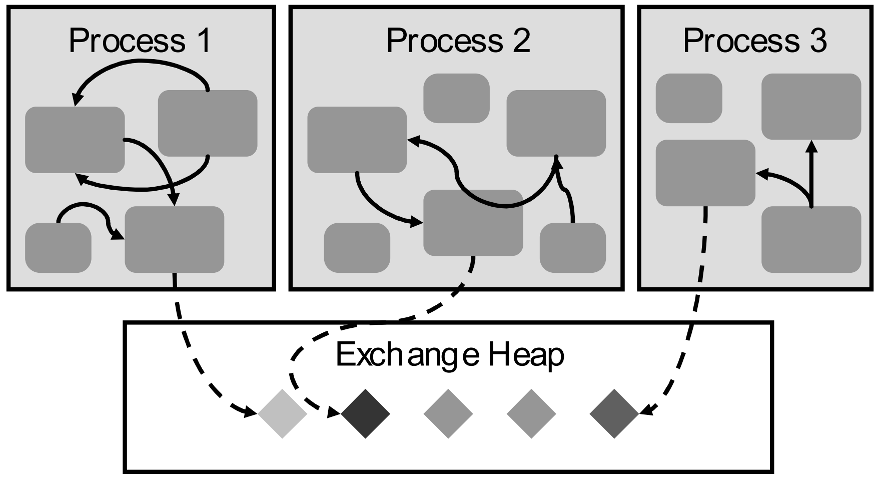
```
linear int x = 5;
linear int y = foo(x);
sendMessage(dest, y);
int z = y + 1  // error
```

R. Ennals *et al*, Linear Types for Packet Processing, Proceedings of the European Symposium on Programming, Barcelona, March 2004. http://www.cl.cam.ac.uk/~am21/papers/esop04.pdf

Efficiency of Message Passing

- Assuming immutable message or linear types, message passing has an efficient implementation
  - Copy message data in distributed systems
  - Pass pointer to data in shared memory systems
  - Neither case needs to consider shared access to message data

- Garbage collected systems often allocate messages from a shared *exchange heap*
  - Collected separately from per-process heaps
  - Expensive to collect, since data in exchange heap owned by multiple threads – need synchronisation
  - Per-process heaps can be collected independently and concurrently – ensures good performance

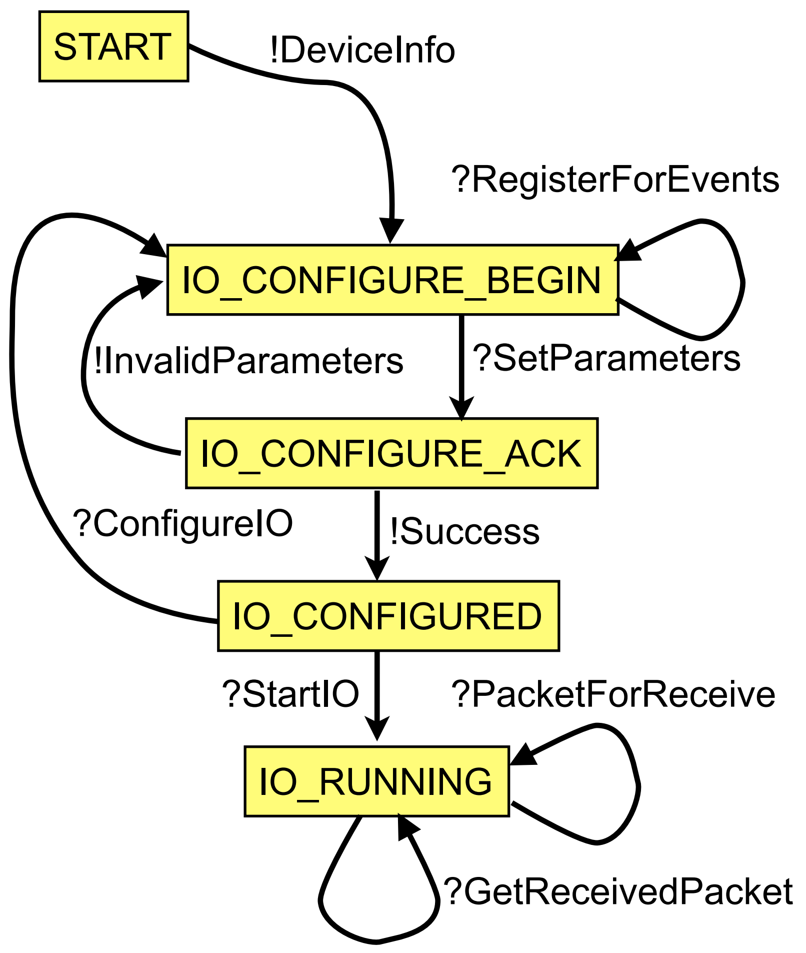


[G. Hunt *et al.*, Sealing OS processes to improve dependability and safety. In Proc. EuroSys 2007, Lisbon, Portugal. DOI 10.1145/1272996.1273032]

Patterns and State Machines

- A set of *states* and *transitions* triggered by/causing events forms a state machine
    - An actor comprises a set of events – *messages* – and various states – *functions* – that process events as they are received
    - Pattern matching operation dictates response to different types of events in each state
- Discussed the idea for device driver robustness – but natural for message passing actors
    - Message passing code naturally contains a formalised description of the state machine

Example: Singularity State Machines



```
contract NicDevice {
  out message DeviceInfo(...);
  in  message RegisterForEvents(NicEvents.Exp:READY
  c);
  in  message SetParameters(...);
  out message InvalidParameters(...);
  out message Success();
  in  message StartIO();
  in  message ConfigureIO();
  in  message PacketForReceive(byte[] in ExHeap p);
  out message BadPacketSize(byte[] in ExHeap p, int
  m);
  in  message GetReceivedPacket();
  out message ReceivedPacket(Packet * in ExHeap p);
  out message NoPacket();

  state START: one {
    DeviceInfo! → IO_CONFIGURE_BEGIN;
  }
  state IO_CONFIGURE_BEGIN: one {
    RegisterForEvents? →
      SetParameters? → IO_CONFIGURE_ACK;
  }
  state IO_CONFIGURE_ACK: one {
    InvalidParameters! → IO_CONFIGURE_BEGIN;
    Success! → IO_CONFIGURED;
  }
  state IO_CONFIGURED: one {
    StartIO? → IO_RUNNING;
    ConfigureIO? → IO_CONFIGURE_BEGIN;
  }
  state IO_RUNNING: one {
    PacketForReceive? → (Success! or BadPacketSize!)
      → IO_RUNNING;
    GetReceivedPacket? → (ReceivedPacket! or
    NoPacket!)
      → IO_RUNNING;
    ...
  }
}
```

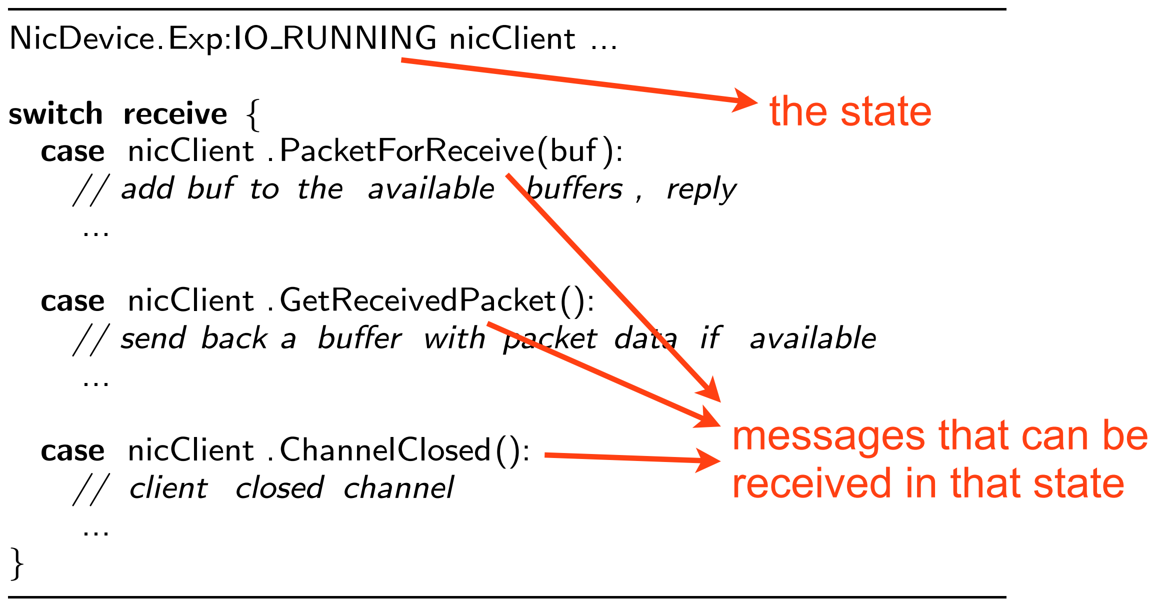
Listing 1. Contract to access a network device driver.

[G. Hunt and J. Larus. Singularity: Rethinking the software stack. ACM SIGOPS OS Review, 41(2), Apr. 2007. DOI 10.1145/1243418.1243424]

- Singularity devices drivers are an example formal state machine in a message passing system

Example: Singularity State Machines

- Contract defines the state machine – essentially an abstract type
- Implementation uses pattern matching against received messages
  - A function for each state
  - Each function switches based on the type of the message object received
- Compiler checks that `switch receive` statements handle all messages defined by the contract
  - Blocks in the switch receive statement must end with a transfer of control, to a function representing a new state or to itself, allowing compiler to check transitions
- Messages are immutable messages sent between actors



```
NicDevice.Exp:IO_RUNNING nicClient ...

switch receive {
  case nicClient.PacketForReceive(buf):
    // add buf to the available buffers, reply
    ...

  case nicClient.GetReceivedPacket():
    // send back a buffer with packet data if available
    ...

  case nicClient.ChannelClosed():
    // client closed channel
    ...
}
```

the state
messages that can be received in that state

[M. Fähndrich *et al.* Language support for fast and reliable message-based communication in Singularity OS. Proc. EuroSys 2006. DOI 10.1145/1218063.1217953]

Modelling State Machine Correctness

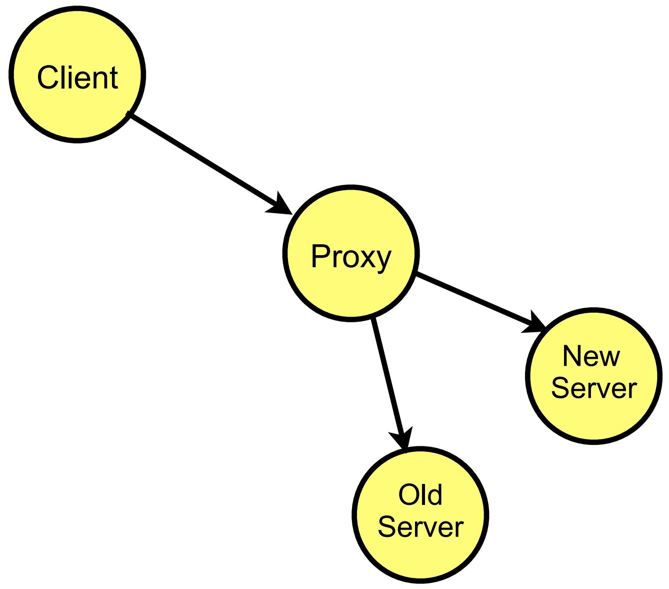
- If state machine is formally defined in code, we can begin to verify it
  - Check that the code implements the defined state machine
  - Check the state machine itself
    - Validate that the driver cannot deadlock
    - Validate that certain states can be reached
    - …
    - [discussed further in the MRS4 course]
  - Code can readily be translated into (fragments of) a Promela model, for example, suitable for verification with a model checker such as SPIN

Remote Actors

- Two approaches to identifying message receiver:
  - Receiver is anonymous, but bound to named channel
  - Receiver is explicitly named as message destination
- Both required a *named* destination for messages
  - Trivial to make this an opaque URL for the application, but meaningful to the runtime – can identify remote actors
  - Since messages either immutable or linearly typed, data can be safely copied across the network
- Most message passing systems allow transparent use of remote actors

System Upgrade and Evolution

- Message passing allows for easy system upgrade
  - Rather than passing messages directly to server, pass via proxy
  - Proxy can load a new version of the server and redirect messages, without disrupting existing clients
  - Eventually, all clients are talking to the new server; old server is garbage collected
- Allows for gradual transparent system upgrade
  - A running system can be upgraded without disrupting service



- Use of dynamic typing can make the upgrade easier
  - New components of the system can generate additional messages, which are ignored by old components
  - Supervisor hierarchy allows system to notice if components fail, and fallback to known good version
  - Backwards compatible extensions are simple to add in this manner

Error Handling

- The system is massively concurrent – errors in one part can be handled elsewhere
- Error handling philosophy in Erlang:
  - Let some other process do the error recovery
  - If you can’t do what you want to do, die
  - Let it crash
  - Do not program defensively

J. Armstrong, “Making reliable distributed systems in the presence of software errors”, PhD thesis, KTH, Stockholm, December 2003, http://www.sics.se/~joe/thesis/armstrong_thesis_2003.pdf

- Be concerned with the overall system reliability, not the reliability of any one component

Let It Crash

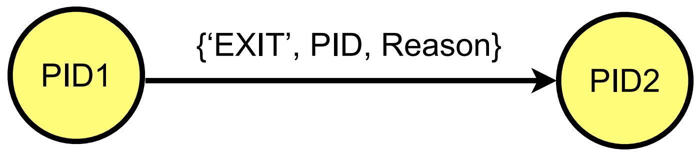
- In a single-process system, that process must be responsible for handling errors
    - If the single process fails, then the entire application has failed
- In a multi-process system, each individual process is less precious – it's just one of many
    - Changes the philosophy of error handling
    - A process which encounters a problem should *not* try to handle that problem – instead, fail loudly, cleanly, and quickly "let it crash"
    - Let another process cleanup and deal with the problem

    - Processes become much simpler, since they're not cluttered with error handling code

Remote Error Handling

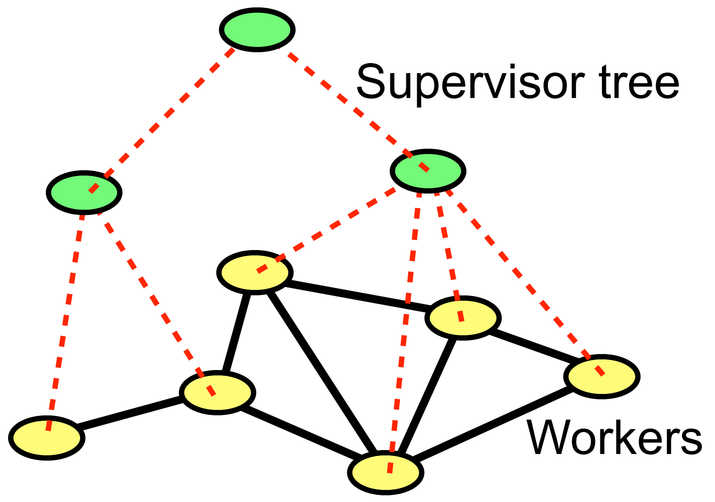
- How to handle errors in a concurrent distributed system?
  - Isolate the problem, let an unaffected process be responsible for recovery
  - Don’t trust the faulty component
  - Analogy to hardware fault tolerance

- Processes are linked, and the runtime is set to trap errors and send a message to the linked process on failure
  - e.g., process PID2 has requested notification of failure of PID1; runtime sends an “EXIT” message on failure, to tell PID2 that PID1 failed, and why
  - Process PID2 then restarts PID1, and any other dependent processes



Supervision Hierarchies

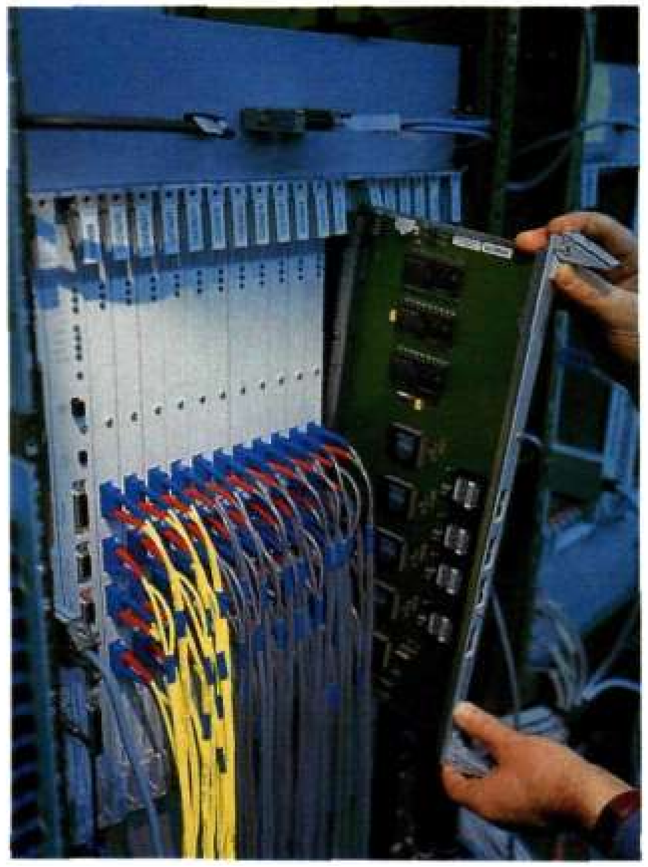
- Organise problems into tree-structured groups of processes, letting the higher nodes in the tree monitor and correct errors in the lower nodes
  - Supervision trees are trees of *supervisors* – processes that monitor other processes in the system
  - Supervisors monitor *workers* – which perform tasks – or other supervisors
  - Workers are instances of *behaviours* – processes whose operation is characterised by callback functions (i.e., the Erlang equivalent of objects)
    - E.g., server, event handler, finite state machine, supervisor, application

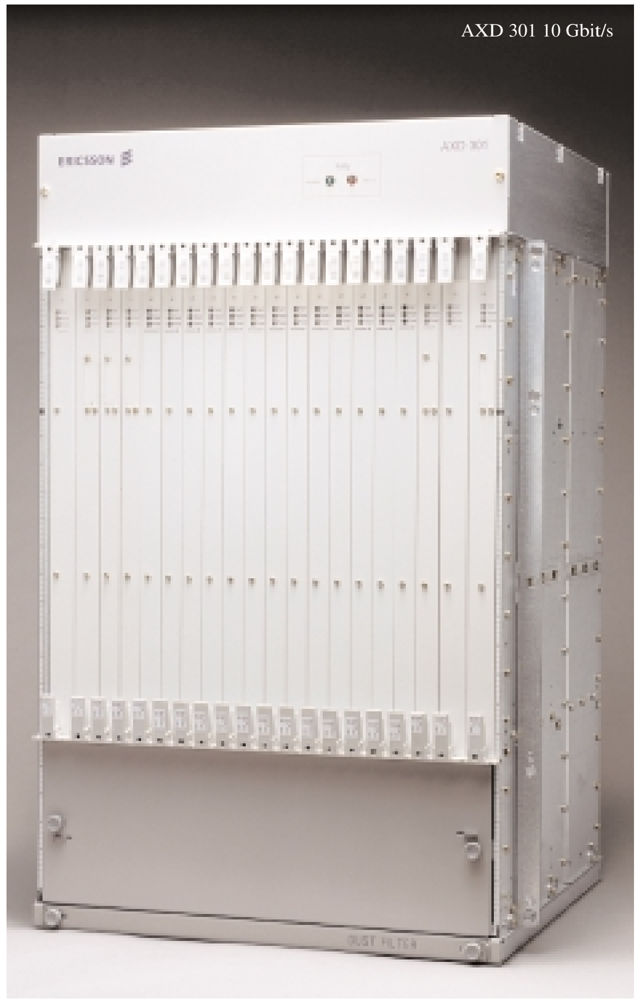


- Abstract common behaviours into objects
- Workers managed by supervisor processes that restart them in the case of failure, or otherwise handle errors

Robustness of Erlang Systems

- Example: Ericsson AXD301 ATM switch
  - Dimensioned to handle ~50,000 simultaneous flows with ~120 in setup or teardown phase at any one time
  - Processes ATM traffic at 160 gigabits per second (16 x 10Gbps links)
  - ~1.1 million lines of Erlang in 2248 Erlang modules
  - ~40 programmers





Images from: S. Blau, J. Rooth, J. Axell, F. Hellstrand, M. Buhrgard, T. Westin, and G. Wicklund, "AXD 301: A new generation ATM switching system", Ericsson Review, 1998.

Robustness of Erlang Systems

- Example: Ericsson AXD301 ATM switch
  - 99.9999999% reliable in real-world deployment on 11 routers at a major Ericsson customer (~0.5 seconds downtime per year)
  - Yet, failures do occur, and are handled by the supervision hierarchy and distributed error recovery
  - Employs restart-and-recover semantics per-connection
  - Failures may disrupts one connection out of tens-of-thousands – assumes failures are transient; system doesn’t employ multi-version programming

Discussion

- The let-it-crash philosophy changes error handling, moving it out-of-process
- There are a few compelling case studies to show it can work well in some domains

- Is this a generally appropriate error-handling tool?