www.jcp.org www.openrules.com

JSR 331
"Constraint Programming API"

CON3255

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Shock Troops for Business Innovation

*"I have concluded that **decision making** and the techniques and technologies to support and automate it will be the next competitive battleground for organizations.*

*Those who are using business rules, data mining, analytics and **optimization** today are the shock troops of this next wave of business innovation"*

Tom Davenport

Optimization Engines

- Optimization usually refers to a mathematical technique used to calculate the *best* possible resource utilization to achieve a desired optimization objective such as:
  - minimizing expenses or travel time
  - maximizing ROI or service level, etc.
- Optimization Engine:
  - Determines how to most effectively allocate resources, automatically balancing trade-offs and business constraints
  - Eliminates the need to manually work out plans and schedules, so your customers can achieve maximum operational efficiency
- Leading Optimization Techniques
  - LP/MIP – Linear and Mixed Integer Programming
  - CP – Constraint Programming

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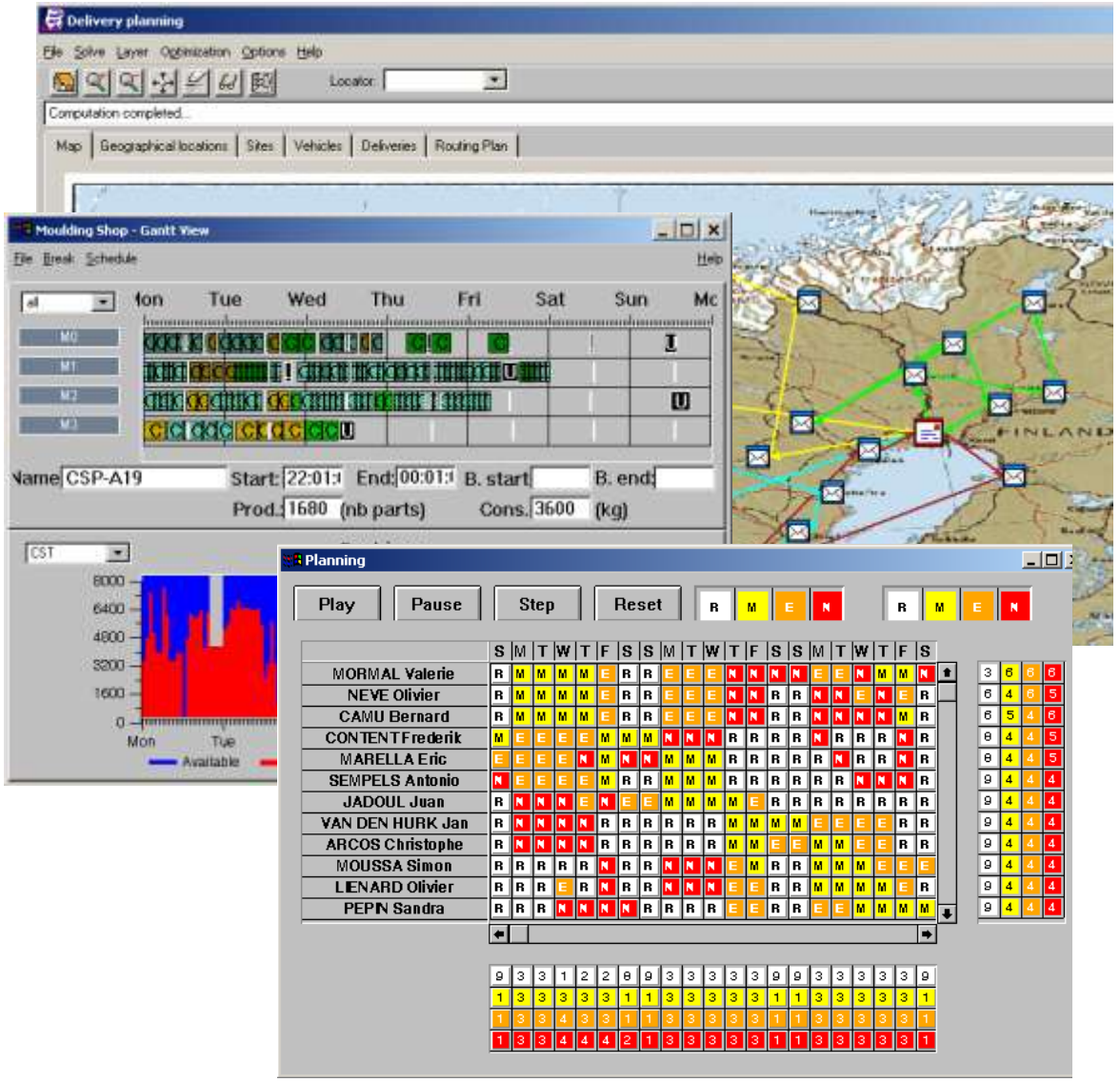
Constraint Programming (CP)

- Constraint Programming (CP) is a proven *optimization* technology supported by many of-the-shelf solvers with C++ and Java APIs
- Constraint Programming has strong roots in Operation Research and AI:
  - *Handbook of Constraint Programming* (Elsevier, 2006)
  - ACP - Association for Constraint Programming
- CP is especially successful dealing with real-world scheduling, resource allocation, and complex configuration problems
  - CP clearly separates Problem Definition from Problem Resolution bringing declarative programming to the real-world
  - CP makes different optimization techniques handily available to regular software developers (without PhD in Operation Research)

Typical CP Applications

- Scheduling and Resource Allocation
- Complex Configuration Problems
- Supply Chain Management
- Staff Rostering
- Vehicle Routing



Some Popular CP Tools

- Java API
  - **Choco, Constrainer, JaCoP, JSetL, Cream**
- C++ API
  - **IBM/ILOG CP** – Commercial (www.ilog.com)
  - **Gecode** – Open Source (www.gecode.org)
- CP environments with specialized modeling languages
  - **OPL** from IBM ILOG (www.ilog.com)
  - **MiniZinc** from G12 group, Australia (http://www.g12.cs.mu.oz.au)
  - **Comet**, Brown University (www.comet-online.org)
  - **Prolog-based tools** (ECLiPSe, SICStus)
- 20+ other CP Solvers: http://slash.math.unipd.it/cp/
- CP Solvers are usually well integrated with other optimization tools (LP, MIP)
- Lack of Standardization

JSR 331: Constraint Programming API

- JSR 331 became an official JCP standard in March 2012 and is in a maintenance mode
- This session describes:
  - Major Constraint Programming *concepts*
  - *Practical examples* of constraint satisfaction and optimization problems including scheduling and resource allocation
  - How OpenRules uses JSR 331 as an optimization component of its open source *decision management system*

JSR 331: Key Objectives

- Make CP more accessible for business software developers
- Allow a Java business application developer to easily switch between different CP solver implementations without any changes in the application code
- Assist CP vendors in creating practical and efficient JSR 331 implementations

Procedural vs Declarative Programming

- **Simple example of a constraint satisfaction problem:**

There are three integers **x**, **y**, and **z** defined from **0** to **10**.
Our goal is to find the solution that would maximize or minimize the objective function represented by the following integer expression:
cost=3x*y-4*z

subjected to:
x < y
x + y = z

- A Pure Java solution
- A CP-based solution

Java solution

```
public static void main(String[] unused) {

    for(int x = 0; x <= 10; x++) {
        for (int y = 0; y <= 10; y++) {
            for (int z = 0; z <= 10; z++) {
                if (x < y && (x + y == z))
                    System.out.println("x="+x + " y="+y + " z=" +z);
            }
```

```
public static void main(String[] unused) {

    for(int x = 0; x < 10; x++) {
        for (int y = x + 1; y <= 10; y++) {
            int z = x + y;
            if (z <= 10)
                System.out.println("x="+x + " y="+y + " z=" +z);
        }
    }
}
```

CP-based Solution

```
public class Test {

    public static void main(String[] args) {
        // ==== PROBLEM DEFINITION ==============================
        Problem p = ProblemFactory.newProblem("Test");
        // ======= Define variables
        Var x = p.variable("X", 1, 10);
        Var y = p.variable("Y", 1, 10);
        Var z = p.variable("Z", 1, 10);
        Var cost = x.multiply(3).multiply(y).minus(z.multiply(4));
        // ======= Define and post constraints
        p.post(x, "<", y); // X < Y
        p.post(x.plus(y), "=", z); // X + Y = Z

        // === PROBLEM RESOLUTION ================================
        p.log("=== Find Solution:");
        Solver solver = p.getSolver();
        Solution solution = solver.findSolution();
        if (solution != null)
            solution.log();
        else
            p.log("No Solution");
        p.log("Cost " + cost);
    }
}
```

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Constraint Satisfaction Problem - CSP

- Typical CSP structure:
  1. **Problem Definition (what to do)**
     a. Define Constrained Variables with all possible values
     b. Define Constraints on the variables
  2. **Problem Resolution (how to do it)**
     a. Find Solution(s) that defines a value for each variable such that all constraints are satisfied or
     b. Find an optimal solution that minimizes/maximizes a certain optimization objective

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How the constraint "X < Y" works

- Let's assume X and Y are defined on the domain [0,10]
- Initial constraint propagation after posting X<Y constraint:

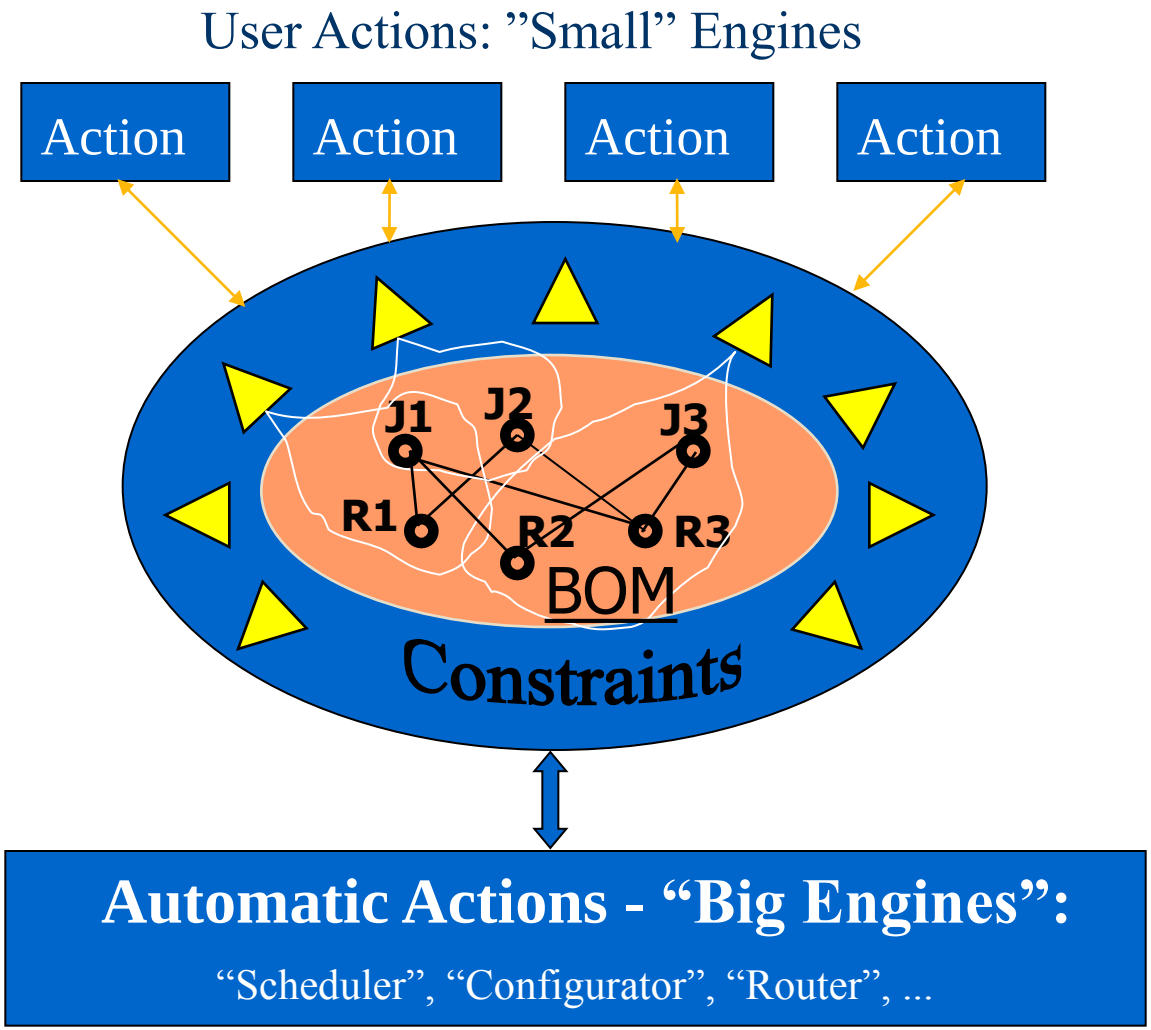
  X[0;9]

  Y[1;10]
- Changes in X cause the changes in Y

  X>3 → Y > 4
- Changes in Y cause the changes in X

  Y<=8 → X<=7
- Bi-Directional constraint propagation

Constraint Propagation (intuitive view)



JSR-331 CP API: Basic Concepts

- **Problem** – the main class that defines constraint satisfaction problems. A placeholder for all other objects and methods
  - **Var** – defines constraint integer variables
  - **VarReal** – defines constraint real variables
  - **VarBool** – defines constraint real variables
  - **VarSet** – defines constraint set variables
  - **Constraint** – defines various constraints
- **Solver** – the main class that solves constraint the problem
  - **Search Strategy**
  - **Solution**

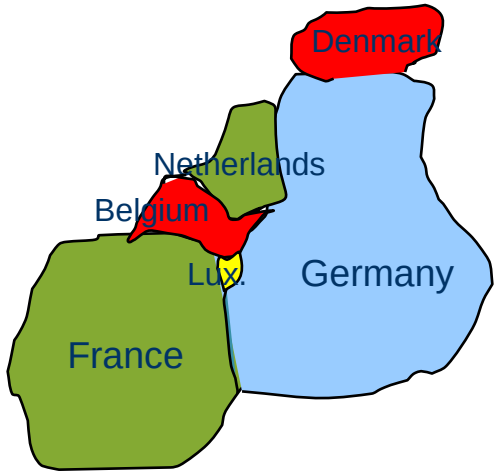
CP API: Examples

- Analyse basic JSR-331 arithmetic examples:
  - Test1 – find a solution
  - Test2 – find all solutions
  - Test3 – find an optimal solution

- Let's analyse and run these problem in Eclipse IDE

CSP Example: "Map Coloring"

- A map-coloring problem involves choosing colors for the countries on a map in such a way that at most 4 colors are used and no two neighboring countries have the same color
- We will consider six countries: Belgium, Denmark, France, Germany, Netherlands, and Luxembourg
- The colors:
  - blue, white, red or green



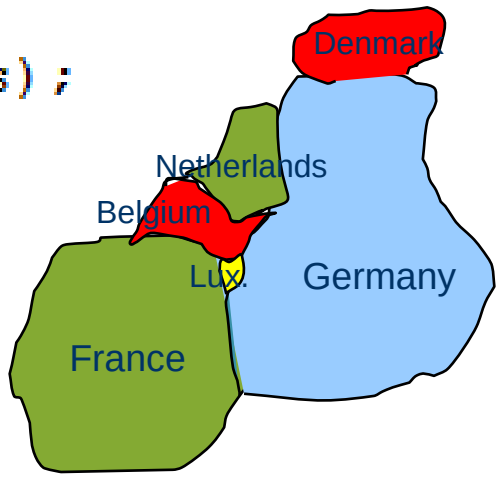
Example "Map Coloring": problem variables

```
Problem  p = ProblemFactory.newProblem("MapColoring");
// Define Variables
Var Belgium      = p.variable("Belgium",0, 3);
Var Denmark      = p. variable("Denmark".0, 3);
Var France       = p.variable("France",0, 3);
Var Germany      = p.variable("Germany",0, 3);
Var Netherlands = p.variable("Netherlands",0, 3);
Var Luxemburg    = p.variable("Luxemburg",0, 3);
```

Each country is represented as a variable that corresponds to an unknown color: 0,1,2, or 3

“Map Coloring”: problem constraints

```
p.post(France, "!=", Belgium);
p.post(France, "!=", Luxemburg);
p.post(France, "!=", Germany);
p.post(Luxemburg, "!=", Germany);
p.post(Luxemburg, "!=", Belgium);
p.post(Belgium, "!=", Netherlands);
p.post(Belgium, "!=", Germany);
p.post(Germany, "!=", Netherlands);
p.post(Germany, "!=", Denmark);
```

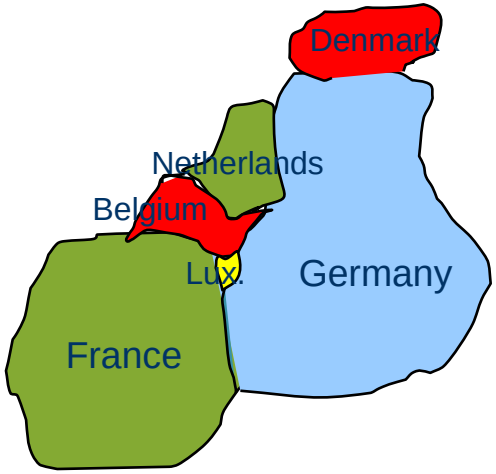


“Map Coloring”: solution search

```
Solution solution = p.getSolver().findSolution();
if (solution != null) {
    solution.log();
    for (int i = 0; i < p.getVars().length; i++) {
        Var var = p.getVars()[i];
        p.log(var.getName() + " - "
                + colors[solution.getValue(var.getName())]);
    }
} else
    p.log("no solution found");
```

// Solution:

Belgium – red
Denmark – red
France – green
Germany – blue
Netherlands – green
Luxemburg - yellow



Solve Logical Puzzle

SEND + MORE = MONEY

This example shows how to represent and solve a simple puzzle:

```
  S E N D
+ M O R E
-----------
M O N E Y
```

where different letters represent different digits.

Eclipse: SendMoreMoney.java

Logical problem: "Zebra"

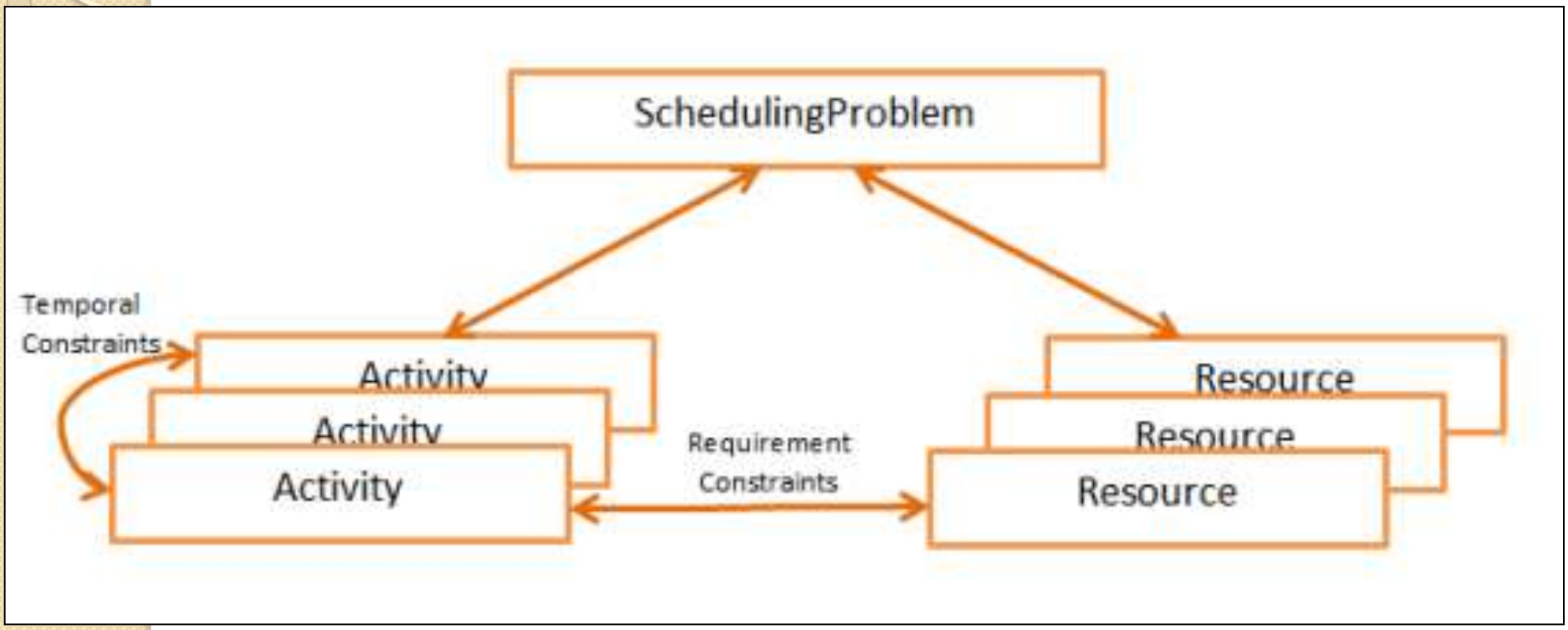
Here are the facts:
(1) There are 5 houses, each painted with a different color.
The house is numbered from 1 to 5, from left to right.
(2) Each house is occupied by only one person; each person has
a different nationality from the others.
(3) Each person drinks a different drink, smokes a different cigarette,
and has a different pet.

Now, here are the known constraints:
(1) The British lives in the red house.
(2) The Spaniard has a dog.
(3) The owner of the green house drinks coffee.
(4) The Ukrainian drinks tea.
(5) The green house is located at the right side of the white house.
(6) The person who smokes OldGolds has a snail.
(7) The owner of the yellow house smokes Kools.
(8) The person, who lives in the house exactly in the middle, drinks milk.
(9) The Norwegian lives in the house numbered one.
(10) The person who smokes Chesterfield lives next to the person who has a fox.
(11) The person who has a horse lives next to the person who smokes Kools.
(12) The person who smokes LuckyStrike drinks juice.
(13) The Japanese smokes Parliament.
(14) The Norwegian lives next to the the blue house.

The question is:
Who has a ZEBRA?

Eclipse: Zebra.java

Scheduling Problems



A special Java package: **org.jcp.jsr331.scheduler**

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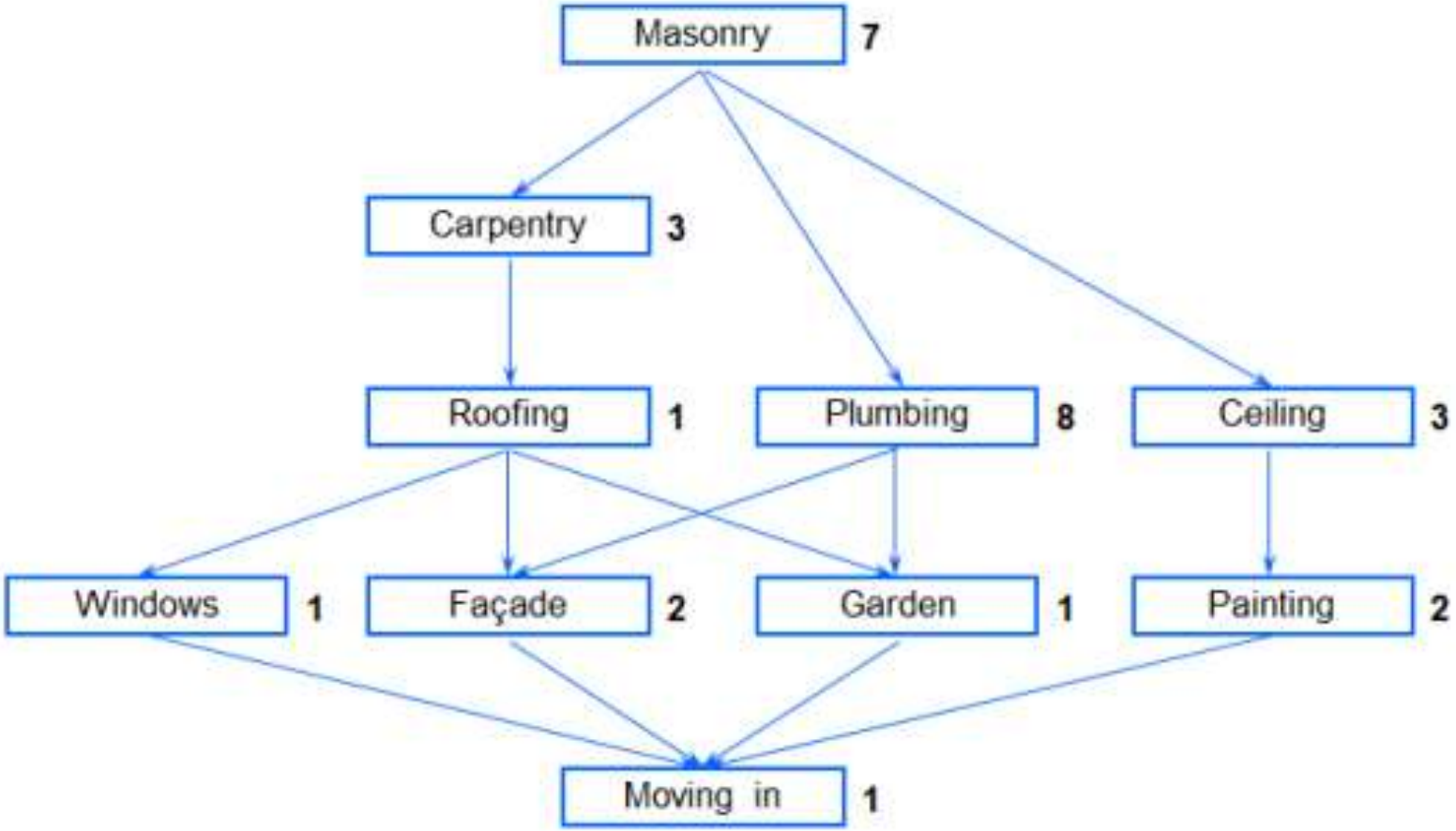
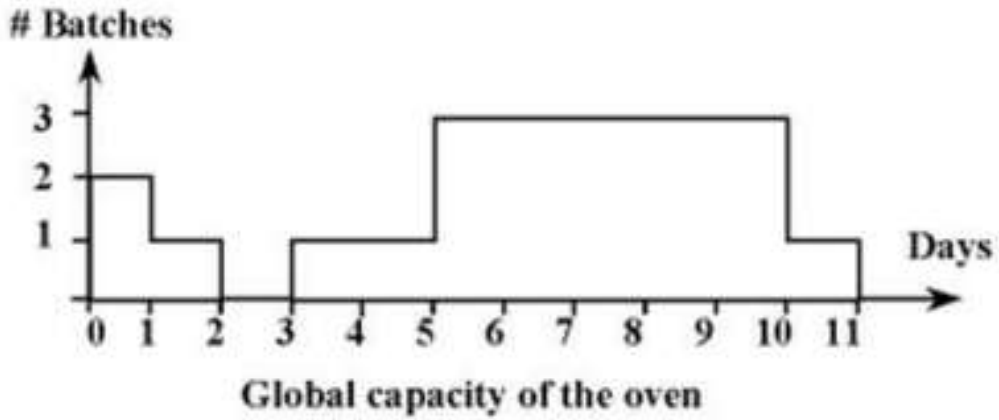
House Construction Problem



Eclipse: ScheduleActivities.java

Resource Allocation Problem

The following problem deals with activities that require a common resource. Let's consider 5 different orders (activities) that fire batches of bricks in an oven (a resource with a limited capacity). Each order 's size and duration, as well as the oven's capacity, are described in the following figure:



A 2 batches, 1 day

B 1 batch, 4 days

C 1 batch, 4 days

D 1 batch, 2 days

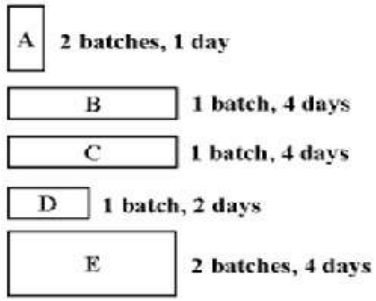
E 2 batches, 4 days

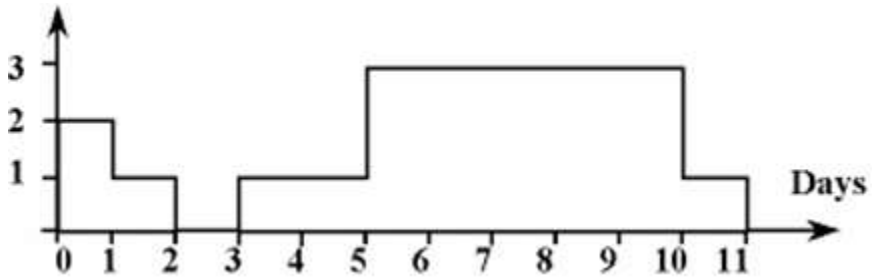
5 Activities

Eclipse: Ovens.java

Oven.java

```
Schedule schedule = ScheduleFactory.newSchedule(“oven”0, 11);
Activity A = schedule.addActivity(1, "A");
Activity B = schedule.addActivity(4, "B");
Activity C = schedule.addActivity(4, "C");
Activity D = schedule.addActivity(2, "D");
Activity E = schedule.addActivity(4, "E");
Resource oven = schedule.addResource(3, "oven");
oven.setCapacityMax(0, 2);
oven.setCapacityMax(1, 1);
oven.setCapacityMax(2, 0);
oven.setCapacityMax(3, 1);
oven.setCapacityMax(4, 1);
oven.setCapacityMax(10, 1);
// Resource Constraints
A.requires(oven, 2).post();
B.requires(oven, 1).post();
C.requires(oven, 1).post();
D.requires(oven, 1).post();
E.requires(oven, 2).post();
// Find Solution
schedule.scheduleActivities();
schedule.displayActivities();
```





SOLUTION:
A[5 -- 1 --> 6) requires oven[2]
B[3 -- 4 --> 7) requires oven[1]
C[7 -- 4 --> 11) requires oven[1]
D[0 -- 2 --> 2) requires oven[1]
E[6 -- 4 --> 10) requires oven[2]

OpenRules "Rule Solver"

- Rule Solver provides an Excel-based interface for JSR-331
- Oriented to business analysts (non-programmers)
- Allows them to model and solve business decision optimization problems without learning Java

Example "Staff Rostering"

As the manager, you are required to hire and set a weekly schedule for your employees as follows:

- Total employees required

Mon	Tue	Wed	Thu	Fri	Sat	Sun
5	8	9	10	16	18	12

- Available employees:

Employee Type	Total	Cost per Day
F/T	14	$100
P/T	4	$150

What is the minimal staffing cost?

	M	T	W	T	F	S	S
FT	5	8	9	10	14	14	12
PT	0	0	0	0	2	4	0

Decision "DefineEmployeeSchedule"

- Presented in Excel file "Decision.xls"
- Decision Variables are defined in the glossary table:

Glossary glossary				
Decision Variable	**Business Concept**	**Attribute**	**Domain**	**Unknown**
Mon FT	Roster	monFT	0-14	TRUE
Mon PT		monPT	0-4	TRUE
Tue FT		tueFT	0-14	TRUE
Tue PT		tuePT	0-4	TRUE
Wed FT		wedFT	0-14	TRUE
Wed PT		wedPT	0-4	TRUE
Thu FT		thuFT	0-14	TRUE
Thu PT		thuPT	0-4	TRUE
Fri FT		friFT	0-14	TRUE
Fri PT		friPT	0-4	TRUE
Sat FT		satFT	0-14	TRUE
Sat PT		satPT	0-4	TRUE
Sun FT		sunFT	0-14	TRUE
Sun PT		sunPT	0-4	TRUE
Total Cost		totalCost	0-20000	TRUE

Decision "DefineEmployeeSchedule"

Decision DefineEmployeeSchedule	
Decisions	**Execute Rules**
Define Employee Daily Demand	:= EmployeeDailyDemand()
Define Total Cost	:= DefineTotalCost()

DecisionTable EmployeeDailyDemand				
ActionXoperYcompareZ				
Variable	Arith Oper	Variable	Compare Oper	Value
Mon FT	+	Mon PT	=	5
Tue FT	+	Tue PT	=	8
Wed FT	+	Wed PT	=	9
Thu FT	+			
Fri FT	+			
Sat FT	+			
Sun FT	+			

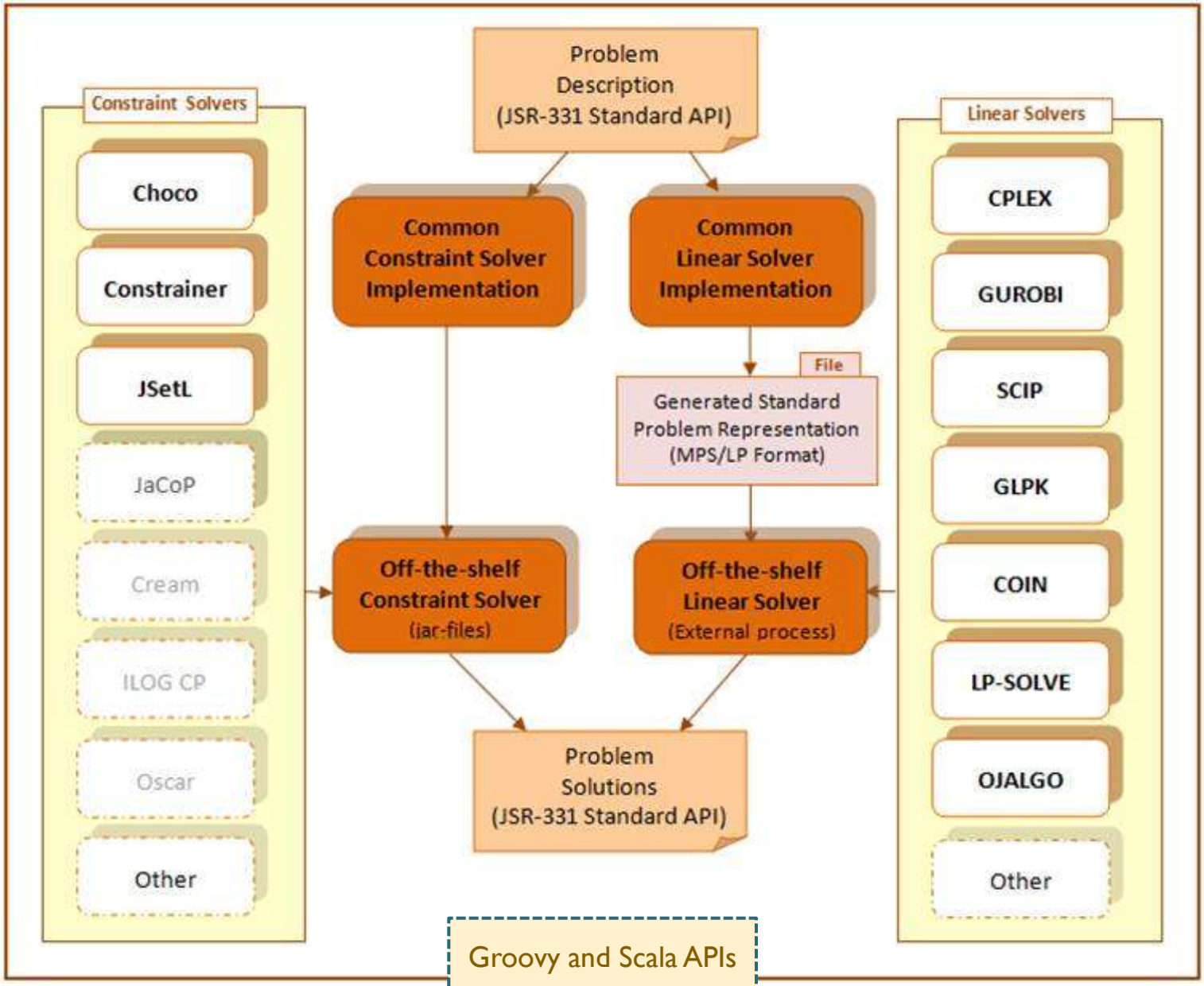
DecisionTable DefineTotalCost		
ActionScalProd		
Name of the Scalar Product	**Numbers**	**Variables**
Total Cost	100,150,100,150,100,150, 100,150,100,150,100,150, 100,150	Mon FT, Mon PT, Tue FT, Tue PT, Wed FT, Wed PT, Thu FT, Thu PT, Fri FT, Fri PT, Sat FT, Sat PT, Sun FT, Sun PT

Run Decision from Java

```
import com.openrules.ruleengine.Decision;

public class Main {

    public static void main(String[] args) {

        String fileName = "file:rules/Decision.xls";
        System.setProperty("OPENRULES_MODE", "Solve");
        Decision decision = new Decision("DefineEmployeeSchedule",fileName);
        decision.put("MaxSolutions", "30");
        decision.put("Minimize","Total Cost");
        decision.execute();
        decision.execute("PrintSolution");
    }
}
```

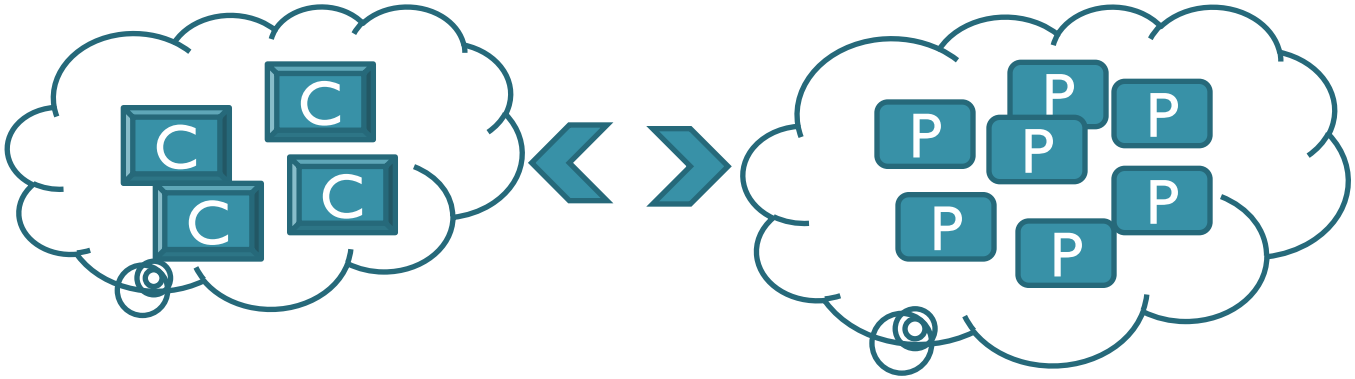
```
==== Optimal Solution =====
    M  T  W   T   F   S   S
FT  5  8  9  10  14  14  12
PT  0  0  0   0   2   4   0
Total Cost:  8100
====================
```

JSR-331 Implementations



Use Case "Cloud Balancing"

- You have a number of cloud computers and need to run a number of processes on those computers
- Each process requires certain CPU power, RAM, and network bandwidth and incurs a certain maintenance cost (which is fixed per computer)
- Objective: assign process to computers while minimize the total maintenance cost



Variable Computer

- Input classes: CloudComputer, CloudProcess
- Decision variables are in this class:

```
public class VarComputer {
    CloudComputer computer;
    Var[] processVars; // processVars[i] = 1 means this computer is used by the i-th process

    public VarComputer(Problem p, CloudComputer computer, CloudProcess[] processes,
            int[] requiredMemories, int[] requiredCpuPowers, int[] requiredNetworkBandwidths) {
        this.computer = computer;
        processVars = new Var[processes.length];
        for (int i = 0; i < processes.length; i++) {
            String name = "P" + processes[i].getId() + "C" + computer.getId();
            processVars[i] = p.variable(name,0,1);
        }
        p.post(requiredMemories, processVars,"<=",computer.getMemory());
        p.post(requiredCpuPowers, processVars,"<=",computer.getCpuPower());
        p.post(requiredNetworkBandwidths, processVars,"<=",computer.getNetworkBandwidth());
    }

    public Var[] getProcessVars() {
        return processVars;
    }
}
```

Modeling and Search for an Optimal Solution

- **A small problem "4 x12"** with a constraint solver
  - 4 computers and 12 processes
  - "Brute force" approach: 650mills
  - "Sort processes first" approach: 490 mills
- **A larger problem "10 x 20"**
  - Constraint solver takes 30 seconds
    - (50x longer) and only when we set a time limit
  - Linear Solver (identical source code, just different jars in classpath)
    - Finds an optimal solution in 1,200 milliseconds

Modeling and Search for an Optimal Solution (2)

- **A large problem "50 x100"**
  - 50 computers and 100 processes
  - Constraint solver requires special selectors and time limits
  - Linear Solver takes 2.5 hours to find an optimal solution
- **A huge problem "5,000 x 55,000"**
  - Offered at the recent ROADEF-2012 competition
  - The winners found the best solution within 5 mins using a unique selection of subsets of processes and computers and a specially written solver

JSR 331 Free Downloads

- Open Source
- Download JSR-331
  - http://openrules.com/jsr331
- Detailed Documentation
- Want to contribute?
  - Email to jacobfeldman@openrules.com to get an SVN access
- Rule Solver
  - http://openrules.com/rulesolver.htm