ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Network Protocol Design and Evaluation

06 - Design Techniques

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Overview

- **In the last lectures:**
  - Specification and Verification

- **In this part:**
  - Design and implementation techniques

Design Decisions

- Communication protocols are subject to resource constraints.
- A communication protocol can be part of a larger system (protocol stack, application), which adds additional constraints
- Resource constraints might be dependent or conflicting, and meeting all constraints is not always possible.
- Design techniques help to find trade-offs.

Resource constraints

- System design is constrained by resource limitations.
- **Basic resource constraints**:
  - Time (response time, throughput)
  - Space (memory, buffer capacity, bandwidth)
  - Computation
  - Labor
  - Money
- **Social constraints**
  - Standards
  - Market requirements

[Keshav 1997]

Bottlenecks

- Identify the most constrained resource, the **binding constraint** or **bottleneck**
- Removing this bottleneck can open other bottlenecks
- Goal: Balancing the whole system
- This is often infeasible. However, there are some design techniques to find trade-offs
- Methodology: Start with identifying constraints, then trade-off one resource for another to maximize utility.

[Keshav 1997]

Multiplexing

- Resource sharing
- Trade-off: Time and space vs. money
- Examples:
  - One server processes client requests simultaneously instead of setting up more servers.
  - If the communication medium is the bottleneck, it can be divided by frequency, or time slots to allow simultaneous communication between different communication partners.

[Keshav 1997]

Parallelism (1)

- Splitting tasks into independent subtasks
- Trade-off: computation vs. time
- Examples:
  - Web browsers download linked images from webpages in parallel.
  - Layers of a protocol stack can process their packets in parallel.

[Keshav 1997]

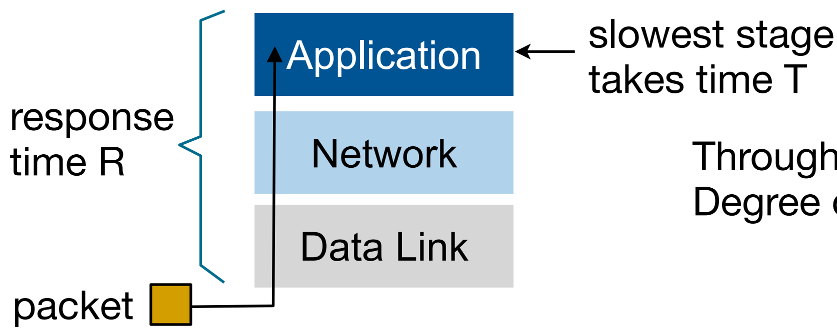
Parallelism (2)

- **Degree of Parallelism**

  *throughput * response time = degree of parallelism*

- Response time = mean time to complete a task [sec/task]
- Throughput = mean number of tasks that can be completed within a unit of time [tasks/sec].

Example: Packet processing



Throughput = 1/T
Degree of Parallelism = R/T

[Keshav 1997]

Batching (1)

- Group tasks together to level the overhead
- Trade-off: Response time vs. throughput
- Example: A remote login application accumulates typed characters and sends them in a batch instead of transmitting each character in a separate packet.
- Batching is only efficient, if the overhead for *N* tasks is smaller than *N* times the overhead for a single task

[Keshav 1997]

Batching (2)

- Worst-case response time for a task: T + O
- Worst-case throughput: 1/(T+O)
- Assume the overhead O’ for a batch of N tasks is smaller than N * O.
- Worst-case response time for the batch: A + N * T + O’ where A is the time for accumulating the tasks
- Worst-case throughput: N/(N * T + O’) = 1/(T + O’/N) (if we assume that the system can process other tasks during accumulation)

[Keshav 1997]

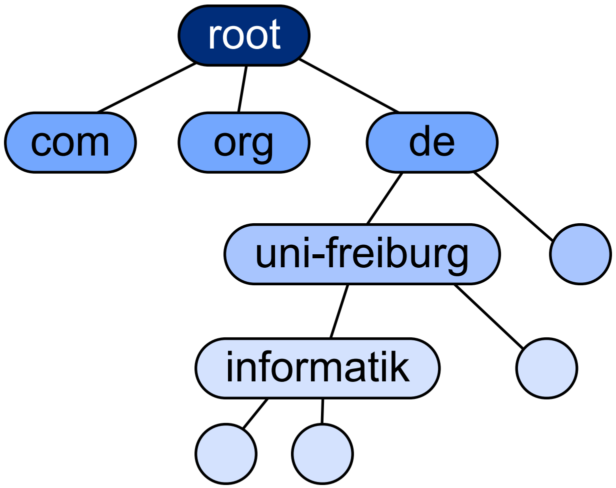
Locality

- Exploiting locality means that data that was accessed often will be kept in fast memory (caching).
- Trade-off: Space vs. time
- Example: During file transfer the sender splits a file into several packets. If it keeps the unacknowledged packets in fast memory, it can retransmit them without generating them again.

[Keshav 1997]

Hierarchy

- Decomposition of a system into smaller subsystems
- Increases scalability
- Example:
  - Hierarchical Addressing (IP Addresses)
  - Internet Domain Name System



DNS: The name space is partitioned into *domains*. Each domain has an associated DNS server.

[Keshav 1997]

Binding and Indirection

- Binding: Referring from an abstraction to an instance
- Indirection: Using the abstraction and dereferencing it automatically
- Examples:
  - eMail aliases
  - In a cellular telephone system, a user may move from one cell to another, but remains reachable by the same number. The system binds the user to a particular cell while the switches use indirection.

[Keshav 1997]

Virtualization

- Combination of multiplexing and indirection
- Allows sharing a resource as if it could be used exclusively
- Examples:
  - Virtual Private Network
  - Virtual Modem

[Keshav 1997]

Randomization

- Powerful tool to increase robustness
- Examples:
  - Ethernet channel access: After a packet collision, a jam signal is sent to make sure that all participants are aware of the collision. Then the packet is retransmitted after R time slots, where R is chosen randomly out of $\{0,1,...,2^j-1\}$ and $j = \min\{i,10\}$.
    Choosing the retransmission time deterministically would lead to repeated collisions.
  - A similar backoff strategy is used in WLAN.

[Keshav 1997]

Soft State

- State: information that determines future behaviour
- State can be stored in the network (call state in a circuit switched telephone network), it has to be created and removed.
- Incomplete removal leads to problems (e.g. if resources remain reserved). Reacting to all kinds of errors and abnormal terminations can lead to a complicated design.
- **Soft state** can be a solution: State is not persistent, it has to be refreshed (requires bandwidth) and will be removed after timeout; i.e. there is an automatic cleanup after failure.

[Keshav 1997]

Exchaning State Explicitly

- Communicating entities often need to exchange state.
- It is advisable to do this explicitly if possible.
- Example: A file transfer protocol splits packets into segments and transmits it to the receiver. How can the receiver detect packet loss?
    - Implicitly by looking into the payload (requires application layer knowledge)
    - Explicitly by assigning sequence numbers to the packets by the sender.

[Keshav 1997]

Hysteresis

- If a system state depends on a variable value, small fluctuations of this value around the threshold result in frequent state changes. This may lead to undesired behaviour.
- Hysteresis means to apply a state-dependent threshold to prevent oscillations.
- Example: Cellular phones are connected to the base station with the best signal quality. As a handover from one cell to another is an expensive operation, it is only performed if the *increase* in signal strength is above a certain threshold.

[Keshav 1997]

Separating data and control

- Separating per-path or per-connection actions and per-packet actions.
- Can increase throughput, but requires state information in the network (less robust, cf. ‘distributed state vs. fate sharing’, Chapter 2)
- Example: In *Virtual Circuits* control packets are to set up a connection. Data packets carry only a virtual circuit identifier.

[Keshav 1997]

Optimizing the common case

- Many systems obey Pareto's law or the 80/20 rule:
  - Only 20% of the code is used in 80% of the time.
- Optimizing these 20% improves the overall performance
- Example: In a certain protocol, most packets to be processed are of the same type. Thus, we should check for this common case first and optimize the code for processing it.

[Keshav 1997]

Extensibility

- Design should allow for future extensions
- Example:
  - The IP packet header contains a version number that indicates the format of the rest of the header.
  - Extension fields in ASN.1 (see Chapter 4.III)

[Keshav 1997]

Overview

What you want	**What you can buy**	**What you have to pay** (other than labour)
Throughput	Parallelism Batching	Computation Larger response time
Response time	Caching (exploiting locality) Optimizing the common case	Space
Reduce bandwidth consumption	Separating data and control	Lack of robustness
Access to a shared resource	Multiplexing Virtualization	Shared bandwidth Control overhead
Robustness	Randomization Soft state Hysteresis	Control overhead

Architectural Considerations

- Architecture: Decomposition into functional modules.
- Common approach: **Protocol Layering**
  - Each protocol layer defines a level of abstraction
  - Design objective: Integration of related functions with well-defined interfaces
  - cf. Chapter 2, “Modularity”
- Alternative Approach: **Integrated Layer Processing (ILP)**
  - Processing of data in an integrated application layer
  - Goal: Minimizing data access and copy operations (especially in the upper layers)

Integrated Layer Processing (1)

- Motivation: Applications that exchange large amounts of data loose performance when copying data between layers.
- Data is processed sequentially in layered architectures.
- *Data manipulation* vs. *Transfer control*: Memory access and data manipulation can require more computation than controlling the communication.
- Thus, data manipulation operations should be integrated in the application layer.

[D. Clark, D. Tennenhouse: “Architectural considerations for a new generation of protocols”, Computer Communication Review, 20(4), 1990]

Manipulation vs. Control

bottleneck

Layer	Data manipulation	Transfer control
Application	copying to appl. address space	
Presentation	encryption, formatting	
Session		
Transport	buffering for retransmission	congestion control, ACKs detection of transmission problems
Network		
Data Link	error detection and correction, buffering	flow control, framing, ACKs
Physical	network access	Multiplexing

[D. Clark, D. Tennenhouse: “Architectural considerations for a new generation of protocols”, Computer Communication Review, 20(4), 1990]

Integrated Layer Processing (2)

ILP	Data manipulation
Application	Integrated Application Layer
Presentation	
Session	
Transport	simple datagram protocol, e.g. UDP
Network	
Data Link	
Physical	

Example: ILP and Internet Protocols

Integrated Layer Processing (3)

- **ILP Principles:**
  - The application deals with out-of-order transmission or loss of data. It triggers retransmissions.
  - The application splits data into data units (rather than letting the transport layer do the segmentation)
  - Repeated data processing is avoided by using one main processing loop
- ILP targets mainly the avoidance of presentation layer processing

[D. Clark, D. Tennenhouse: “Architectural considerations for a new generation of protocols”, Computer Communication Review, 20(4), 1990]

Application Level Framing

- The application splits the data into Application Data Units (ADUs).
- Requirements:
  - The sender can label each ADU such that the receiver can determine its place in the sequence of ADUs.
  - The application must be able to process ADUs out of order. Their size has to be defined accordingly.

[D. Clark, D. Tennenhouse: “Architectural considerations for a new generation of protocols”, Computer Communication Review, 20(4), 1990]

Benefits and Limitations of ILP

- **Advantages**
  - No additional presentation conversion
  - Permits efficient implementation of data manipulation

- **Disadvantages**
  - The principles of layering are abandoned
  - ILP implementations can lead to various protocol stack variants (with customized implementations)
    - Losing flexibility and maintainability

[D. Clark, D. Tennenhouse: “Architectural considerations for a new generation of protocols”, Computer Communication Review, 20(4), 1990]

Protocol Building Blocks

- Basic methods that most protocols implement or rely on:
  - **Error control**: Detection and correction of transmission errors
  - **Flow Control**: Adaption of the transmission rate to the service rate of the receiver
    (Related: congestion control)
- Both exist as point-to-point or end-to-end mechanisms (in multihop networks)
- They are usually implemented in the link layer and in the transport layer

Error control

- **Error control**
  - Error detection (e.g. CRC)
  - Error correction
    - Forward Error Correction
    - Backward Error Correction (ARQ schemes)

- see Lecture “Systeme II” for more details.

Types of Errors

- **Bit Errors**
  - Corruption of single bits
  - due to noise, loss of synchronization, etc.
  - Error control typically on the link layer

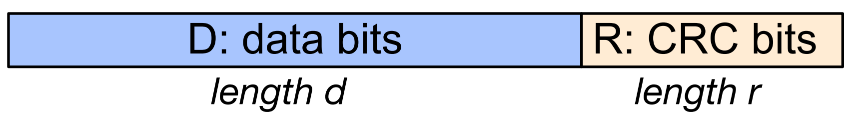
- **Packet Errors**
  - Loss, duplication and re-ordering
  - Error control typically on the transport layer

Error Control

- **Bit error detection and correction**
  - Basic idea: adding redundant information, e.g. parity codes, hamming codes, CRC
- **Packet error detection and correction**
  - Detection by sequence numbers or handshakes
  - Retransmission
  - Forward Error Correction

Cyclic Redundancy Check (CRC)

- View data bits D as a binary number
- Choose r+1 bit pattern G (generator)
- Idea: choose r CRC bits, R, such that
  - <D,R> exactly divisible by G (modulo 2)
  - receiver knows G, divides <D,R> by G. If non-zero remainder: error detected!



$$D * 2^r \text{ XOR } R$$

- widely used in practice (Ethernet, 802.11 WiFi, ATM)

[Kurose, Ross, 2007]

CRC Example

Data: 1101011011

Generator: 10011

Coding:

```
11010110110000
10011
-----
 10011
 10011
 -----
  000010110
      10011
      -----
       010100
        10011
        -----
          1110  (R)
```

Decoding:

```
11010110111110
10011
-----
 10011
 10011
 -----
  000010111
      10011
      -----
       010011
        10011
        -----
         00000
```

Decoding with error:

```
11110110111110
10011
-----
 11011
 10011
 -----
  10001
  10011
  -----
   0010011
     10011
     -----
      00001110
```

CRC

- **Detects**
  - all single bit errors
  - almost all 2-bit errors
  - any odd number of errors
  - all bursts up to M, where generator length is M
  - longer bursts with probability 2^{-M}

- **Advantage:**
  - Can be checked on-the-fly with a shift register

[Keshav 1997]

Types of packet errors (1)

- **Loss**
  - due to uncorrectable bit errors
  - due to buffer overflow
    - especially with bursty traffic
    - loss rate depends on burstiness, load, and buffer size
  - fragmented packets can lead to error multiplication
    - the longer the packet, the more the loss

[Keshav 1997]

Types of packet errors (2)

- **Duplication**
  - The same packet is received twice
    (usually due to retransmission)
- **Insertion**
  - Packet from some other conversation received
    - header corruption
- **Reordering**
  - Packets received in wrong order
    - usually due to retransmission
    - some routers also re-order

[Keshav 1997]

Packet error detection and correction

- **Automatic Repeat reQuest (ARQ)**
  - Detection
    - Sequence numbers
    - Timeouts
  - Correction
    - Retransmission

- **Basic ARQ schemes:**
  - Stop-and-Wait, Go-back-N, Selective Repeat

[Keshav 1997]

Sequence numbers

- Sequence numbers are added to each packet header
- Incremented for new (non-retransmitted) packets
- Sequence space
  - set of all possible sequence numbers
  - for a 3-bit seq #, space is {0,1,2,3,4,5,6,7}
- Sequence numbers should be long enough so that the sender does not confuse sequence numbers on acks

[Keshav 1997]

Using sequence numbers

- **Loss**
  - Gap in sequence space allows receiver to detect loss
    - e.g. received 0,1,2,5,6,7 => lost 3,4
  - ACKs carry cumulative sequence number
  - Redundant information
  - If no ACK for a while, sender suspects loss
- **Reordering**
- **Duplication**
- **Insertion**
  - If the received seq. number is “very different” from what is expected

[Keshav 1997]

Loss detection

- **By the receiver**, from a gap in sequence space
  - send an NACK to the sender?
  - Disadvantages of NACKs:
    - Extra load in case of loss
    - Moves retransmission problem to the receiver
- **By the sender**, by looking at cumulative ACKs, and after timeout
  - requires to choose timeout interval

[Keshav 1997]

Timeouts

- **Retransmission after timeout**:
  - Set timer on sending a packet
  - If timer goes off, and no ACK received, then retransmit
- **How to choose timeout value?**
  - Intuitively, we expect a reply in about one round trip time (RTT)
  - Static scheme: RTT known a priori
  - Dynamic scheme: RTT measurement

[Keshav 1997]

Retransmissions

- Sender detects loss on timeout
- Which packets to retransmit?
  - Depends on the chosen scheme
  - Typically based on the concept of the **error control window**

[Keshav 1997]

Stop-and-Wait ARQ

- After each data packet wait for an ACK.
- Retransmit after timeout.

- Simple scheme, easy implementation
- Can be used for flow control as well.

[Keshav 1997]

Error control window

- Set of packets sent, but not acked

1 2 **3 4 5 6 7** 8 9	(original window)
1 2 3 **4 5 6 7** 8 9	(recv ack for 3)
1 2 3 **4 5 6 7 8** 9	(send 8)

- May want to restrict max size = window size
- Sender blocked until ack comes back

[Keshav 1997]

Go-back-N

- On a timeout, retransmit the entire error control window
- Receiver only accepts in-order packets

- Advantages:
  - simple, no buffer at receiver
- Disadvantages:
  - can add to congestion, wastes bandwidth

- used in TCP

[Keshav 1997]

Selective Repeat

- Find out which packets were lost, then only retransmit them
- **How to find lost packets?**
  - Each ACK has a bitmap of received packets
    - e.g. cum_ack = 5, bitmap = 101
      => received 5 and 7, but not 6
    - wastes header space
  - Sender periodically asks receiver for bitmap
  - **Fast retransmit**
    - If sender gets the same cumulative ACK repeatedly
    - then retransmit packet with number = cum_ack + 1

[Keshav 1997]

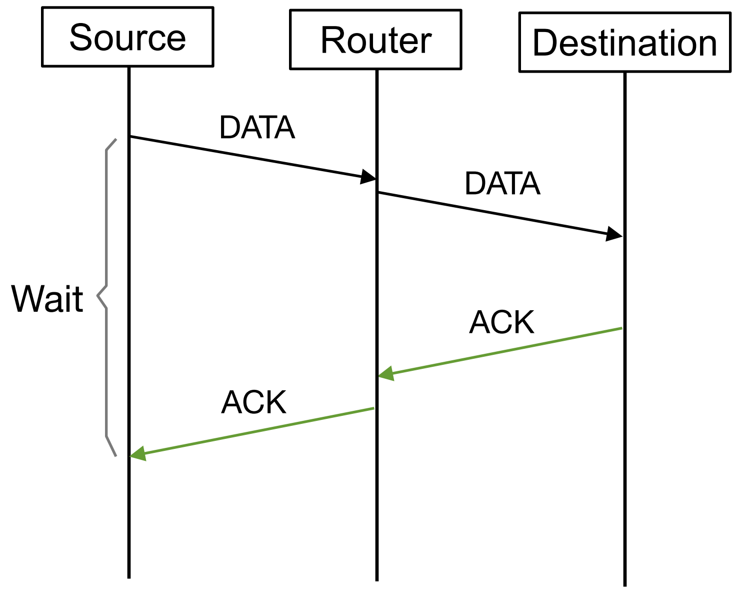
Flow control

- **Open-loop flow control**
  - Description of the traffic by the source upon connection establishment
  - Resource reservation
- **Closed-loop flow control**
  - Dynamic adaption upon feedback
- There are also combined (hybrid) schemes

- see Lecture “Systeme II” for more details.

Closed-loop Flow Control

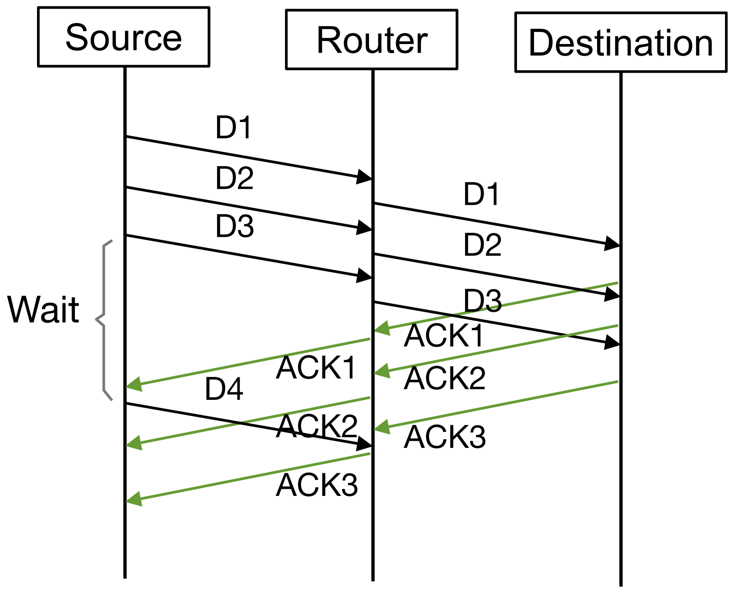
- **Example 1:** Stop-and-Wait Protocol



[Keshav 1997]

Closed-loop Flow Control

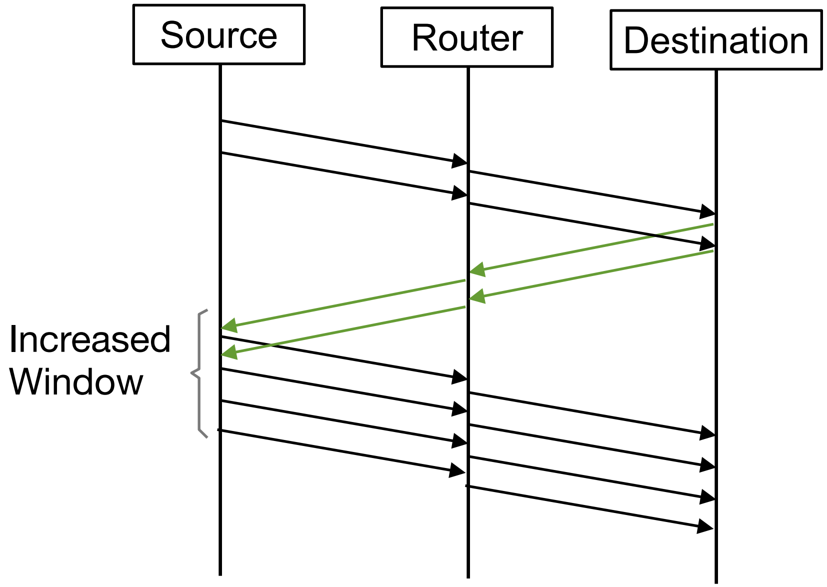
- **Example 2:** Static-window



[Keshav 1997]

Closed-loop Flow Control

- **Transport layer congestion control** in the Internet:
  - Adaptive window size: In the absence of loss, the window is increased, on loss the size is reduced using the AIMD policy. (TCP-Tahoe and TCP-Reno)



[Keshav 1997]

Implementation Techniques

- Prococol behaviour is modeled by extended finite state machines.
- Standard techniques to transform state machine diagrams or state transition tables into code (cf. Chapter 4.I):
  - Nested switch/case
  - Table-driven
  - State design pattern
- Code generators available for UML/SDL state machines
- Various libraries available that support state transition tables or state machine generation

Nested switch/case

```
enum State {q0, q1, q2, ...};
enum Event {e1, e2, ...};

static State s = q0;

void handle(Event e)
{
  switch(s)
  {
  case q0:
    switch(e)
    {
    case e1:
      s = q1;
    break;
    case e2:
      s = q2;
    break;
    [...]
    }
  break;

  case q1:
    switch(e)
    {
    case e1:
      s = q2;
    break;
    case e2:
      s = q0;
    break;
    [...]
    }
  break;

  case q2:
    switch(e)
    {
    case e1:
      s = q0;
    break;
    case e2:
      s = q1;
    break;
    [...]
    }
  break;
  [...]
  }
}
```

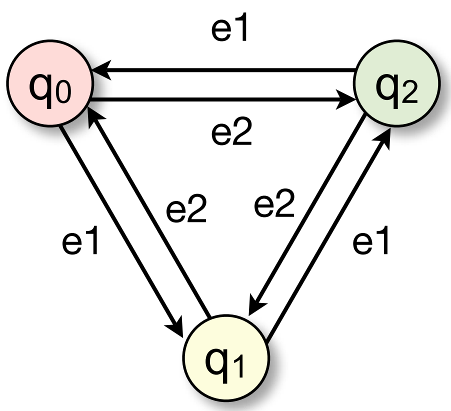


Table-driven Implementation (1)

- Implementation of a state transition table as a two-dimensional array (mapping states and events to next states).

```
enum State {s0, s1, s2};
enum Event {e1, e2};

transition[s2+1][e2+1]  =
{
    {s1, s2},
    {s2, s0},
    {s0, s1},
};
```

- The next state can be derived as follows:

```
State changeState(State s, Event e) {
  return transition[s][e];
}
```

[Wagner et al: “Modeling Software with Finite State Machines: A Practical Approach”, Auerbach Publications, 2006]

Table-driven Implementation (2)

- Switch/case solution for a Mealy machine (transitions have events and actions)

```
switch (state) {
  case state_0:
    eventHandler_0(event);
    break;
  ...
  case state_N:
    eventHandler_N(event);
    break;
  default:
    error(“unexpected state”);
}
state =
  nextState(state,event);
```

this should actually be obsolete! → default:

```
void eventHandler_0(Event e) {
  switch(e) {
    case event_0:
      executeAction_0_0;
      break;
    ...
    case event_M:
      executeAction_0_M;
      break;
    default:
      error(“unexpected event”);
  }
}
```

[Wagner et al: “Modeling Software with Finite State Machines: A Practical Approach”, Auerbach Publications, 2006]

Table-driven Implementation (3)

- Switch/case solution for a Moore machine (transitions have only events, states have entry actions)

```
next_state =
nextState(state,event);

if (state != next_state) {
  state = next_state;
  executeEntryAction(state);
}
```

```
void executeEntryAction() {
  case state_0:
    executeAction_0;
    break;

  ...

  case state_N:
    executeAction_N;
    break;
  default:
    error("unexpected state");
}
```

[Wagner et al: "Modeling Software with Finite State Machines:
A Practical Approach", Auerbach Publications, 2006]

Variant with Function Pointers

- Table-driven solution with function pointers:

```
enum State {s0, s1, s2};
enum Event {e1, e2};

typedef void (*fptr)();

typedef struct StateEntry {
  State nextState;
  fptr action;
}

transition[s2+1][e2+1]  =
{
    { {s1,a11}, {s2,a22},
    { {s2,a12}, {s0,a20} ,
    { {s0,a10}, {s1,a21} },
};
```

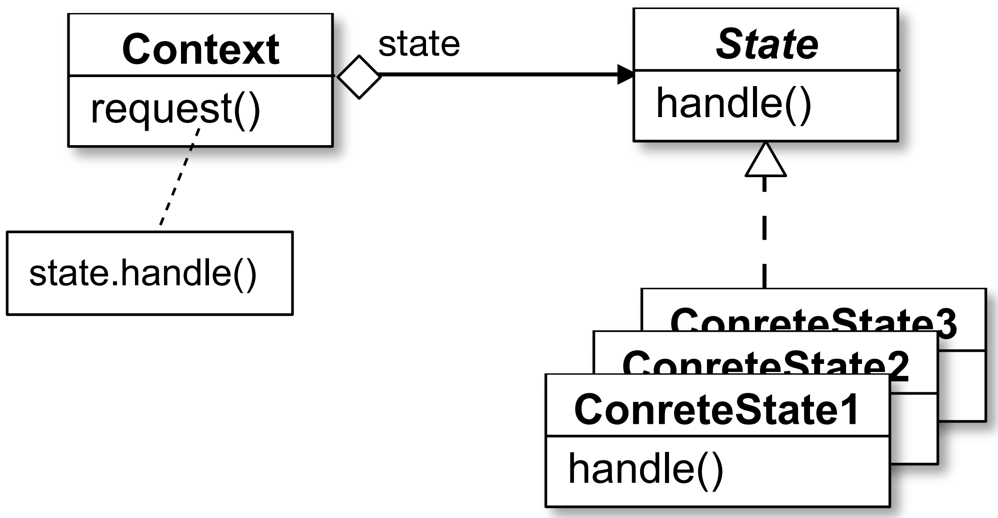
```
void changeState(State s, Event e) {
  stateEntry se = transition[s][e];
  state = se.nextState;
  (*se.action)();
}

void a10() {
  ...
}

void a11() {
  ...
}

...
```

State Design Pattern

- Object-oriented technique
- **The State Design Pattern**
  - define an abstract superclass with an event handler and derive a concrete class for each state
  - associate the state with the class holding the context (the state machine)
  - change of behaviour by object change

State pattern

- Each state is represented by a separate class
- State change is performed by instantiating a new object



[Gamma et al., Design Patterns, Addison Wesley, 1994]

State pattern

```
class Context {
  private State state;
  public void setState(State s) {
    state = s;
  }
  handleEvent(Event e) {
    state.handle(e, this);
  }
}

interface State {
  public void handle(Event e, Context c)
}

class ConcreteState1 implements State {
  public void handle(Event e, Context c) {
    switch (e)
    case e1: context.setState(new State1);
break;
    case e2: context.setState(new State2);
break;
  }
}

class ConcreteState2 implements State {
  [...]
}
[...]
```

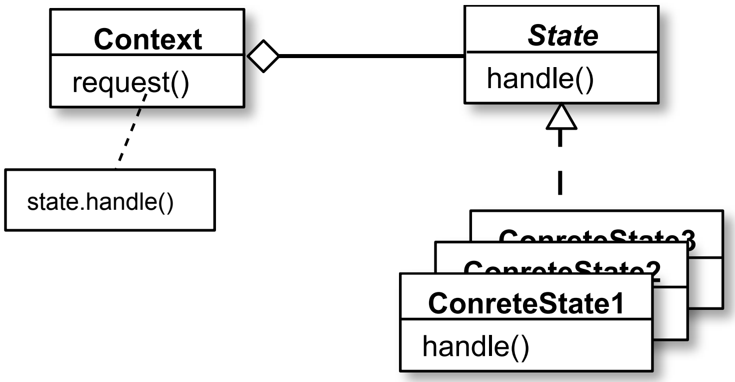


Table-driven vs. State pattern

- State pattern models state-specific behaviour
  - Transition logic can be implemented in the context class or in the state subclasses
  - Implementing transitions in state subclasses is more flexible, but introduces dependencies!

- Table-driven implementation focuses on state transitions
  - Table lookups are less efficient than function calls

[Gamma et al., Design Patterns, Addison Wesley, 1994]

From FSM to Code

- All states and events should be well-defined
- The state machine or state transition table has to cover **all** combinations of states and events and define the corresponding action
- This includes also conditions on state transitions
- Don't forget to optimize the common case!