3. Modelling Dynamic Behavior with Petri Nets

1) Basics
   1) Elementary Nets
   2) Special Nets
   3) Colored Petri Nets

2) Patterns in Petri Nets
3) Composability of Colored Petri Nets
4) Parallel Composition with CPN
5) Application to modelling
Obligatory Readings

► Balzert 2.17 or Ghezzi. **Chapter 5**
http://www.scholarpedia.org/article/Petri_net

http://www.springerprofessional.de/konzepte-der-petrinetze/5120122.html


www.pervasive.dk/publications/files/CPN02.pdf

► Web portal “Petri Net World”
http://www.informatik.uni-hamburg.de/TGI/PetriNets
Further Literature

► K. Jensen. **Colored Petri Nets.** Lecture Slides [http://www.daimi.aau.de/~kjensen](http://www.daimi.aau.de/~kjensen)

► [www.daimi.aau.dk/CPnets](http://www.daimi.aau.dk/CPnets) the home page of CPN. Contains lots of example specifications. Very recommended


► [http://www.daimi.au.dk/CPnets/intro/example_indu.html](http://www.daimi.au.dk/CPnets/intro/example_indu.html)
Relationship of PN and other Behavioral Models

  

- E.E.Roubtsova, M. Aksit. Extension of Petri Nets by Aspects to Apply the Model Driven Architecture Approach. University of Twente, Enschede, the Netherlands

- Other courses at TU Dresden:
  
  Entwurf und Analyse mit Petri-Netzen
  Lehrstuhl Algebraische und logische Grundlagen der Informatik
  Dr. rer. nat. W. Nauber
Goals

► Understand **Untyped** (Page/Transition nets) and **Colored Petri nets** (CPN)
► Understand that PN/CPN are a verifiable and automated technology for safety-critical systems
► PN have subclasses corresponding to finite automata and data-flow graphs
► PN can be refined, then reducible graphs result
You work for PowerPlant Inc. Your boss comes in and says: “Our government wants a new EPR reactor, similarly, in the way Finland has it.”

How can we produce a verified control software? We need a good modelling language!

How do we produce software for safety-critical systems?
Projects with Safety-Critical, Parallel Embedded Software

Aerospace

- The WITAS UAV unmanned autonomously flying helicopter from Linköping
  http://www.ida.liu.se/~marwz/papers/ICAPS06_System_Demo.pdf

Automotive

- Prometheus: driving in car queues on the motorway
  http://www.springerlink.com/content/j06n312r36805683/

Trains

- www.railcab.de Autonomous rail cabs
- www.cargocab.de Autonomous cargo metro
- http://www.rubin-nuernberg.de/ Autonomous mixed metro
### 3.1 Basics of PN

**Petri Net Classes**
- Predicate/Transition Nets: simple tokens, no hierarchy.
- Place-Transition Nets: multiple tokens
- High Level Nets: structured tokens, hierarchy
- There are many other variants, e.g., with timing constraints
Petri Nets

- Over many years developed within GMD (now Fraunhofer, FhG)
- PNs specify diagrammatically:
  - Infinite state systems, regular and non-decidable
  - Concurrency (parallelism) with conflict/non-deterministic choice
  - Distributed memory ("places" can be distributed)
- Modeling of parallelism and synchronization
  - Behavioral modeling, state modeling etc.
**Integer Place/Transition Nets**

- **Tupel** $(P, T, F, W, m_0)$
  - $P = \text{Places}$
  - $T = \text{Transitions}$
  - $F = \text{Flow Relations}$
  - $W = \text{(Relation) Weight}$
  - $m_0 = \text{Start Marking}$

- $P \cap T = \emptyset$
- $F \subseteq (P \times T) \cup (T \times P)$
- $W : F \rightarrow \mathbb{N}_0$ wobei
  - $W(p,t) = 0 \iff (p,t) \notin F, p \in P \text{ und } t \in T$
  - $W(t,p) = 0 \iff (t,p) \notin F, p \in P \text{ und } t \in T$
- $m_0 : P \rightarrow \mathbb{N}_0$

---

**Example**

- $P = \{P_1, P_2\}$
- $T = \{T_1\}$
- $F = \{(P_1, T_1), (T_1, P_2)\}$
- $W = f(x) = 1$
- $m_0 = \{P_1\}$
Integer Place/Transition Nets

- A marking \( m(p) \to \mathbb{N}_0, \ p \in P \) assigns a non-negative Integer to places
  - Number of tokens in a place

- A weight \( W(f) \to \mathbb{N}_0, \ f \in F \) assigns a non-negative Integer to arcs
  - How many tokens can they carry

\[ \begin{align*}
  P1 & \xrightarrow{2} T1 \xrightarrow{} P2 \\
  m(P1) & \to 0 \\
  m(P2) & \to 0 \\
  \end{align*} \]

\[ \begin{align*}
  P1 & \xrightarrow{} T1 \xrightarrow{} P2 \\
  m(P1) & \to 1 \\
  m(P2) & \to 0 \\
  \end{align*} \]

\[ \begin{align*}
  P1 & \xrightarrow{} T1 \xrightarrow{} P2 \\
  m(P1) & \to 2 \\
  m(P2) & \to 1 \\
  \end{align*} \]
Transition $t \in T$ is **enabled** when

$$m(p) - W(p, t) > 0, \ \forall p \in P$$

- For all incoming arcs, the places must contain at least $n$ tokens
  
  $\Rightarrow n = \text{the weight of the incoming arc}$

[Diagram of Integer Place/Transition Nets]
When a transition is Enabled, it may or may not fire

When a transition \( t \in T \) **fires**

\[
m(p) = m(p) - W(p, t), \forall p \in P
\]

- \( N \) Tokens are removed from all incoming places

\[
m(p) = m(p) + W(t, p), \forall p \in P
\]

- \( M \) Tokens are added to all outgoing places

The state (marking) of the Petri Net is changed
Language Levels

- PN extend finite automata with indeterminism
- Asynchronous execution model (partial ordering)

**CH-0** computable

**CH-1** context sensitive

**CH-2** context free

**CH-3** regular

- Petri Nets
  - Finite State Machines
- Algebraic Specifications
Elementary Nets: Predicate/Transition Nets

- A Petri Net (PN) is a directed, bipartite graph over two kinds of nodes
  1. Places (circles)
  2. Transitions (bars or boxes)

- A Integer PN is a directed, weighted, bipartite graph with integer tokens
  - Places may contain several tokens
  - Places may contain a capacity (bound=k)
  - k tokens in a place indicate that k items are available
An **Elementary PN** (predicate/transition or condition/event nets)

- **Boolean tokens**
  One token per place (bound of place = 1)

- **Arcs have no weights**

- Presence of a token = condition or predicate is true

- *Firing* of a transition = from the input the output predicates are concluded

- Thus elementary PN can represent simple forms of logic
High-Level Nets

A **High-Level PN** (Colored PN, CPN) allows for *typed places* and *typed arcs*

- For types, any DDL can be used (e.g., UML-CD)

High-level nets are modular

- Places and transitions can be refined
- A Colored Petri Net is a reducible graph

The upper layers of a reducible CPN are called *channel agency nets*

- Places are interpreted as channels between components
Cookie Automaton with Counter

- **Send**: (Int, Data)
- **Receive**: (Data)
- **Transmit**: (n,d)
- **Receive Ack**: (Int)
- **Transmit Ack**: (Int)
- **Sender**: (Int, Data)
- **Receiver**: (Int, Data)
- **Sender Ack**: (Int)
- **Receive Packet**: (n,d)
- **Transmit Packet**: (n,d)
- **Next Packet**: (Int)
- **Next To Send**: (Int)

 transitions:

- **if n = k then d else null**
- **if n = k then n else null**
- **if n = k then k+1 else k**

symbols:

- n
- d
- k
Application Areas of Petri Nets

► Reliable software (quality-aware software)
  ■ PetriNets can be checked on deadlocks, liveness, fairness, bounded resources

► Safety-critical software that require proofs
  ■ Control software in embedded systems or power plants

► Hardware synthesis
  ■ Software/Hardware co-design

► User interface software
  ■ Users and system can be modeled as parallel components
Instead of describing the behavior of a class with a statechart, a CPN can be used.

- Statecharts, data flow diagrams, activity diagrams are special instances of CPNs.

CPN have several advantages:

- They model parallel systems naturally.
- They are compact and modular, can be reducible.
- They are suitable for aspect-oriented composition, in particular of parallel protocols.
- They can be used to generate code, also for complete applications.

Informal: for CPN, the following features can be proven:

- **Liveness**: All parts of the net are reachable.
- **Fairness**: All parts of the net are equally “loaded” with activity.
- **K-boundedness**: The tokens, a place can contain, aber n-bounded.
- **Deadlock**: The net cannot proceed but did not terminate correctly.
- **Deadlock-freeness**: The net contains no deadlocks.
Application Area II: Contract checking (Protocol Checking) for Components

- Petri Nets describe behavior of components (dynamic semantics)
  - They can be used to check whether components fit to each other

- Problem: General fit of components is undecidable
  - The protocol of a component must be described with a decidable language
  - Due to complexity, context-free or -sensitive protocol languages are required

- Algorithm:
  - Describe the behavior of two components with two CPN
  - Link their ports
  - Check on *liveness* of the unified CPN
  - If the unified net is not live, components will not fit to each other…

- Liveness and fairness are very important criteria in safety-critical systems
3.1.1 Elementary Nets
(Predicate/Transition Nets)
Meaning of Places and Transitions in Elementary Nets

- Predicate/Transition (Condition/Event-, State/Transition) Nets:
  - Places represent conditions, states, or predicates
  - Transitions represent the firing of events:
    - If a transition has one input place, the event fires immediately if a token arrives in that place
    - If a transition has several input places, the event fires when all input places have tokens

- A transition has *input* and *output* places (pre- and postconditions)
  - The presence of a token in a place is interpreted as the condition is true
Example of 2 Robots as Predicate/Transition Net

Diagram:
- Robot 1 free
- Piece equipped
- Taking Up
- Laying Down
- Piece moving
- Piece available
- Robot 2 free
- Taking Up
- Laying Down
- Piece equipped
Example of 2 Robots as Predicate/Transition Net

- Places represent predicates
- Tokens show validity
Example of 2 Robots as Predicate/Transition Net

- Robot 1 free
- Piece equipped
- Taking Up
- Piece available
- Piece ready
- Taking Up
- Laying Down
- Robot 2 free
- Piece equipped
- Taking Up
- Piece available
- Piece ready
- Taking Up
- Laying Down
Example of 2 Robots as Predicate/Transition Net

- Robot 1 free
- Piece equipped
- Taking Up
- Laying Down
- Piece moving
- Piece available
- Piece ready
- Taking Up
- Robot 2 free
- Piece equipped
- Laying Down
Example of 2 Robots as Predicate/Transition Net
Comparing PN to Automata

Petri Nets
- Tokens encode parallel “distributed” global state
- Can be switched “distributedly”

Automata
- Sequential
- One global state
  - Can only be switched “centrally”
3.1.2 Special Nets
3.1.2.a Marked Graphs (MG)

- A **Marked Graph** (MG) is a PN such that:
  1. Each place has only 1 incoming arc
  2. Each place has only 1 outgoing arc

- MG provide *deterministic parallelism without confusion*
- Then the places can be abstracted (identified with one flow edge)
- Transitions may split and join, however

- Marked Graphs correspond to a special class of data-flow graphs
  (Data flow diagrams with restricted stores, DFD)
  - Transitions correspond to processes in DFD, places to stores
  - States can be *merged* with the ingoing and outcoming arcs → DFD without stores
  - Restriction: Stores have only one producer and consumer
  - But activities can join and split

- All theory for CPN holds for marked graph - DFD, too
Is the production PN a MG?
3.1.2.a Marked Graphs (MG)

The production PN is no MG

→ Some places have more than 1 incoming/outgoing arc
3.1.2.a Marked Graphs (MG)

The production robot PN is a MG
More General Data-Flow Diagrams

- General DFD without restriction can be modeled by PN, too.
  - Places cannot be abstracted
  - They correspond to stores with 2 feeding or consuming processes
- Example: the full robot has places with 2 ingoing or outgoing edges,
  - They cannot be abstracted
For DFD, Many Notations Exist

- Notation from Structured Analysis [Balzert]

```
Produce tea

<table>
<thead>
<tr>
<th>Put tea in pot</th>
<th>GreenTea</th>
<th>Water</th>
<th>add boiling water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prozess</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pot

- Datenfluss

wait

TeaDrink

Datenspeicher

Cup

```
3.1.2.b State Machines are PN with Cardinality Restrictions

A **Finite State Machine PN** is an elementary PN such that:

1. Each transition has only 1 incoming arc
2. Each transition has only 1 outgoing arc
   - Then, it is equivalent to a finite automaton or a *statechart*
   - From every class-statechart that specifies the behavior of a class, a State Machine can be produced easily
     - Flattening the nested states
   - Transitions correspond to transitions in statecharts, states to states
   - Transitions can be *merged* with the ingoing and outcoming arcs
   - In a FSM there is only one token

- All theory for CPN holds for Statecharts, too
3.1.2.b State Machines

Is the production PN a FSM?

Diagram:
- **Robot 1 free**
- **Piece equipped**
- **Taking Up**
- **Laying Down**
- **Piece available**
- **Piece ready**
- **Taking Up**
- **Laying Down**
- **Robot 2 free**

Transitions include:
- Piece moving to Piece available
- Piece available to Piece ready
- Piece ready to Taking Up
- Taking Up to Laying Down
- Laying Down to Taking Up
- Robot 2 free to Robot 1 free
- Robot 1 free to Robot 2 free
- Taking Up to Piece equipped
- Laying Down to Piece equipped
3.1.2.b State Machines

The production PN is no FSM

→ Some transitions have more than 1 incoming/outgoing arc
3.1.2.b State Machines

One Robot is a FSM but not with incoming/outgoing arc

Taking Up -> Laying Down

Piece equipped

Robot 2 free
Hierarchical StateCharts from UML

- States can be nested in StateCharts
- This corresponds to StateMachine-PN, in which states can be refined and nested
3.1.2.c Free-Choice Nets

- Two transitions are in conflict if the firing of one transition deactivates another
  - R1: no conflicts (t1 and t3 activated) → in this example t1 fires
  - R2: t2 and t3 are in conflict → in this example t2 fires
  - R3: t3 is deactivated because of t2
3.1.2.c Free-Choice Nets

Free-Choice Petri Net provides deterministic parallelism
- Choice between transitions never influence the rest of the system
- Rule conflicts out
- AND-splits and AND-joins

Keep places with more than one output transitions away from transitions with more than one input places (forbidden are “side actions”)
- outdegree(place) → in(out(place)) = {place}
3.1.3 Colored Petri Nets as Example of High Level Nets

- Modularity
- Refinement
- Reuse
- Preparing “reducible graphs”
Colored Petri Nets, CPN

Colored (Typed) Petri Nets (CPN) refine Petri nets:

- Tokens are typed (colored)
- Types are described by data structure language (e.g., Java, ML, UML class diagrams, data dictionaries, grammars)
- Concept of time can be added

Full tool support

- Fully automated code generation in Java and ML (in contrast to UML) e.g., DesignCPN of Aarhus University [http://www.daimi.aau.dk](http://www.daimi.aau.dk)
- Possible to proof features about the PN
- Net simulator allows for debugging

Much better for safety-critical systems than UML, because proofs can be done
Annotations in CPN

- Places are annotated by
  - Token types
    \[ \text{STRING} \times \text{STRING} \]
  - Markings of objects and the cardinality in which they occur:
    \[ 2'("Uwe","Assmann") \]

- Edges are annotated by
  - Type variables which are unified by unification against the token objects
    \[ X, Y \]
  - Guards
    \[ [ X == 10] \]
  - If-Then-Else statements
    \[ \text{if } X < 20 \text{ then } Y := 4 \text{ else } Y := 7 \]
  - Switch statements
  - Boolean functions that test conditions
CPN are Modular

- A subnet is called a page (module)
  - Every page has ports
  - Ports mark in- and out-going transitions/places

- Transition page: interface contains transitions (transition ports)

- Place page (state page): interface contains place (place ports)

- Net class: a named page that is a kind of "template" or "class"
  - It can be instantiated to a net "object"

- Reuse of pages and templates possible
  - Libraries of CPN "procedures" possible
Robots with Transition Pages, Coupled by Transition Ports

Transitions replicated

Reused Transition Page

Robot 1 free

Taking Up

Laying Down

Piece moving

Piece available

Taking Up

Piece ready

Taking Up

Robot 2 free
Robots with Place (State) Pages, Coupled by Replicated State Ports

Place Page

Port states replicated

Reused Place Page
CPN are Hierarchical

- Places and transitions may be hierarchically refined
  - Two pointwise refinement operations:
    - Replace a transition with a transition page
    - Replace a state with a state page
  - Refinement condition: Retain the embedding (embedding edges)

- CPN can be arranged as hierarchical graphs (reducible graphs, see later)
  - Large specifications possible, overview is still good
  - Subnet stemming from refinements are also place or transition pages
Pointwise refinement:

- *Transition refining page*: refines a transition, transition ports
- *Place refining page (state refining page)*: refines a place, place ports

**Law of syntactic refinement:**
The graph interface (attached edges) of a refined node must be retained by the refining page.
Point-wise Refinement Example

Hyperedge refinement:

- Hyperedges and regions in PN can be refined
Industrial Applications of CPN

- Large systems are constructed as reducible specifications
  - They have 10-100 pages, up to 1000 transitions, 100 token types

- Example: ISDN Protocol specification
  - Some page templates have more than 100 uses
  - Corresponds to millions of places and transitions in the expanded, non-hierarchical net
  - Can be done in several person weeks
3.2 Patterns in Petri Nets

Analyzeability:
Petri Nets can be analyzed for patterns (by pattern matching)
Modelling of Parallelism and Synchronization

- Petri Nets have a real advantage when parallel processes and synchronization must be modelled
  - Many concepts can be expressed as *PN patterns*
Simple PN Buffering Patterns

- Reservoir Place
  - Does not generate objects

- Permanently active transaction
  - Generates objects
    - (Object source, Event source)

- Process
  - Sequential

- Intermediate Archive
  - Buffer

- Archive
  - Stores objects

- Sink
  - Deletes/Destroys objects
Patterns for Synchronization (Barrier)

- Coupling processes with parallel continuation
Patterns for Synchronization (n-Barrier)

- Bridges: Transitions between phases
Adding Delays in Transitions by Feedback Loops

- Adding a delay
  Behaves like a semaphore
Adding Delays in Transitions by Feedback Loops

- Adding a delay
  Behaves like a semaphore
3.1.2.d Workflow Nets

- **Workflows** are executable sequences of actions, sharing data from several repositories or communicating with streams.
- **Workflow nets** are reducible with single sources and single sinks (*single-entry/single-exit*):
  - Only reducible nets can be specified
  - DFD with control flow and synchronization
  - They avoid global repositories and global state
  - They provide richer operators (AND, XOR, OR), inhibitor arcs, and synchronization protocols
- Workflow nets can be compiled to Petri Nets.
- Further, specialized workflow languages exist, such as:
  - ARIS workflow language
  - YAWL Yet another workflow language
  - BPMN Business Process Modeling Notation
  - BPEL Business Process Execution Language
Complex Transition Operators in Workflow Nets: Join and Split Operators of YAWL

**AND-Join**
All ingoing places are ready (conjunctive input)

**AND-Split**
All outgoing places are filled (conjunctive output)

**XOR-Join**
Exactly one of n ingoing places is ready (disjunctive input)

**XOR-Split**
Exactly one of the outgoing places are filled (disjunctive output)

**OR-Join**
At least one of n ingoing places is ready (selective input)

**OR-Split**
Some of the outgoing places are filled (selective output)
Simple YAWL example
Parallelism Patterns – Transitional Operators

**Joining Parallelism**
- Synchronization Barrier
- AND-Join

**Replication and Distribution**
- Forking
  - (AND-Split)

**Collecting Objects**
- From parallel processes
- OR-Join

**Decision**
- Indeterministically
  - (OR-Split)
Example: Reduction Semantics of OR-Join Operator

- Complex operators refine to special pages with multiple transition ports
Example: Reduction Semantics of XOR-Join Operator

- XOR-Join with bound state (only 1 token can go into a place)
Example: Reduction Semantics of XOR-Join Operator

- XOR-Join with inhibitor arc
  (transition is activated when no token is in the place)
Parallelism Patterns – Transitional Operators (2)

Ordering Synchronization Barrier
Ordering-AND-Join
Parallelism Patterns – Transitional Operators (2)

Output Ordering Generator
Ordering-AND-Split
Patterns for Communication

- Producer Consumer

```
message available
produce
send
no message
```

```
receive
ready
received message store
message
```
Patterns for Communication

- Producer Consumer
Patterns for Communication

- Producer Consumer
Patterns for Communication

- Producer Consumer

Diagram:
- Producer:
  - Messages available
  - Produce
  - Send
  - No message

- Consumer:
  - Receive
  - Demand
  - Received message store
Patterns for Communication

- Producer Consumer
Patterns for Communication

Producer Consumer with Buffer
Patterns for Communication

Producer Consumer with Buffer

- message available
- produce
- no message
- send
- buffer
- receive
- demand
- received message store
Patterns for Communication

- Producer Consumer with Buffer
Patterns for Communication

- Producer Consumer with Buffer

Diagram:
- Produce
- Send
- Message available
- No message
- Buffer
- Receive
- Demand
- Received message store
Patterns for Communication

- Producer Consumer with Buffer
Patterns for Communication

Producer Consumer with Buffer

- message available
- produce
- send
- no message

- buffer
- demand
- received message store
- receive
Patterns for Communication

- Producer Consumer with Buffer
Patterns for Communication

- Producer Consumer with Buffer
Patterns for Communication

- Producer Consumer with Buffer (size 1 message)
Patterns for Communication

- Producer Consumer with Buffer (size n message)

Diagram:
- Message available
- Produce
- Send
- No message
- Buffer
- N
- Receive
- Demand
- Received message store
Patterns for Communication

- Producer Consumer with Buffer and indeterministic delivery
- OR Split
Patterns for Communication

- Producer Consumer with Buffer and broadcast communication
- AND-Split
Semaphores For Mutual Exclusion

- Binary or counting semaphores offer their lock and free operations as transitions
- Distinguished by the capacity of the semaphore place
Semaphores For Mutual Exclusion

- Binary or counting semaphores offer their lock and free operations as transitions
- Distinguished by the capacity of the semaphore place
Semaphores For Mutual Exclusion

- Binary or counting semaphores offer their lock and free operations as transitions.
- Distinguished by the capacity of the semaphore place.
Semaphores For Mutual Exclusion

- Binary or counting semaphores offer their lock and free operations as transitions.
- Distinguished by the capacity of the semaphore place.
Dining Philosophers (Shared Resources)

- Getting hungry
- waiting for fork1
- waiting for fork2
- start eating
- eating
- Lock
- Free
- Lock
- Free
Advantage

- Patterns can be used to model specific requirements

- PN can be checked for patterns by Pattern Matching (context-free Graph Rewriting)
  - Patterns can be restructured (refactorings)
  - Patterns can be composed (composition)

- Further semantic analysis of PN: Parallel, indeterministic systems can be checked for
  - Absence of deadlocks: will the parallel system run without getting stuck?
  - Liveness: will all parts of the system work forever?
  - Fairness: will all parts of the system be loaded equally?
  - Bounded resources: will the system use limited memory, and how much? (important for embedded systems)
  - Whether predicates hold in certain states (model checking)
3.3 Composability of CPN
In development at the Pervasive Computing Center, University of Aarhus

Basic idea:
- Specify the structure of an application with UML
- Specify the behavior with CPN
  - Describing the behavior of the classes/objects (object lifecycle)
- Glue behavior together with page glueing mechanism

Electronic patient records (EPR) replace the papers
- First version in 2004, on stationary PC
- Next versions for pervasive computing (PDA, wireless):
  - Hospital employees will have access to the patient's data wherever they go, from Xray to station to laboratories
  - For instance, medication plans are available immediately
A *session* is entered by several mobile devices that collaborate.
The session manager manages all mobile devices that collaborate in a certain scenario.
Class Diagram Session Manager

Session Manager

1

Session

nr: int

* active

Device

nr: int

* inactive

1

LockManager

Configuration Manager

1

View Manager
Sequence Diagram Session Manager

Session Manager

Device1:Device

createSession()

shipDefaultController()

shipDefaultViewer()

joinSession()

Device2:Device

acquireLock()

freeLock()

leaveSession()
Double arrows indicate that arrows run in both directions

Basic Types

- **Session** ::= SessionId DeviceList LockType
- **ConfiguredDevice** ::= Device Viewer Controller

Transitions subpages
Refined Configuration Manager Page

- Page is fused along common names of nodes

```
Configuration Manager

CreateSession

JoinSession

LeaveSession

createSession(s,d)

joinSession(s,d)

leaveSession(d,s)

Inactive:Device

Sessions:Session

detachViewCtr(d,v,c)

s == (d,default viewer, default controller)

[joinOK(d,s) ]

s == (d,default viewer, default controller)

ActiveConfigs:
ConfiguredDevice ==
Device x Viewer x Controller

[leaveOK(d,s) ]

s == (d,v,c)

Guard

NextId: int

sid

sid+1

(d, default viewer, default controller)
```
Lock Manager

```
setLock(session, device)

releaseLock(session, device)
```

**ActiveConfigs:**
Device x Viewer x Controller

**Sessions:**
```
not(sessionLocked(session) and not participant(device, session))
```

```
setLock(session, device)
```

```
releaseLock(session, device)
```

```
[hasLock(session, device)]
```
Refined View Manager Page

![Diagram of View Manager and its components: ActiveConfigs, Detach Viewer, NoViewer, Attach Viewer, Detach Controller, NoController, Attach Controller. The diagram illustrates the relationships and actions between different components in the View Manager system.]
Remarks

The CPN pages are attached to UML classes, i.e., describe their behavior
- States and transitions are marked by UML types

Every subpage is coupled to other pages of classes (composed with other classes)
- via common states (*fusing/join states*)
  - The union of the pages via join states is steered by OR, i.e., the pages add behavior, but do not destroy behavior of other pages
- Via common transitions (*fusing/join transitions*)
  - The union of the pages via join transitions is steered by AND, i.e., the pages add behavior and synchronize with transitions of other pages

Transitions are interpreted as coarse-grain events
- On the edges, other functions (actions) are called
- Hence, CPN are *open*: if something is too complicated to model as a PN, put it into functions
Coupling of Place and Transition Pages

- **Port state coupling** (or fuse, merge, composition): Place pages are coupled to other place pages via common states (port states)
  - The union of the pages is steered by OR, i.e., the pages add behavior, but do not destroy behavior of other pages

- **Port transition coupling**: Transition pages are coupled to other transition pages via common transitions (port transitions)
  - The union of the pages is steered by AND, and every page changes the behavior of other page
  - Events must be available on every incoming edge of a transition
  - The transitions of the combined net only fire if the transitions of the page components fire
Robots with Place (State) Pages, Coupled by Replicated State Ports

Robot 1 free

Taking Up → Laying Down

Piece moving

Piece available

Piece ready

Taking Up

Reused

Place Page

Port states replicated

Robot 2 free
A Robot OR-composed View

Robots get pieces A or B

Robot 1 free

Taking Up

Laying Down

Robot 2 free

Taking Up

Laying Down

Piece moving

Piece available

Piece moving

Piece available

Piece ready

Taking Up
Robots with Transition Pages, Coupled by Transition Ports

Diagram showing the process of taking up and laying down pieces with transition pages and ports.
Robots with Transition Pages, Coupled by Transition Ports

Piece moving → Piece available → Taking Up

Robot gets piece A and B

Laying Down → Robot 1 free

Piece ready → Taking Up

Robot 2 free → Laying Down

Taking Up
Advantages of CPN for the PHM

- The PHM is a distributed and mobile scenario
  - Devices can fail (battery empty, wireless broken, etc)
  - The resulting CPN can be checked on deadlock, i.e., will the PHM session manager get stuck?

- Compact specification
  - Usually, CPN are much more compact than statecharts

- Variability
  - The pages are modular, i.e., can be exchanged for variants easily (e.g., other locking scheme)
3.4 Parallel Composition of Colored Petri Nets
Parallel composition of PN

- Complex synchronization protocols can be abstracted to a pattern (also called transition page or a place page)

- When joining PN with AND (i.e., joining transition pages), synchronization protocols can be overlayed to existing sequential specifications
Unforeseeable Extensible Workflows

- Workflows are described by Colored Petri Nets (CPN) or languages built on top of CPN:
  - YAWL language [van der Aalst]
  - Workflow nets

- CPN composition can be used to enriching a workflow core with a workflow aspect:
  - **Place extension (State extension):**
    - adding more edges in and out of a place
      - OR-based composition: Core OR view: Core-place is ORed with Aspect-Place
  - **Transition extension (Activity extension):**
    - adding more edges in and out of a transition (activity)
      - AND-based composition: Core-transition is ANDed with Aspect-transition
Complex synchronization protocols can be abstracted to a transition page.

Weaving them with AND, they can be overlayed to existing sequential specifications.
Semaphores For Mutual Exclusion Revisited

- Forms a synchronisation aspect via ANDed Lock transitions
3.4.2 Extension of CPN
CPN can be Easily Extended

- By AND- and OR-composition, every CPN can be extended later
  - Planned
  - Unforeseen

- OR-composition retains the contracts of the original specification

- AND-composition restricts the original specification
Insight

- AND-Merge and OR-Merge of CPN are sufficient basic composition operators for building complex extension tools
  - such as aspect weavers for workflow languages
  - product-line tools

AND-weaving for synchronization

OR-weaving for functional extension
3.5 The Application to Modelling
Activity Diagrams

- Activity Diagrams are similar to PN, but not formally grounded
  - Without markings
  - No liveness analysis
  - No resource consumption analysis with boundness
  - No correspondence to UML-Statechart

- Difficult to prove sth. about activity diagrams and difficult to generate parallel code

Data-flow diagrams

- DFD are special form of activity diagrams, and correspond to Marked Graphs

Statecharts

- Finite automata are restricted form of Petri nets
- Hierarchical structuring in Statecharts is available in High-Level Petri Nets (e.g., CPN)
Petri Nets Generalize UML Sequence Diagrams

The life lines of a sequence diagram can be grouped into states such that a PN results.

All of a sudden, liveness conditions can be studied:
- Is there a deadlock in the sequence diagram?
- Are objects treated fair?

```
Customer Service Station Credit Card System Purchase Refuel

refuel() refuel()

verify() denied not ok

payCash() denied
```

refuel()
Petri Nets Generalize UML Sequence Diagrams

- The life lines of a sequence diagram can be grouped into state such that a PN results in a Petri net.

- All of a sudden, liveness conditions can be studied:
  - Is there a deadlock in the sequence diagram?
  - Are objects treated fair?

![Petri Net Diagram](image)
Elaboration:
1. Identify active and passive parts of the system
   - Active become transitions, passive to places
2. Find the relations between places and transitions
3. How should the tokens look like: boolean? Integers? Structured data?
   - Active become transitions, passive to places

Restructure: Group out subnets to separate “pages”

Refactor: Simplify by reduction rules

Verify: Analyse the specification on liveness, boundedness, reachability graphs, fairness. Use a model checker to verify the CPN

Transform Representation: Produce views as statecharts, sequence, collaboration, and activity diagrams.
How to Solve the Reactor Software Problem?

➤ Specify with UML and CPN
  ■ Verify it with a model checker
  ■ Let a prototype be generated
  ■ Test it
  ■ Freeze the assembler

➤ Verify the assembler, because you should not trust the CPN tool nor the compiler
  ■ Any certification agency in the world will require a proof of the assembler!

➤ However, this is much simpler than programming reactors by hand...
The Gloomy Future of PN

- PN will become the major tool in a future CASE tool or IDEs
  - Different views on the PN: state chart view, sequence view, activity view, collaboration view!

- Many isolated tools for PN exist, and the world waits for a full integration into UML

- CPN will be applied in scenarios where parallelism is required
  - Architectural languages
  - Web service languages (BPEL, BPMN, ...)
  - Workflow languages
  - Coordination languages
The End