# Parallel Programming Concepts

# Theory of Concurrency - Multicomputer

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# History

- *1963: Co-Routines concept by Melvin Conway*
  - Foundation for message-based concurrency concepts
- *Late 1970‘s*
  - Parallel computing moved from shared memory towards multicomputers
- *1975, Concept of „recursive non-deterministic processes“ by Dijkstra*
  - Foundation for Hoare‘s work on *Communicating Sequential Processes (CSP),* relies on generator idea
- *1978, Distributed Processes: A Concurrent Programming Concept, B. Hansen*
  - Synchronized procedure called by one process and executed by another
  - Foundation for RPC variations in Ada and other languages
- *1978, Comunicating Sequential Processes, C.A.R. Hoare*

# Co-Routines

- *Conway, Melvin E. (1963). "Design of a Separable Transition-Diagram Compiler". Communications of the ACM (New York, NY, USA: ACM) 6 (7): 396–408. doi: 10.1145/366663.366704.*
- Explicit language primitive to indicate transfer of control flow
- Co-routines allow caller / callee model to be expressed in code
- Routines can suspend (yield) and resume in their execution
- Co-routines may always yield new results -> *generators*
- Good for concurrent, not for parallel programming
- Foundation for theoretical and practical message passing concepts
- Broad language support today

```
var q := new queue
coroutine produce
    loop
        while q is not full
            create some new items
            add the items to q
        yield to consume
coroutine consume
    loop
        while q is not empty
            remove some items from q
            use the items
        yield to produce
```

# Communicating Sequential Processes

- Developed by Tony Hoare at University of Oxford, starting in1977
- Formal process algebra to describe concurrent systems
- Book: T. Hoare, Communicating Sequential Processes, 1985
- Basic idea
  - Computer **systems** act and interact with the environment continuously
    - Decomposition in **subsystems** (**processes**) which operate concurrently
    - **Interact** with other processes or the environment, modular approach
- Based on mathematical theory, described with algebraic laws
- Direct mapping to Occam programming language
- *Hoare, C. Antony Richard, "Communicating Sequential Processes," Commun. ACM, vol. 21, 1978, pp. 666-677.*

# CSP: Processes

- Behavior of real-world objects can be described through their interaction with other objects, leaving out internal implementation details
- Interface of a process is described as set of atomic events
- Event examples for an ATM:
  - *card* – insertion of a credit card in an ATM card slot
  - *money* – extraction of money from the ATM dispenser
- **Alphabet** - set of relevant (!) events for the description of an object
  - Event may never happen in the interaction
  - Interaction is restricted to this set of events
  - $\alpha_{ATM} = \{card, money\}$
- A CSP **process** is the behavior of an object, described with its alphabet

# CSP: Processes

- **Event** is an atomic action without duration
  - Time is expressed with start/stop events
  - Timing of events is not relevant for logical correctness, but ordering
  - Makes reasoning independent of execution speed and performance
- No concept of simultaneous events
  - May be represented as single event, if synchronization is modeled
- **$STOP_A$**
  - Process with alphabet A which never engages in any of the events of A
  - Expresses a non-working part of the system

# CSP: Process Description through Prefix Notation

- **(x -> P)** **„x then P“**
  - x: event, P: process
  - Behavioral description of an object which first engages in x and than behaves as described with P
  - Prefix expression itself is a process (== behavior), chainable approach
  - **α(x -> P) = αP** - Processes must have the same alphabet
  - Example 1:
    **(card -> $STOP_{\alpha ATM}$)**
    „ATM which takes a credit card before breaking“
  - Quiz:
    „ATM which serves one customer and breaks while serving the second customer“ **- $\alpha ATM_Q$={card, money}**

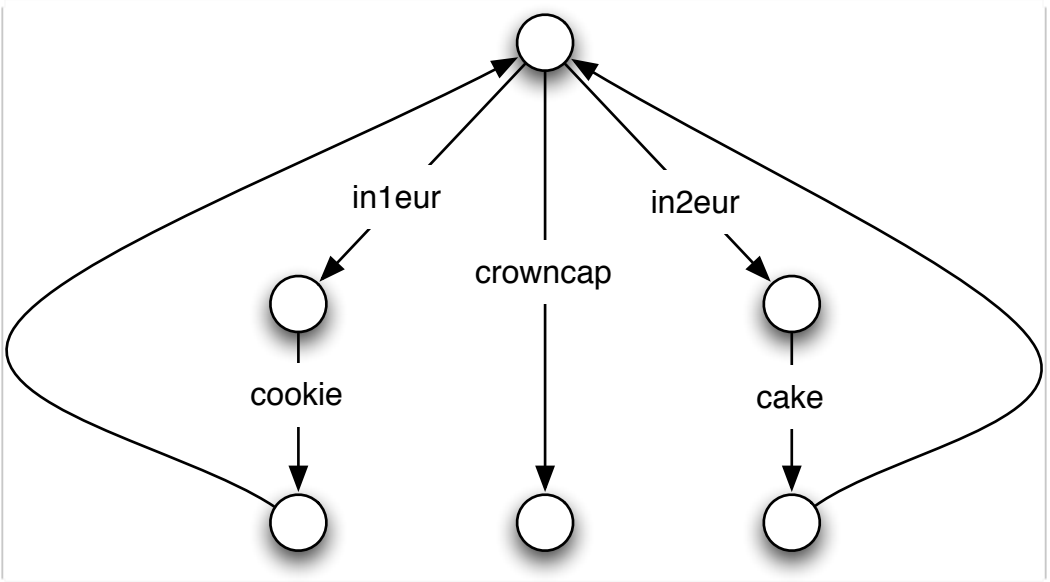
# CSP: Recursion

- Prefix notation may lead to long chains of repetitive behavior for the complete lifetime of the object (until **STOP**)
  - Solution: Self-referential recursive definition for the object
- Example: An everlasting clock object
  **$\alpha_{CLOCK}$ = {tick}**
  **CLOCK = (tick -> CLOCK)**
  - **CLOCK** is the process which has the alphabet **{tick}** and which is the same as the **CLOCK** process which has a prefix event
  - Allows (mathematical) endless unfolding
- Enables description of an object with one single stream of behavior through prefixing and recursion

# CSP Process Description - Choice

- Object behavior may be influenced by the environment
  - Support for multiple ‘behavior streams’ triggered by the environment
- Externally-triggered choice between two ore more events, leads to different subsequent behavior (== processes), forms a process by itself
  **(x -> P | y -> Q)**
- Example: Vending machine offers choice of slots for 1€ coin or 2€ coin
  **VM = ( in1eur -> (cookie -> VM) |**
  **in2eur -> (cake -> VM) | crowncap -> STOP)**
- **|** is an operator on prefix expression, not on the processes itself

# Process Description: Pictures




**VM =**

**( in1eur -> (cookie -> VM) |**

**in2eur -> (cake -> VM) |**

**crowncap -> STOP)**

- Single processes as circles, events as arrows
- Pictures may lead to problems - difficult to express equality, hard with large or infinite number of behaviors

# Traces

- Trace – recording of the events which occurred until a given point in time
- Simultaneous events simply recorded as two subsequent events
- Finite sequence of symbols:
  **<>**
  **<card, money, card, money, card>**
- Concatenation of traces: **s^t**
- **{card} = <card>**
- Trace t of a breakage (STOP) scenario:

  *There is no event x such that the trace s = t^<x> exists*

# Traces of a Process

- Before process start the trace which will be recorded is not specified
- Choice depends on environment, not controlled by the process
- All possible traces of process P: **traces(P)**
  - As a tree: All paths leading from the root to a particular node of the tree
- **Specification** of a product = they way it is intended to behave
  - Arbitrary trace *tr* as free variable
  - Example: Vending machine owner want to ensure that the number of 2€ coins and number of dispensed cakes remains the same:
    *NOLOSS = ( #(tr {cake}) ≤ #(tr {in2eur}) )*
  - *P sat S* : Product P meets the specification S
    - Every possible observation of P's behaviour is described by S
    - Set of laws for mathematical reasoning about the system behavior

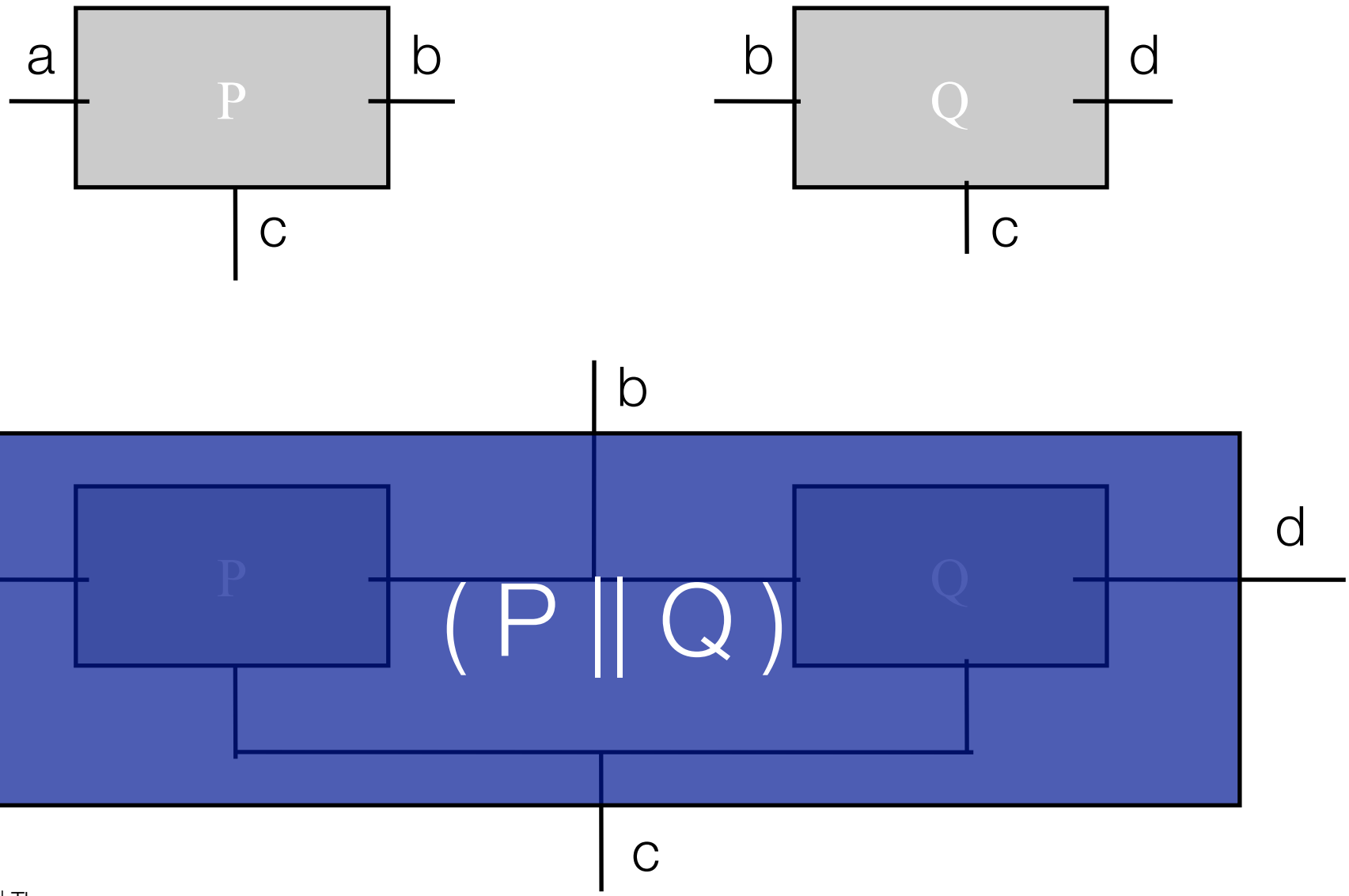
# Concurrency in CSP

- Process = Description of possible behavior
- Set of occurring events depends on the environment, which may also be described as a process
- Allows to investigate a complete system, were the description is again a process
- Formal modelling of interacting processes
  - Formulate events that trigger simultaneous participation of multiple processes
- **Parallel combination**: Process which describes a system composed of the processes P and Q:

$$P \parallel Q \qquad\qquad \alpha(P \parallel Q) = \alpha P \cup \alpha Q$$

- **Interleaving**: Parallel activity with different events

# Graphical Representation

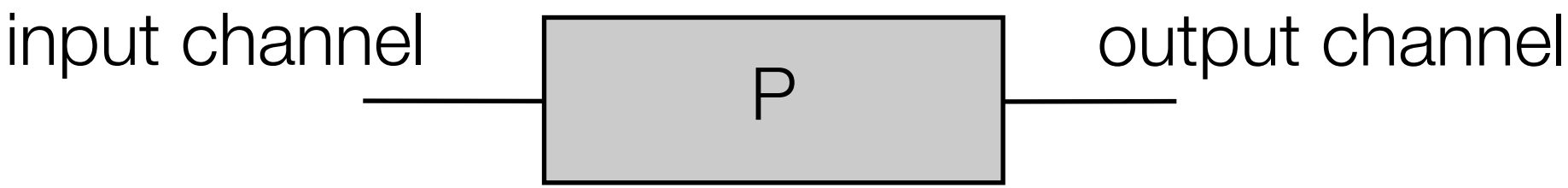


# Communication in CSP

- Special class of event: **Communication**
  - Modeled as uni-directional channel, only between two processes
  - Channel name is a member of the alphabets of both processes
  - Described by multiple **c.v** events, which are part of the process alphabet
    - **c**: name of a channel on which communication takes place
    - **v**: value of the message being passed
- Set of all messages which P can communicate on channel c:
  **α c(P) = {v | c.v ε αP}**
- **channel(c.v) = c, message(c.v) = v**
- Input choice: **( c?x -> P(x) | d?y -> Q(y) )**

# Communication (contd.)

- Process which first outputs v on the channel c and then behaves like P:
  **(c!v -> P) = (c.v -> P)**
- Process which is initially prepared to input any value x from the channel c and then behave like P(x):
  **(c?x -> P(x)) = (y: {y | channel(y) = c} -> P(message(y)))**



# Communication (contd.)

- Channel approach assumes **rendezvous behavior**
  - Sender and receiver block on the channel operation until the message was transmitted
  - Meanwhile common concept in messaging-based concurrency approaches
- Based on the formal framework, mathematical proofs can now be derived !
  - When two concurrent processes communicate with each other only over a single channel, they cannot deadlock (see book)
  - Network of non-stopping processes which is free of cycles cannot deadlock
    - Acyclic graph can be decomposed into subgraphs connected only by a single arrow

# Example for System Deadlock

- VM = ( in1eur -> (cookie -> VM) |
  in2eur -> (cake -> VM) |
  crowncap -> STOP)

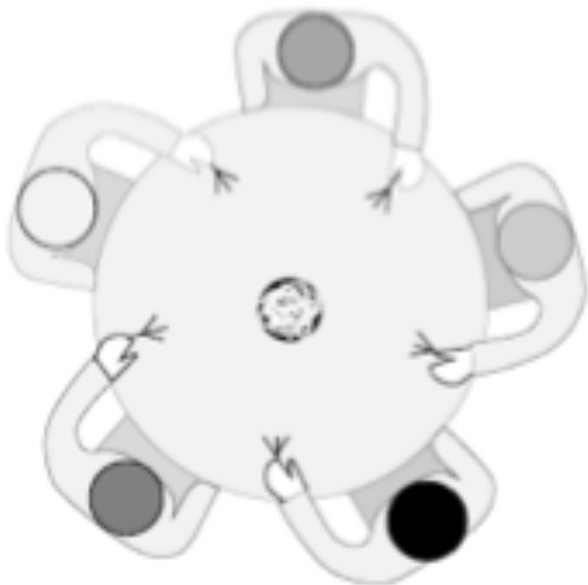
- FOOLCUST = ( in1eur -> cake -> FOOLCUST |
  in2eur -> cake -> FOOLCUST |
  lookaround -> FOOLCUST )

- (VM || FOOLCUST) = μX • ( in1eur -> STOP | in2eur -> cake -> X)

- Deadlock:
  Each process of the system would be able perform some further action, but the processes in the composed system can not agree on what the next action shall be

# Example: The Dining Philosophers (E.W.Dijkstra)

- Five philosophers work in a college, each philosopher has a room for thinking
- Common dining room, furnished with a circular table, surrounded by five labeled chairs
- In the center stood a large bowl of spaghetti, which was constantly replenished
- When a philosopher gets hungry:
  - Sits on his chair
  - Picks up his own fork on the left and plunges it in the spaghetti, then picks up the right fork
  - When finished he put down both forks and gets up
  - May wait for the availability of the second fork



# Mathematical Model

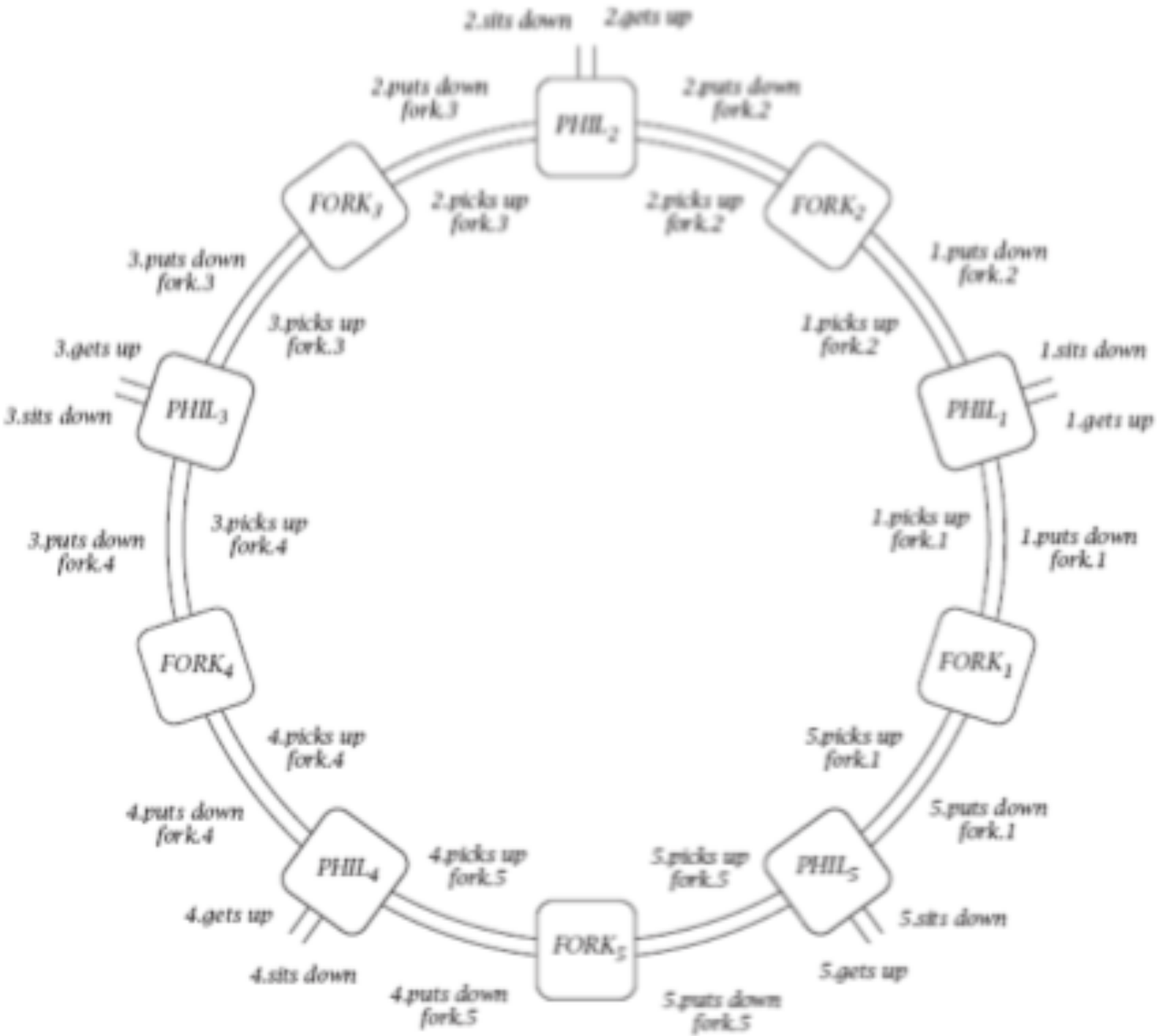
- Philosophers: $PHIL_0$ … $PHIL_4$

- $\alpha PHIL_i$ = { i.sits down, i.gets up,
  i.picks up fork.i, i.picks up fork.(i⊕1),
  i.puts down fork.i, i.puts down fork.(i⊕1) }

- ⊕: Addition modulo 5 == i⊕1 is the right-hand neighbor of $PHIL_i$

- Alphabets of the philosophers are mutually disjoint, no interaction between them

- $\alpha FORK_i$ = { i.picks up fork.i,
  (i⊖1).picks up fork.i,
  i.puts down fork.i,
  (i⊖1).puts down fork.i }


2.sits down
2.gets up
2.puts down fork.3
2.puts down fork.2
PHIL2
FORK3
FORK2
2.picks up fork.3
2.picks up fork.2
3.puts down fork.3
1.puts down fork.2
3.picks up fork.3
1.picks up fork.2
3.gets up
1.sits down
PHIL3
PHIL1
3.sits down
1.gets up
3.puts down fork.4
3.picks up fork.4
1.picks up fork.1
1.puts down fork.1
FORK4
FORK1
4.picks up fork.4
5.picks up fork.1
4.puts down fork.4
5.puts down fork.1
PHIL4
PHIL5
4.picks up fork.5
5.picks up fork.5
4.gets up
5.sits down
FORK5
4.sits down
5.gets up
4.puts down fork.5
5.puts down fork.5

# Behavior of the Philosophers

- $PHIL_i$ = ( i.sits down ->
  i.picks up fork.i ->
  i.picks up fork.(i⊕1) ->
  i.puts down fork.i ->
  i.puts down fork.(i⊕1) ->
  i.gets up -> $PHIL_i$ )

- $FORK_i$ = ( i.picks up fork.i ->
  i.puts down fork.i -> $FORK_i$ |
  (i⊖1).picks up fork.i ->
  (i⊖1).puts down fork.i -> $FORK_i$ )

- $PHILOS=(PHIL_0||PHIL_1||PHIL_2||PHIL_3||PHIL_4)$

- $FORKS=(FORK_0||FORK_1||FORK_2||FORK_3||FORK_4)$

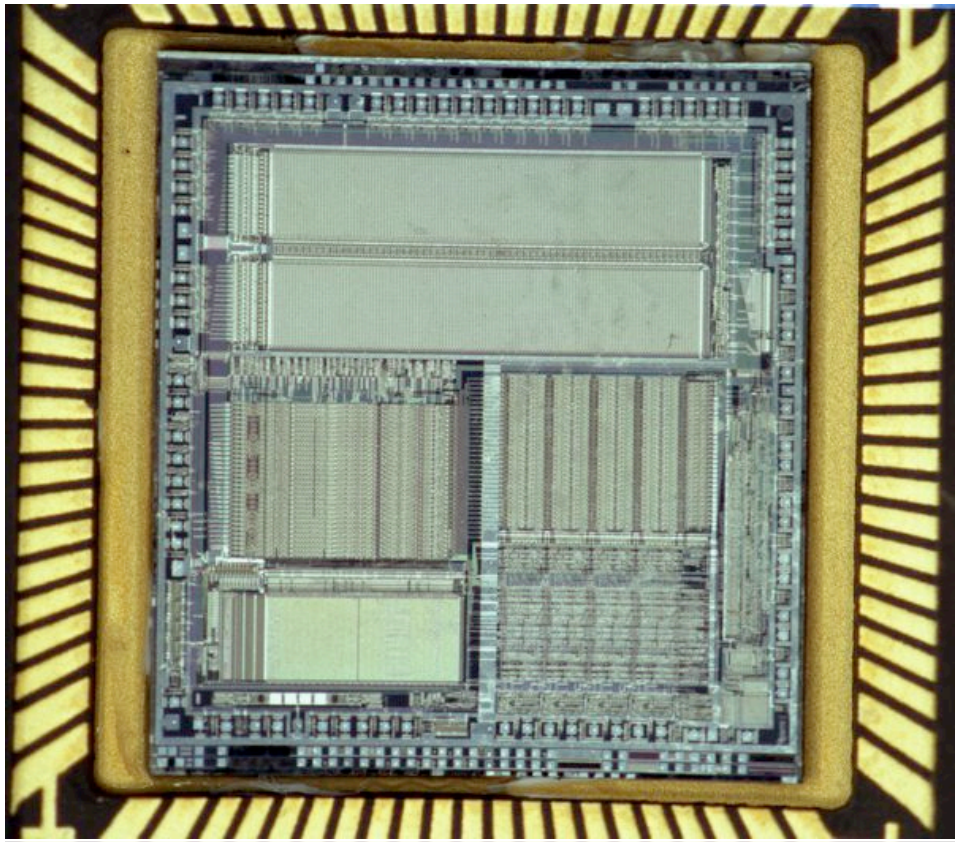
- COLLEGE=(PHILOS||FORKS)

We leave out the proof here ;-) ...

# What‘s the Deal ?

- Any possible system can be modeled through event chains
  - Enables mathematical proofs for deadlock freedom, based on the basic assumptions of the formalism (e.g. channel assumption)
- Some tools available (look at the CSP archive)
- CSP was the formal base for the Occam language
  - Language constructs follow the formalism, to keep proven properties
  - Mathematical reasoning about behavior of written code
- Still active research (Welsh University), channel concept frequently adopted
  - CSP channel implementation for Java, MPI design
  - Other formalisms based on CSP, e.g. Task / Channel model

# Occam Example



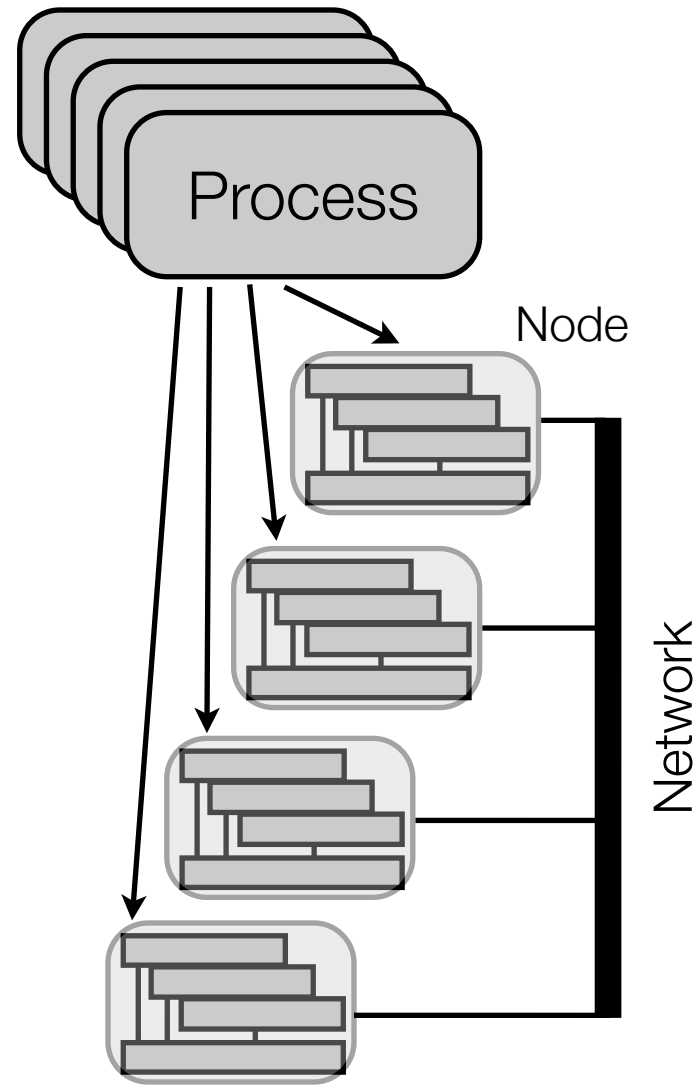
```
PROC producer (CHAN INT out!)
  INT x:
  SEQ
    x := 0
    WHILE TRUE
      SEQ
        out ! x
        x := x + 1
:

PROC consumer (CHAN INT in?)
  WHILE TRUE
    INT v:
    SEQ
      in ? v
      .. do something with `v'
:

PROC network ()
  CHAN INT c:
  PAR
    producer (c!)
    consumer (c?)
:
```

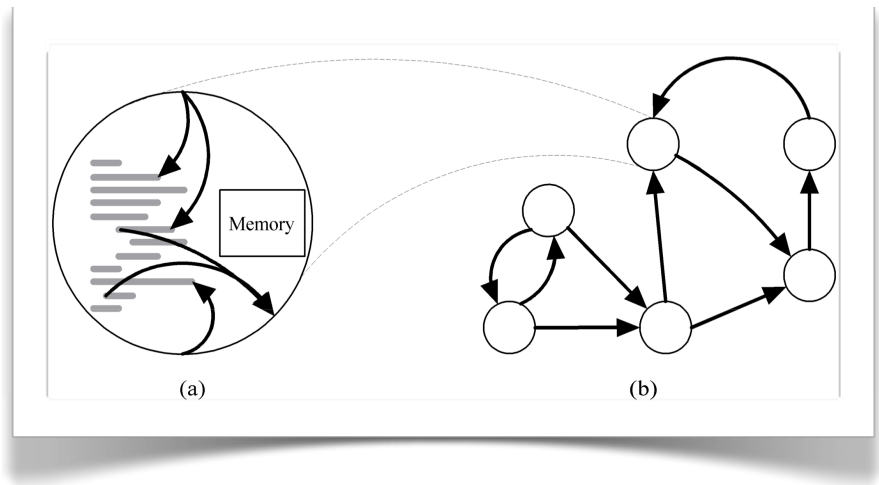
# Task-Channel Model [Foster]

- **Computational model** for multi-computer case
- Parallel computation consists of one or more **tasks**
  - Tasks execute concurrently
  - Number of tasks can vary during execution
  - Task encapsulates **sequential program** with **local memory**
  - A task has **in-ports** and **outports** as interface to the environment
  - **Basic actions**: read / write local memory, send message on outport, receive message on in-port, create new task, terminate



# Task-Channel Model [Foster]

- Outport / in-port pairs are connected by message queues called **channels**
  - Channels can be created and deleted
  - Channels can be referenced as **ports**, which can be part of a message
  - **Send** operation is asynchronous
  - **Receive** operation is synchronous
  - Messages in a channel stay in order
- Tasks are **mapped** to physical processors
  - Multiple tasks can be mapped to one processor
- Data locality is explicit part of the model
- Channels can model **control** and **data dependencies**



# Task-Channel Model [Foster]

- Effects from channel-only interaction model
  - Performance optimization does not influence semantics
    - Example: Shared-memory channels for multiple tasks on one machine
  - Task mapping does not influence semantics
    - Align number of tasks to problem, not to execution environment
    - Improves scalability of implementation
  - Modular design with well-defined interfaces
  - Determinism made easy
    - Verify that each channel has a single sender and receiver

# Task-Channel Model [Foster]

- Model results in some algorithmic style
  - Task graph algorithms, data-parallel algorithms, master-slave algorithms
- Theoretical performance assessment
  - Execution time: Period of time where at least one task is active
  - Number of communications / messages per task
- Rules of thumb
  - Communication operations should be balanced between tasks
  - Each task should only communicate with a small group of neighbors
  - Task should perform computations concurrently (task parallelism)
  - Task should perform communication concurrently

# Actor Model

- *Carl Hewitt, Peter Bishop and Richard Steiger. A Universal Modular Actor Formalism for Artificial Intelligence IJCAI 1973.*
  - Another mathematical model for concurrent computation
  - No global system state concept (relationship to physics)
  - Actor as computation primitive, which can make local decisions, concurrently creates more actors, or concurrently sends / receives messages
  - Asynchronous one-way messaging with changing topology (CSP communication graph is fixed), no order guarantees
  - CSP relies on hierarchy of combined parallel processes, while actors rely only on message passing paradigm only
  - Recipient is identified by *mailing address*, can be part of a message
- „Everything is an actor“

# Actor Model

- Influenced the development of the Pi-Calculus
- Serves as theoretical base to reason about concurrency, and as underlying theory for some programming languages
  - Erlang, Scala -> later in this course
- Influences by Lisp, Simula, and Smalltalk
- Behavior as mathematical function
- Describes activity on message processing

# Other Formalisms

- Lambda calculus by Alonzo Church (1930s)
  - Concept of procedural abstraction, originally via variable substitution
  - Functions as first-class citizen
  - Inspiration for concurrency through functional programming languages
- Petri Nets by Carl Adam Petri (since 1960s)
  - Mathematical model for concurrent systems
  - Directed bipartite graph with places and transitions
  - Huge vibrant research community
- Process algebra, trace theory, ...