CPLEX Optimization – IBM Germany
2015-10-06

# Using computing resources with IBM ILOG CPLEX

## CO@W2015

- Hardware resources
  - Multiple cores/threads
  - Multiple machines
  - No machines
- Software resources
  - Interfacing with CPLEX
  - Interacting with Python

# Using more than one core/thread to solve a problem

# Sequential branch and bound

Search tree

T

min $c^T x$
$Ax = b$
$x_j$ in {0, 1}

Pseudo code:

```
while !T.is_empty
  n = T.get_next()
  n.solve()
  if not (n.is_integer() ||
          n.is_infeasible())
    j = n.fractional_index()
    v = n.fractional_value(j)
    T.create(n + “x[j] <= floor(v)”)
    T.create(n + “x[j] >= ceil(v)”)
```

# Sequential branch and bound

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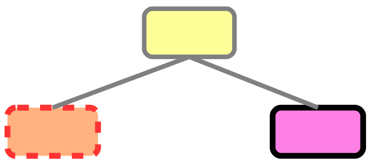

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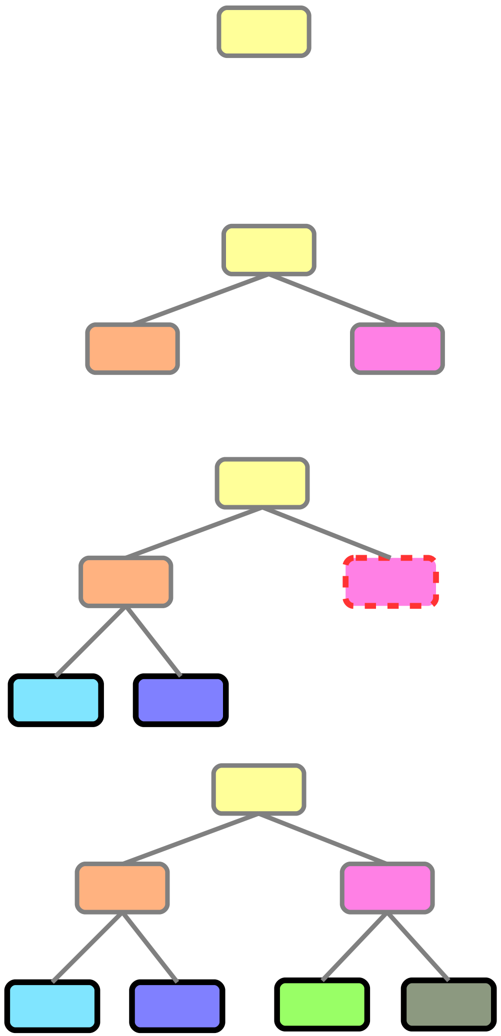
3.

4.



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# Parallel branch and bound

```
while !T.is_empty
  T.lock()
  n = T.get_next()
  T.unlock()
  n.solve()
  if not (n.is_integer() ||
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    j = n.fractional_index()
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    T.lock()
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```
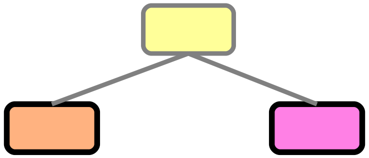

# Parallel branch and bound

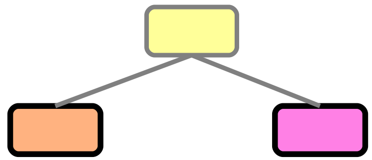
Thread 1



Thread 2

# Parallel branch and bound

Thread 1

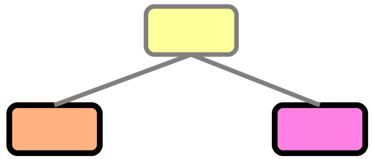


Thread 2

T.lock()

T.lock()

# Parallel branch and bound



## Thread 1

T.lock()

T.get_next()

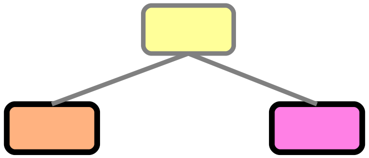
T.unlock()

## Thread 2

T.lock()

**suspended**

# Parallel branch and bound



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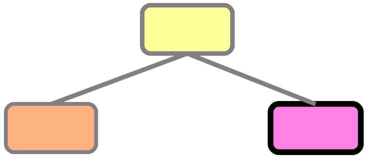


## Thread 2

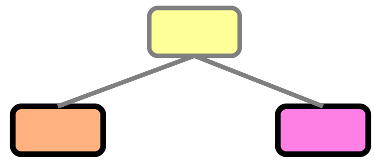
T.lock()

**suspended**

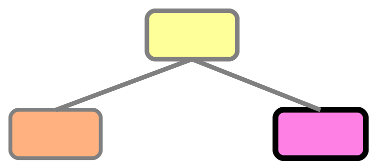
T.get_next() 

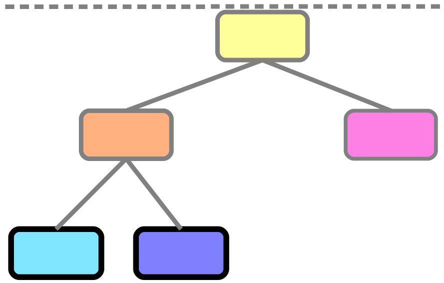
T.unlock()

# Parallel branch and bound



| Thread 1 | Thread 2 |
|---|---|
| T.lock() | T.lock() |
| T.get_next()<br>T.unlock() | **suspended** |
| solve | T.get_next()<br>T.unlock() |
| T.lock()<br>T.create()<br>T.unlock() | solve<br>T.lock()<br>**suspended** |





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| --- | --- |
| T.lock() | T.lock() |
| T.get_next()<br>T.unlock() | **suspended** |
| solve | T.get_next()<br>T.unlock() |
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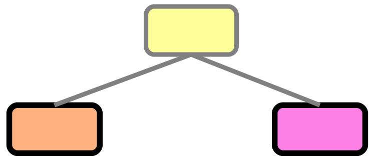
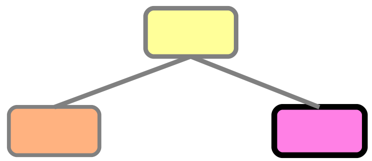
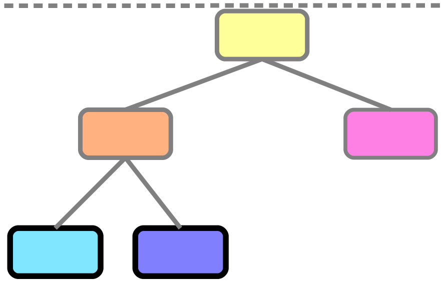
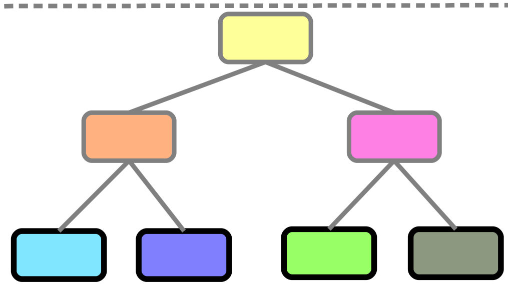
| | T.create()<br>T.unlock() |

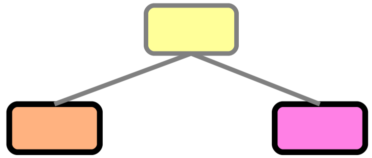








# Not deterministic!



| Thread 1 | Thread 2 |
| --- | --- |
| T.lock() | T.lock() |
| T.get_next()<br>T.unlock() | |
| solve | **suspended** |
| T.lock()<br>T.create()<br>T.unlock() | |
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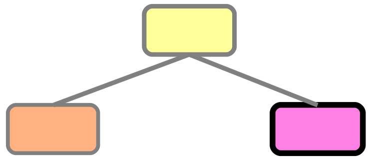

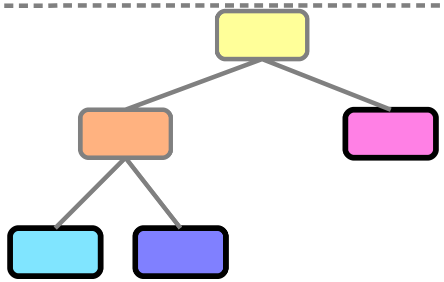

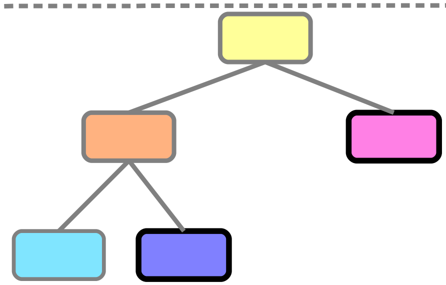

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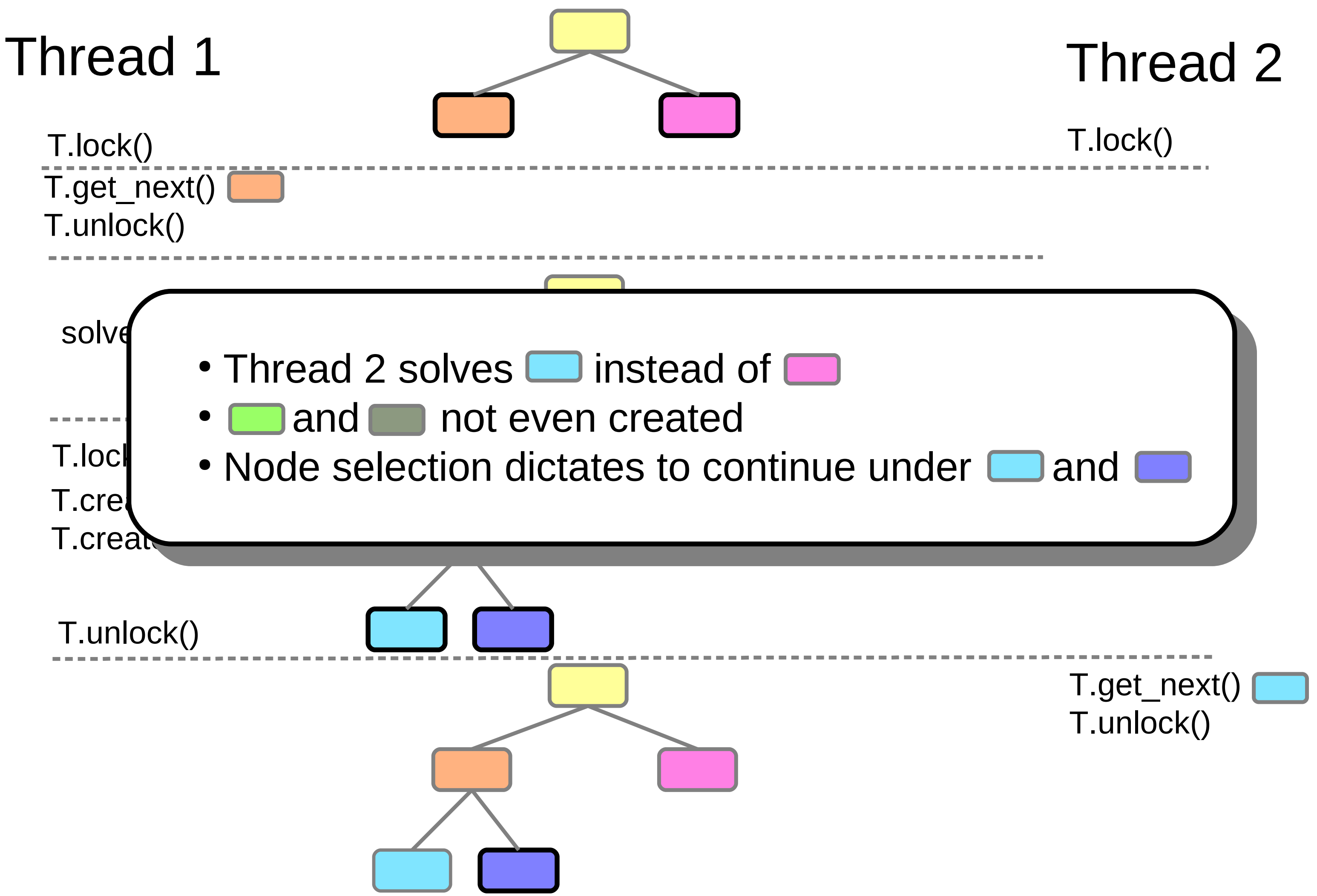

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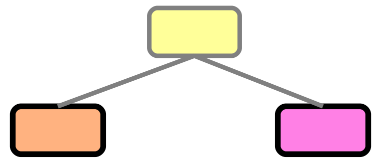
Thread 2



T.lock()

T.get_next()
T.unlock()

T.lock()

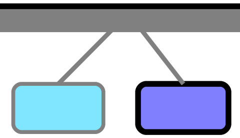
solve

T.lock
T.crea
T.crea

T.unl

- Thread 2 solves instead of
- and not even created
- Node selection dictates to continue under and

Assume must be processed to find optimal solution
Assume processing is enough to prove optimality
→ very different node counts, although same problem, code, hardware



# Issues with non-determinism

- opportunistic behavior of OS scheduler
- very minor side effects (cache misses, page swaps, …) can change order of threads

This is a problem in practice:

| gmu-35-40 | | |
|---|---|---|
| Time | Iterations | Nodes |
| 21.31 | 2236199 | 444838 |
| 18.46 | 2060789 | 322282 |
| **4.62** | **253871** | **51778** |
| 31.55 | 3300767 | 509641 |
| 11.89 | 1238162 | 177236 |
| **79.50** | **7212334** | **1307340** |
| 21.10 | 2955104 | 595939 |
| 16.27 | 1953450 | 401507 |
| 13.61 | 1410170 | 261508 |
| 17.10 | 1948228 | 410949 |

| iis-pima-cov | | |
|---|---|---|
| Time | Iterations | Nodes |
| **62.92** | **1678290** | **17744** |
| 139.72 | 5475373 | 47428 |
| 84.39 | 2075243 | 26460 |
| 80.37 | 2766163 | 22016 |
| 71.25 | 1753092 | 17513 |
| 69.18 | 1615592 | 21636 |
| 117.43 | 3002680 | 40299 |
| 72.41 | 1704471 | 21301 |
| 124.01 | 4863607 | 42298 |
| **191.31** | **7898071** | **71043** |

| glass4 | | |
|---|---|---|
| Time | Iterations | Nodes |
| 41.60 | 6577338 | 340192 |
| 70.57 | 11800428 | 637471 |
| **29.30** | **4075955** | **304913** |
| 34.31 | 6026804 | 208466 |
| 160.12 | 29207354 | 1082067 |
| **244.62** | **35189917** | **1893985** |
| 54.40 | 8700758 | 512053 |
| 74.64 | 11307243 | 698508 |
| 47.19 | 8600157 | 389436 |
| 54.42 | 8275014 | 544172 |

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- → results are not repeatable
- → debugging becomes painful
- → benchmarking is complicated
- → assessment of algorithmic changes is difficult
  “Is my new cut really helpful or is this just a random change?”

**→ We need a solver that operates in a <u>deterministic</u> way!**

# Deterministic multi-threading

opportunistic — OS scheduler, cache misses, swaps, ...
→ order in which lock is granted to threads is not deterministic

deterministic — make this order deterministic:

- use **deterministic time** → same in any run
- grant lock to first thread to arrive in **deterministic time**

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| Kendo | “Kendo: Efficient Deterministic Multithreading in Software”<br>http://people.csail.mit.edu/mareko/asplos073-olszewski.pdf<br>→ use number of retired store instructions as time (x86) |

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CPLEX
deterministic time = number of array accesses
- ➔ works the same on all hardware
- ➔ explicit instrumentation of source code

```
for (int i = 0; i < n; ++i)
   x[i] = y[i] * 0.5;
DETCLOCK_INDEX_ARRAY (2 * i);
```

# Deterministic multi-threading

- Deterministic threading is not for free
  - settle for a particular path through the search tree
  - increases wait/idle times in locks

| gmu-35-40 | | |
|---|---|---|
| Time | Iterations | Nodes |
| 4.62 | 253871 | 51778 |
| 79.50 | 7212334 | 1307340 |
| **38.48** | **4124364** | **737994** |

| iis-pima-cov | | |
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| 62.92 | 1678290 | 17744 |
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| **72.84** | **1382605** | **20449** |

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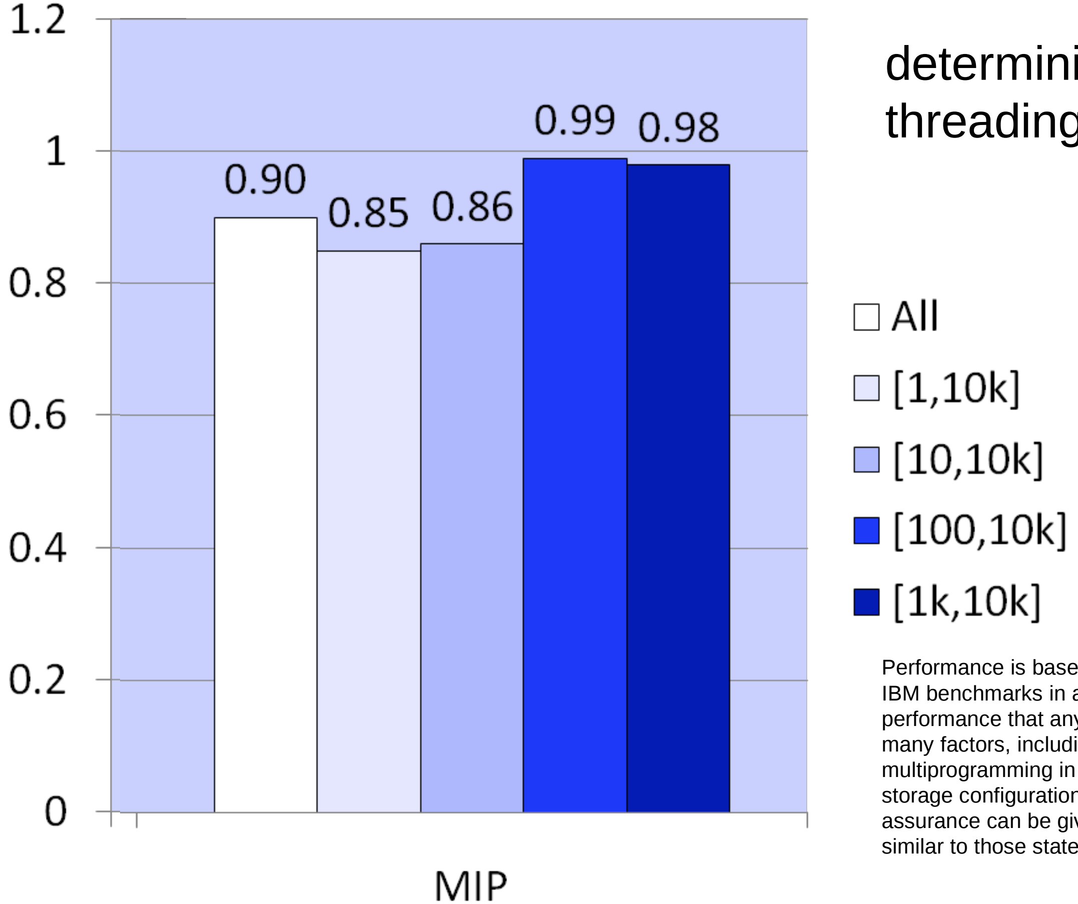


deterministic vs. opportunistic threading

Performance is based on measurements and projections using standard IBM benchmarks in a controlled environment. The actual throughput or performance that any user will experience will vary depending upon many factors, including considerations such as the amount of multiprogramming in the user's job stream, the I/O configuration, the storage configuration, and the workload processed. Therefore, no assurance can be given that an individual user will achieve results similar to those stated here.

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- Deterministic threading is unrelated to performance variability
  - parallel cut loop is still meaningful

- CPLEX extensions of Kendo framework allow efficient parallel cutloop
  - → opportunistic code, but results are deterministic

- All parallel algorithms in CPLEX are available as opportunistc/deterministic
  - → select at runtime with a parameter

# Using more than one machine to solve a problem

# Distributed parallel MIP

CPLEX implements distributed parallel MIP solving

- one master process to coordinate the search
- several worker processes to perform the heavy lifting
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- 3 different ways of communication:

`ssh` → master starts workers via ssh
→ communication via pipes

`TCP/IP` → workers run a server-like process to which master connects
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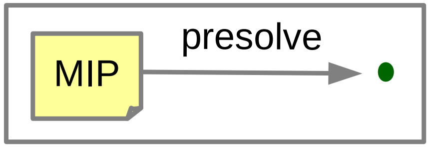
- 2 phases:
  1. “rampup” → create an initial set of open nodes
  2. “tree search” → perform distributed parallel b&b

# Phase I: rampup

1. master runs presolve to create a root node



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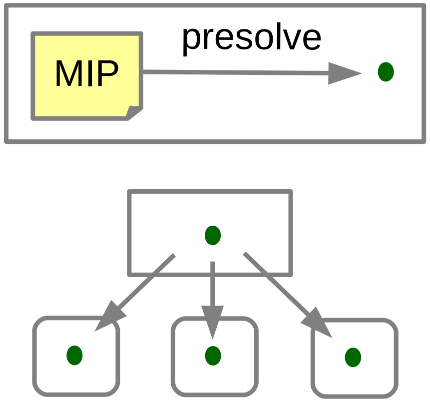


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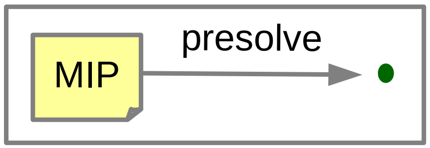


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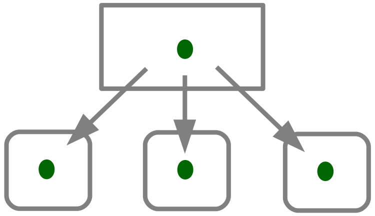
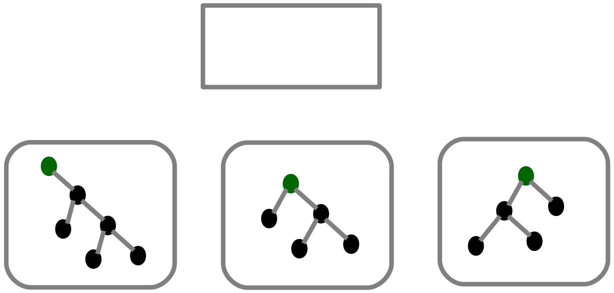


3. each worker starts b&b with different parameters
→ each worker produces a different tree



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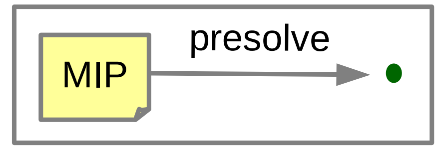


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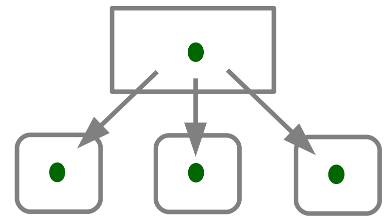

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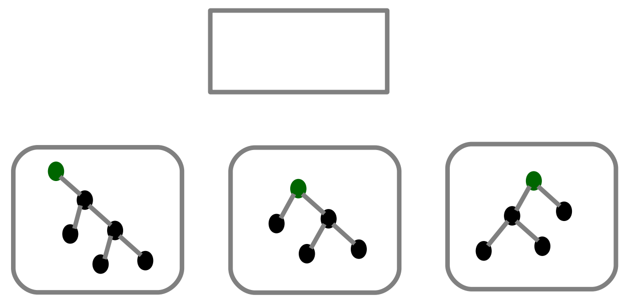
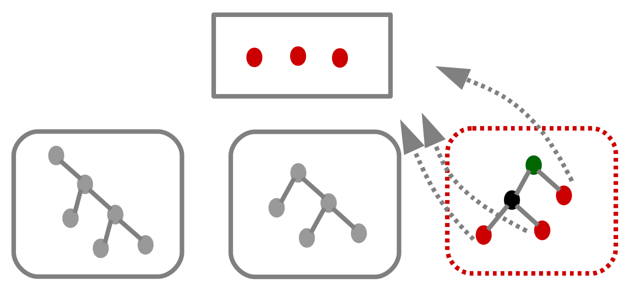


4. master eventually
   - stops workers
   - selects a winner
   - collects open nodes from winner

   → list of “supernodes”



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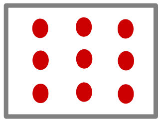
5. master starts with list of supernodes



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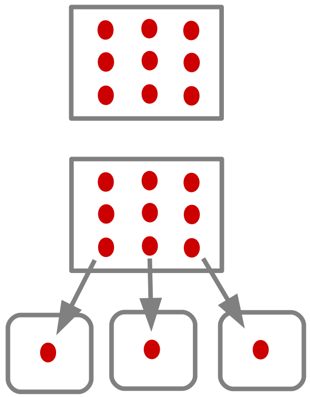

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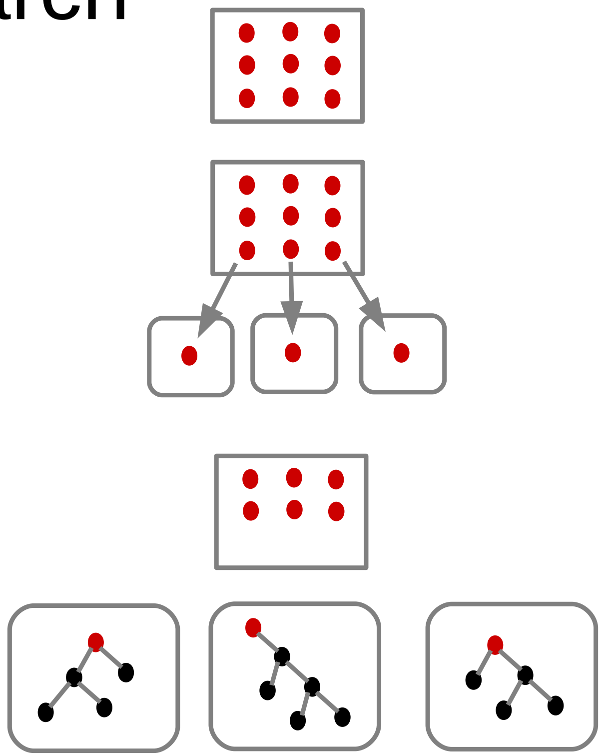

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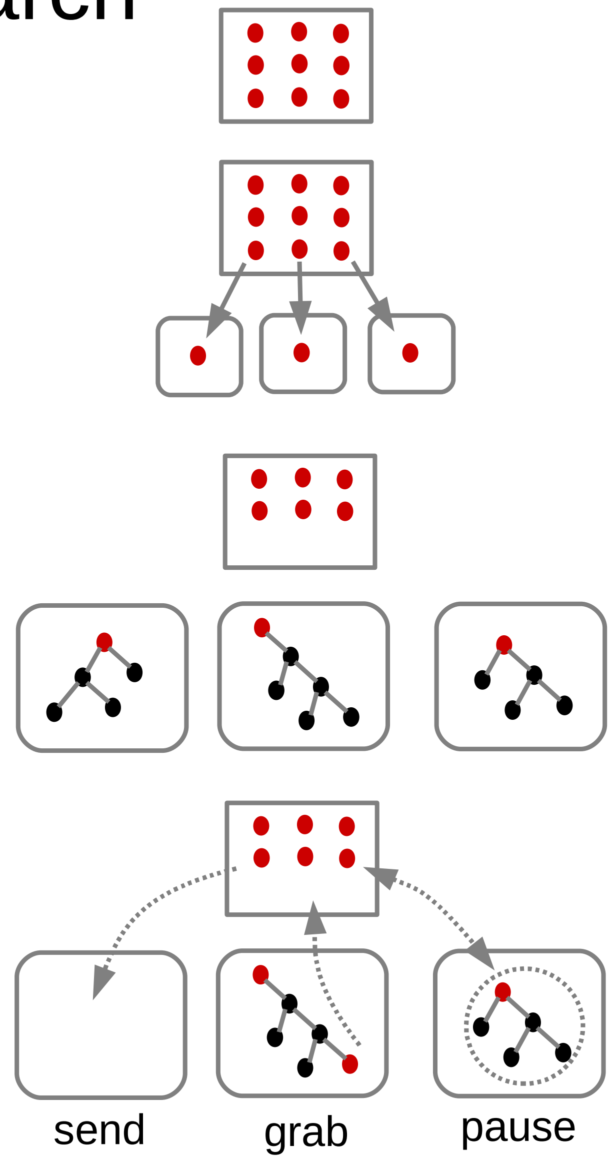
6. master sends a supernode to each worker
7. workers solve supernode as MIP
8. Master can
   - send new supernodes (if idle)
   - grab nodes to produce new supernodes
   - pause supernode (exchange)



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Variants/improvements

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   - aggressive heuristics → quickly find good solutions
   - aggressive cuts → quickly improve dual bound
   - ...

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Variants/improvements

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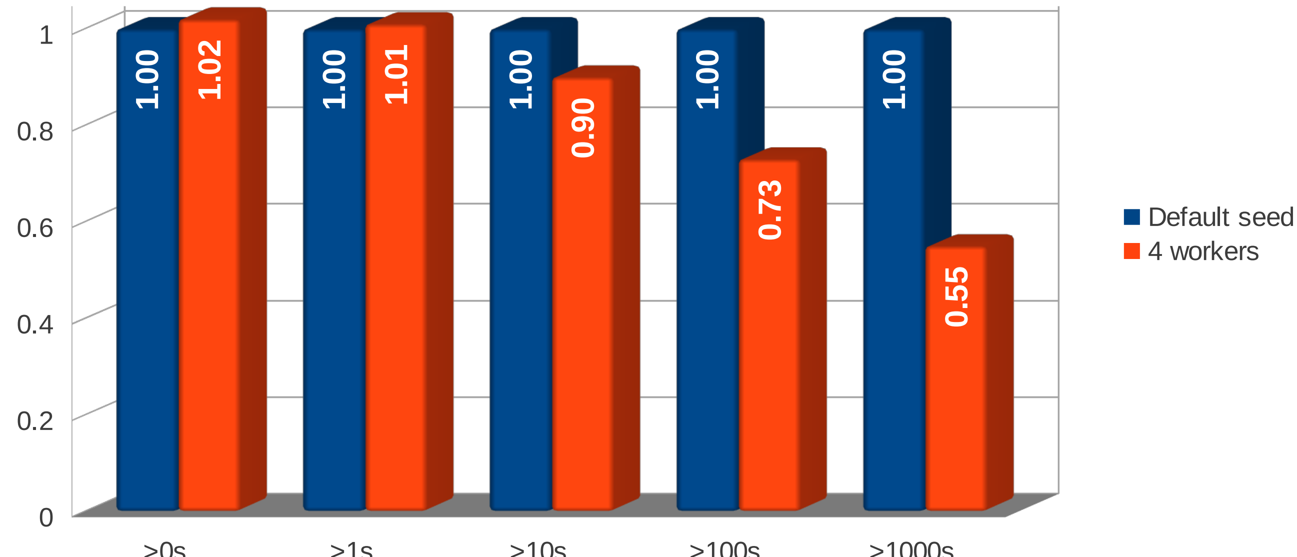
2. in rampup, start some workers with special settings
   - aggressive heuristics → quickly find good solutions
   - aggressive cuts → quickly improve dual bound
   - ...
3. never stop the rampup phase → exploit performance variability




Performance is based on measurements and projections using standard IBM benchmarks in a controlled environment. The actual throughput or performance that any user will experience will vary depending upon many factors, including considerations such as the amount of multiprogramming in the user's job stream, the I/O configuration, the storage configuration, and the workload processed. Therefore, no assurance can be given that an individual user will achieve results similar to those stated here.

# Solving a problem without a machine

# CPLEX in the cloud

What if no local resources to solve model?

- model too hard
- only need to solve once in a while
- ...

→ solve in the cloud

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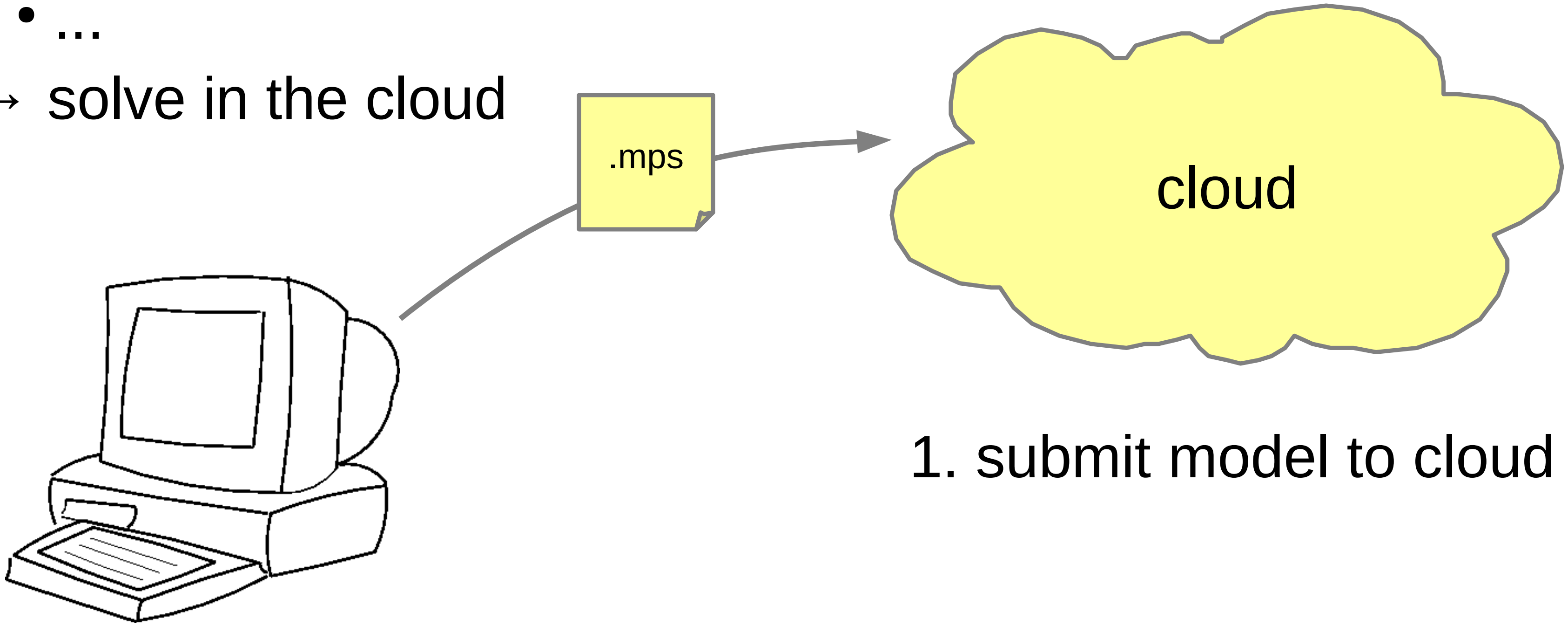


1. submit model to cloud

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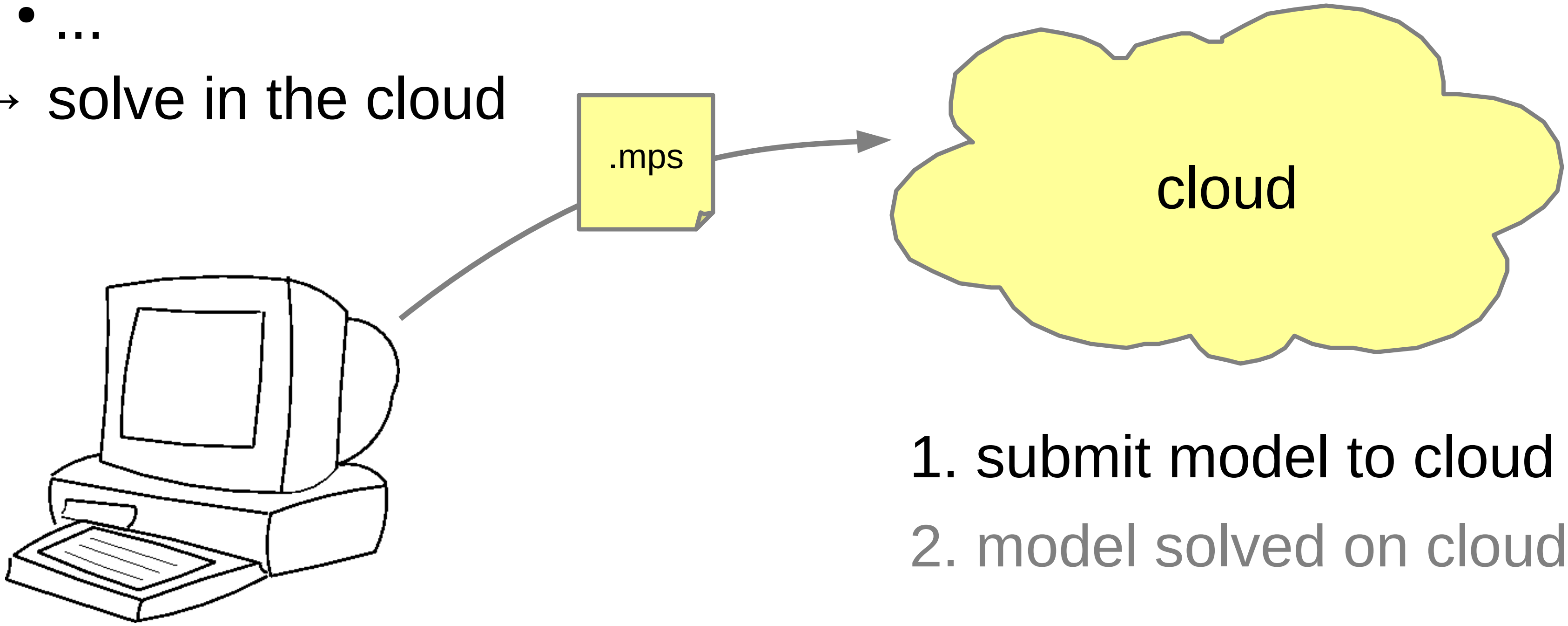


1. submit model to cloud
2. model solved on cloud

# CPLEX in the cloud

What if no local resources to solve model?

- model too hard
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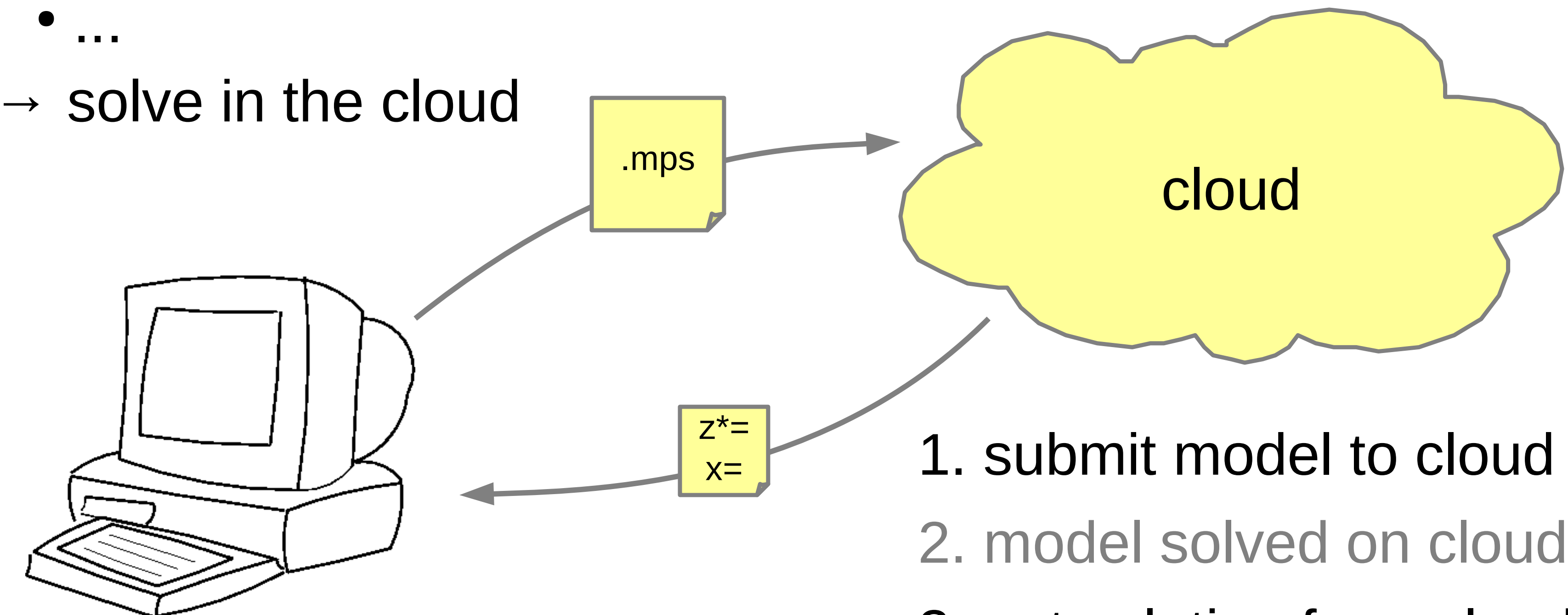
→ solve in the cloud




1. submit model to cloud
2. model solved on cloud
3. get solution from cloud

# CPLEX in the cloud

Two ways to access CPLEX in the cloud

1. Dropsolve

`www.ibm.com/software/analytics/docloud`
`dropsolve-oaas.docloud.ibmcloud.com/software/analytics/docloud`

Drag and drop your model file from disk to web browser

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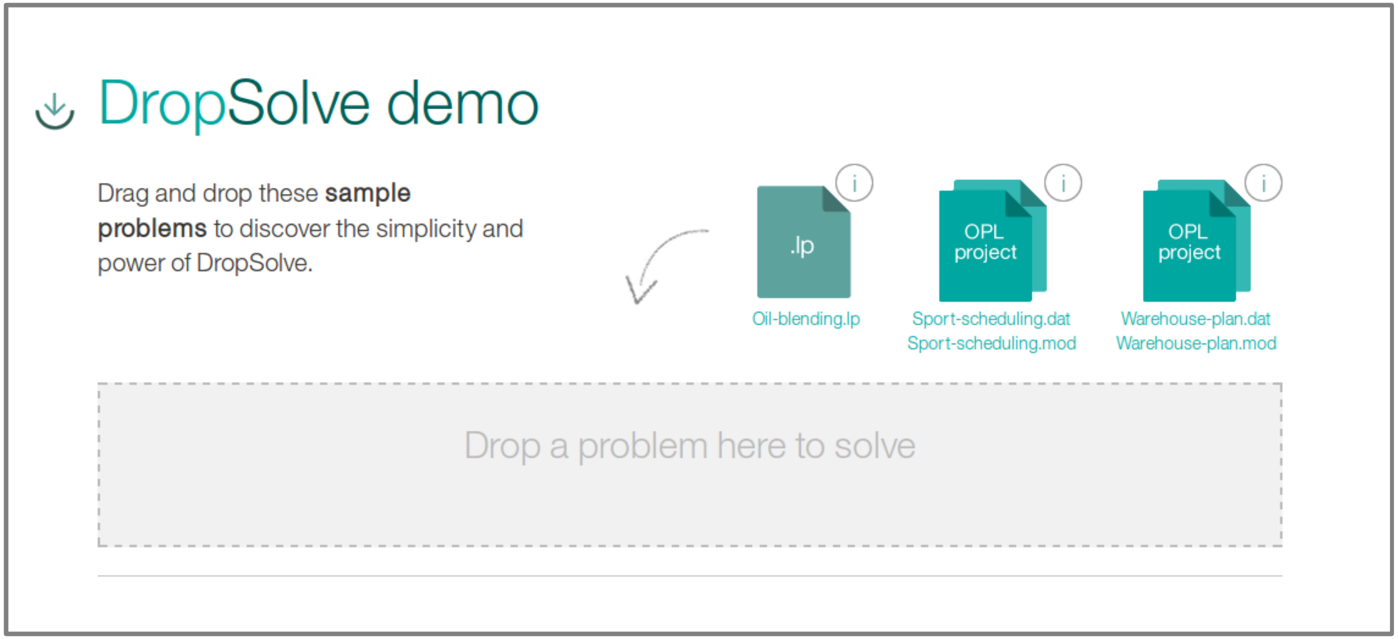

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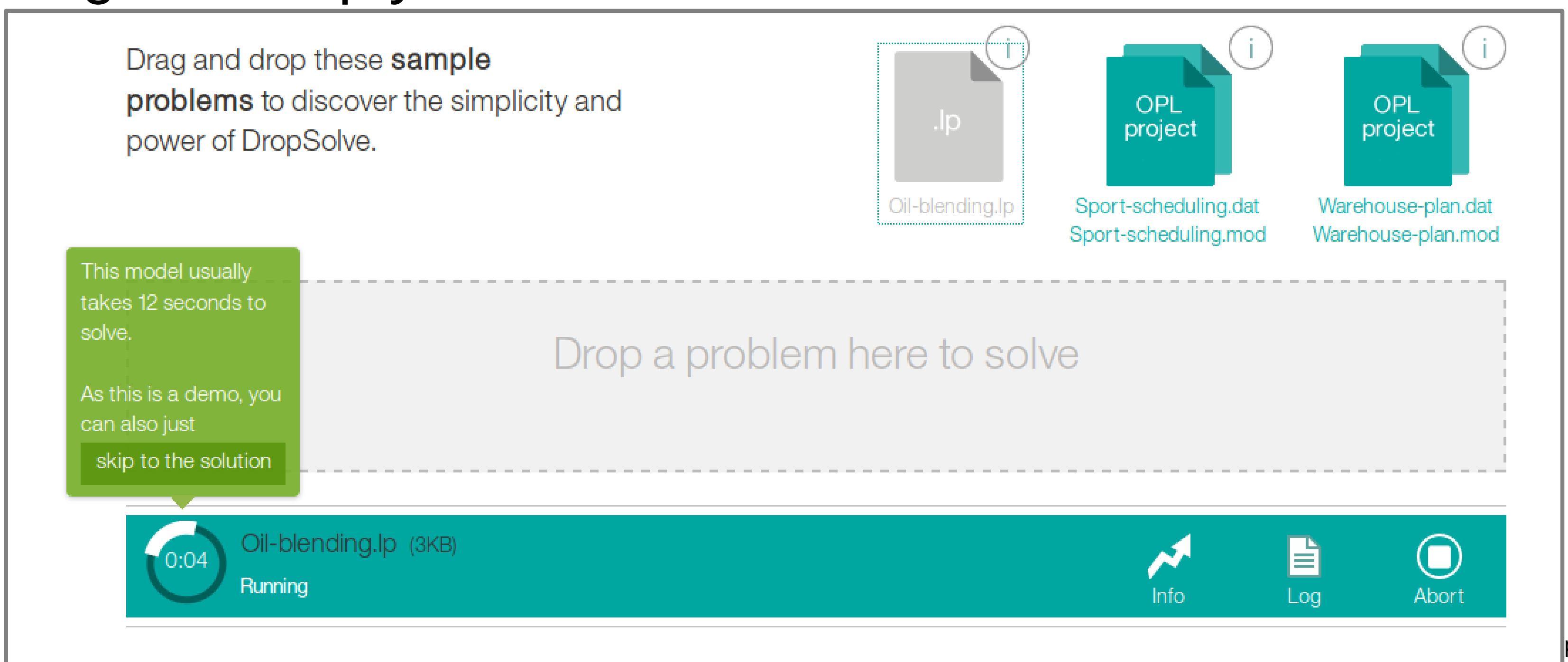

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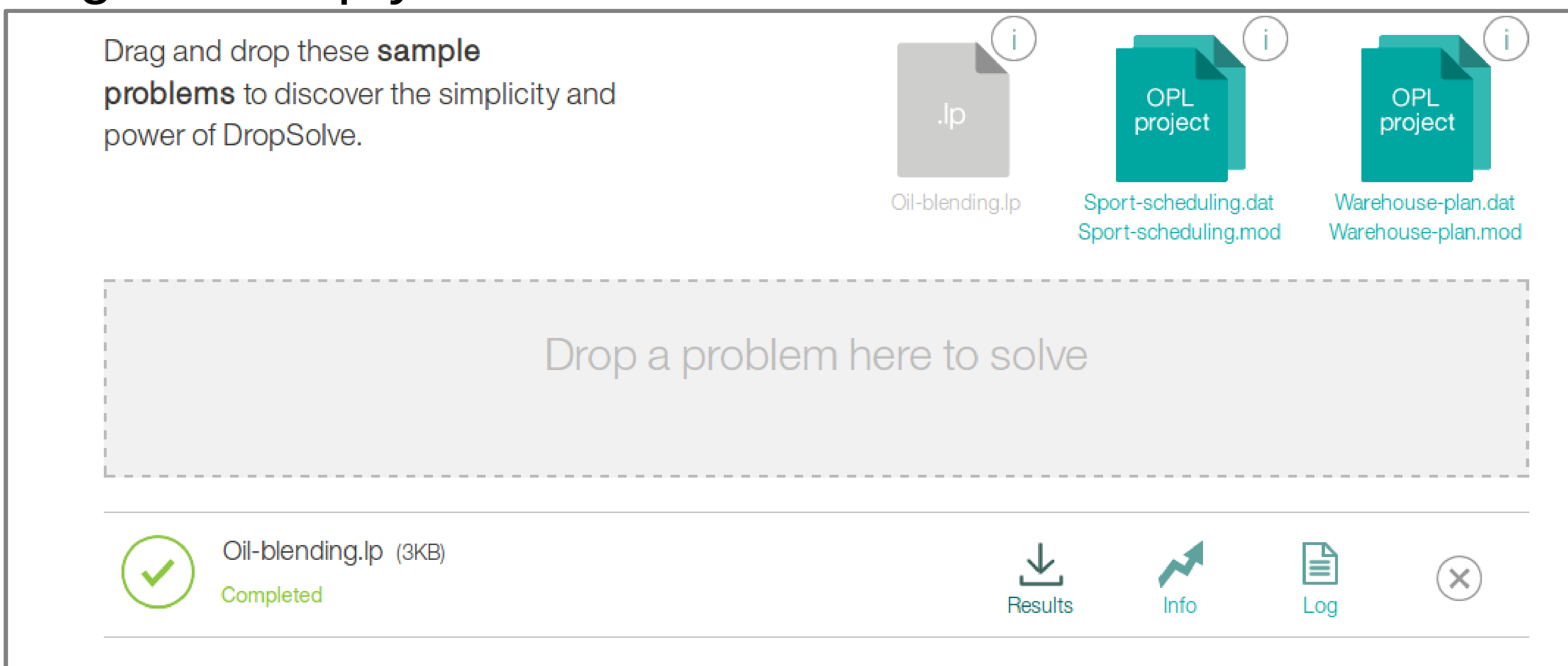

# CPLEX in the cloud

Two ways to access CPLEX in the cloud

2. REST API

https://developer.ibm.com/docloud/
https://developer.ibm.com/docloud/docs/welcome/

Access the solve service via its REST API

# CPLEX in the cloud

## Two ways to access CPLEX in the cloud

## 2. REST API

https://developer.ibm.com/docloud/
https://developer.ibm.com/docloud/docs/welcome/

Access the solve service via its REST API

- ready-to-use clients provided for Java™ and Python, e.g.

```
JobExecutor executor = JobExecutorFactory.createDefault();
JobClient jobclient = JobClientFactory.createDefault(BASE_URL,
                                                     APIKEY_CLIENTID);
jobclient.newRequest().input(new File("model.mps"))
                      .output(new File("x.sol"))
                      .execute(executor).get();
```

- With any HTTP client (cURL, ...)

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# CPLEX in the cloud

Sign up for a free trial

www.ibm.com/software/analytics/docloud

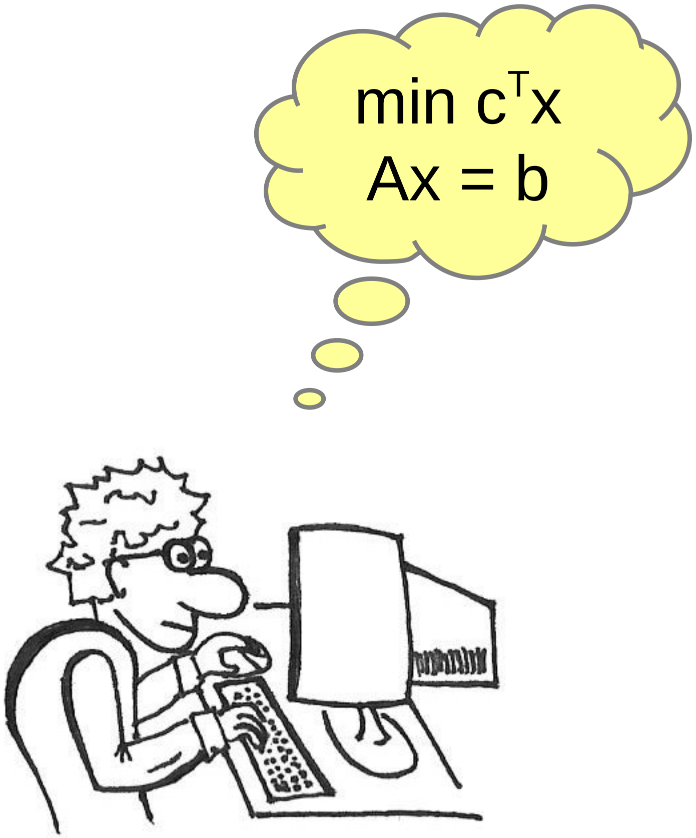
https://developer.ibm.com/docloud/

free CPLEX community edition

www.cplex.com

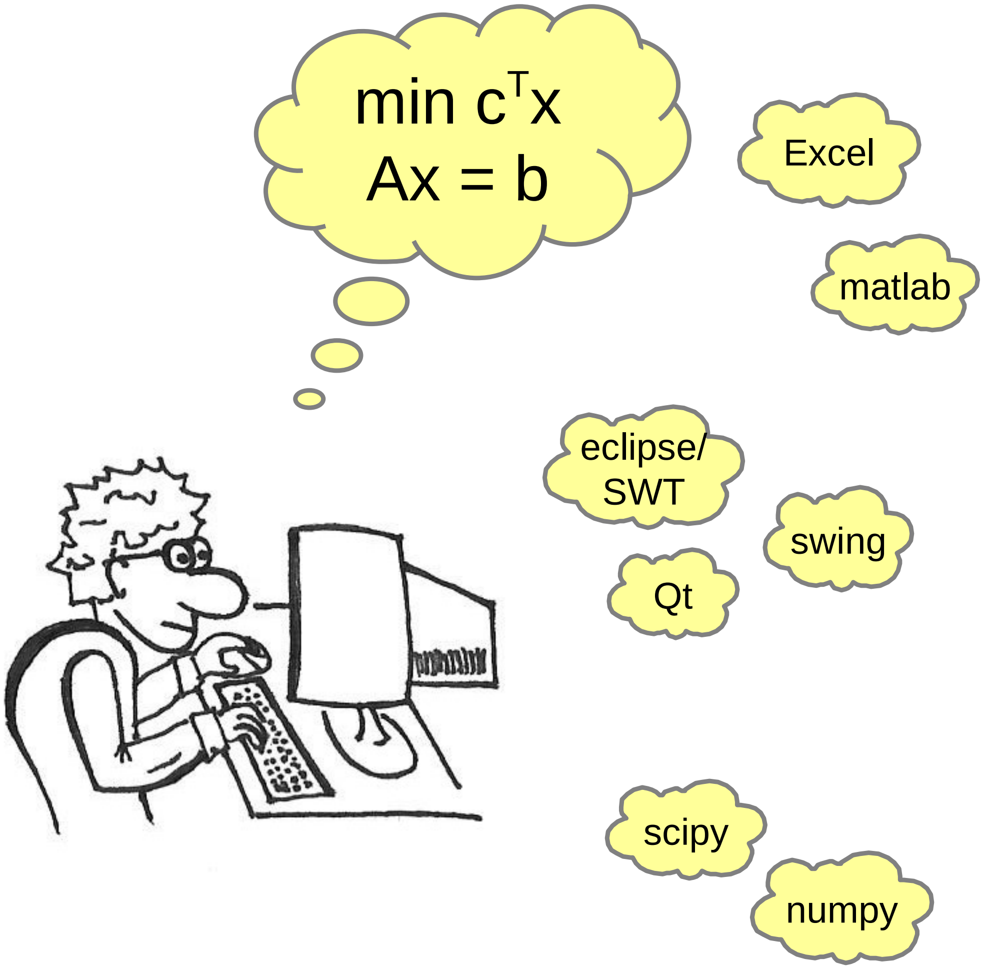
# Exploiting existing software resources

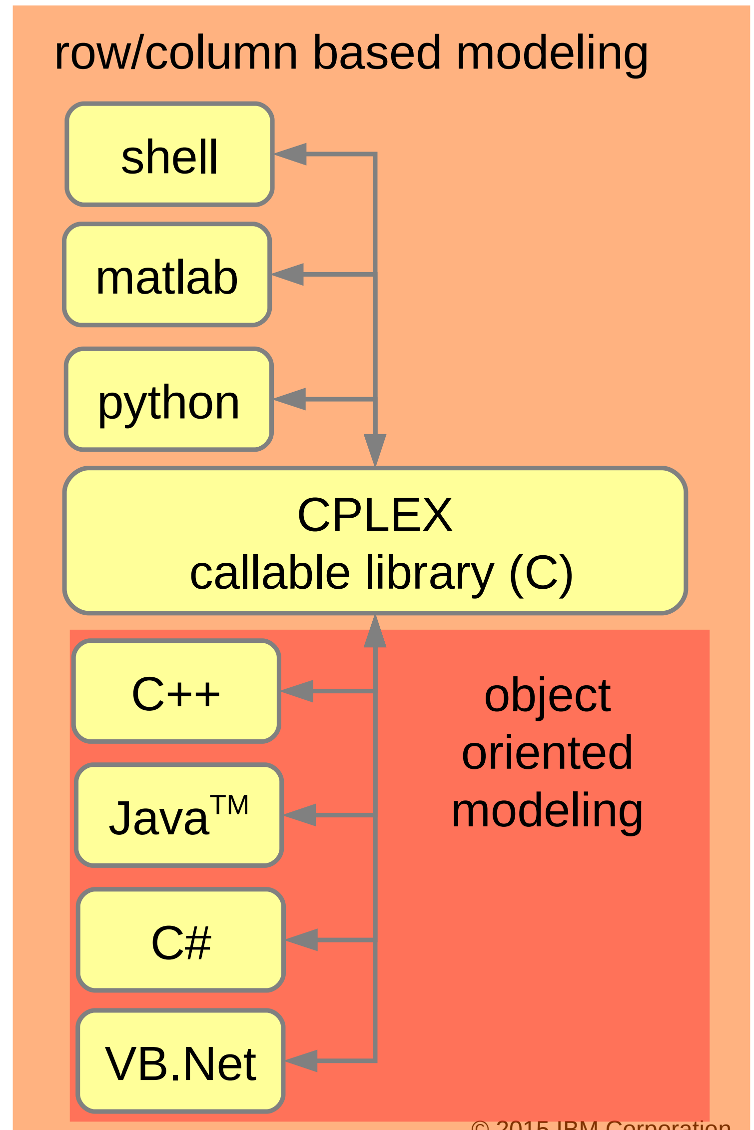
# Interfacing with CPLEX



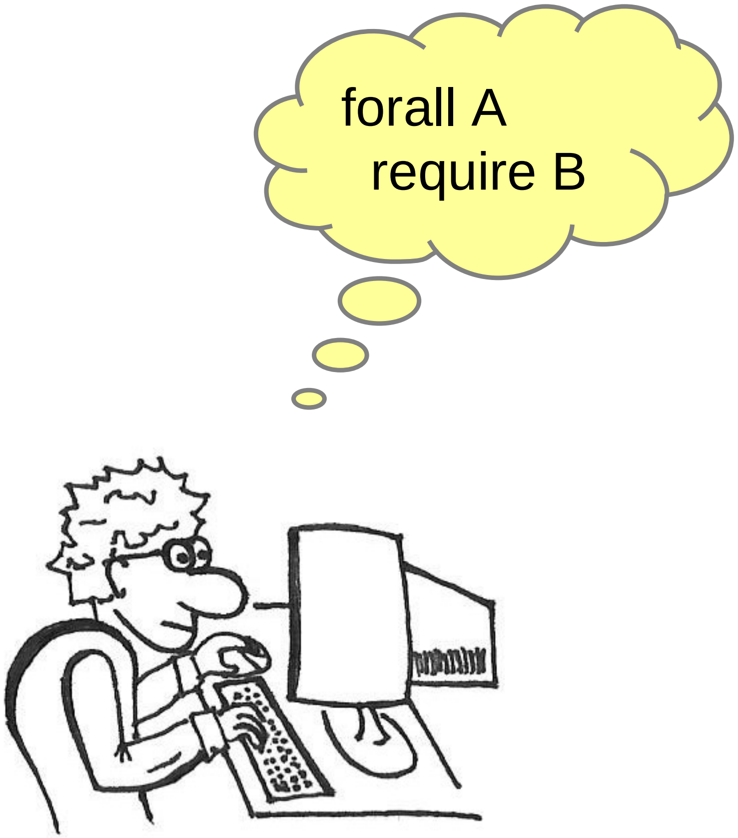

CPLEX
callable library (C)

# Interfacing with CPLEX



# Interfacing with CPLEX




## **O**ptimization **P**rogramming **L**anguage (OPL)

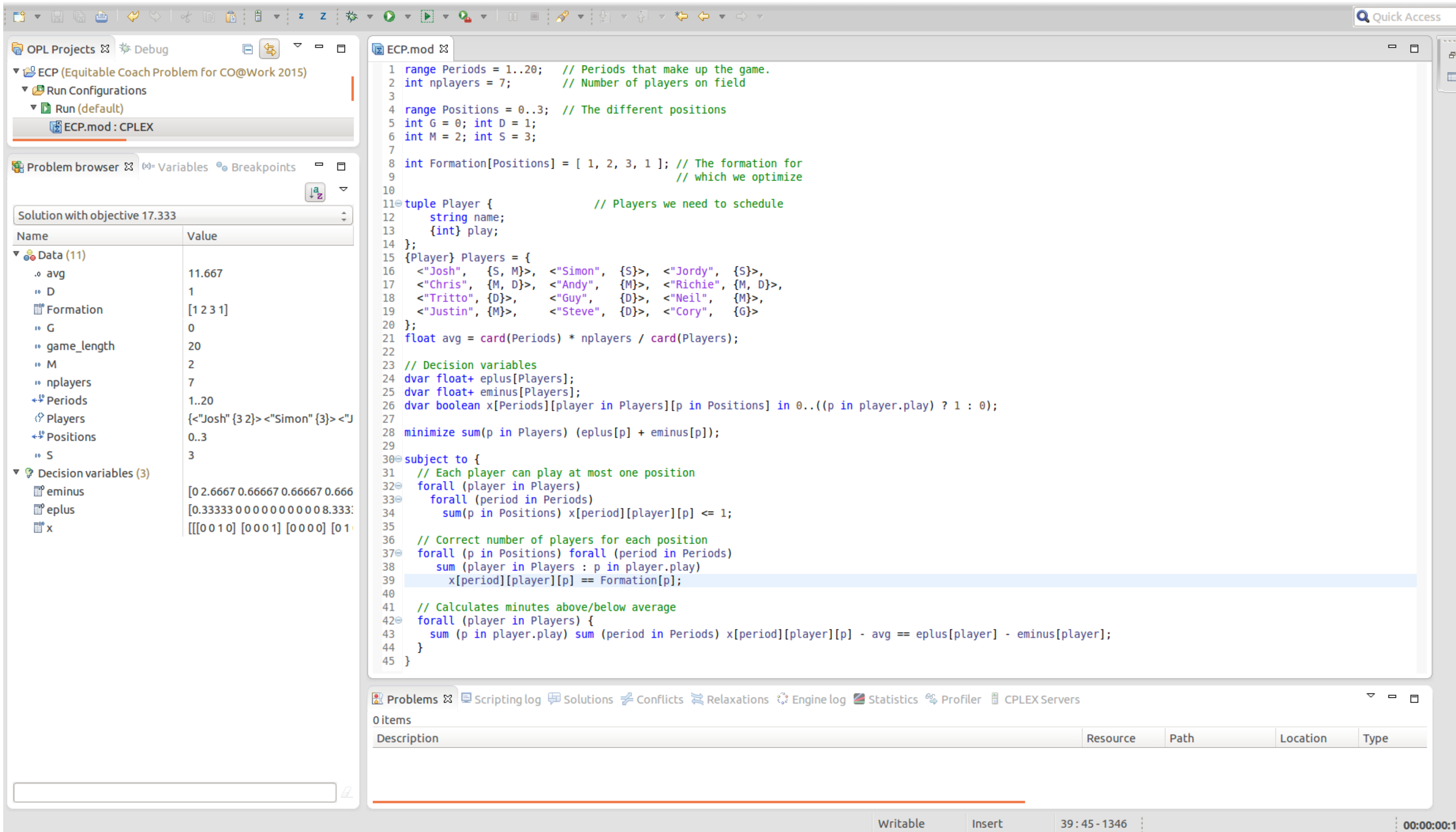
- write models in a more descriptive form
- write models in a more compact form
- faster prototyping, easier maintenance
- easier access to data (Excel, database, ...)

$\sum\sum x_{ijk} \leq 1$ for i in I

```
forall (i in I)
  sum (j in J)
    sum (k in K)
      x[i][j][k] <= 1;
```

- scriptable
- model editor
- IDE support (eclipse based)

# Interfacing with CPLEX



# Interfacing with CPLEX

ECP.mod

```
range Periods = 1..20;   // Periods that make up the game.
int nplayers = 7;        // Number of players on field

range Positions = 0..3;  // The different positions
int G = 0; int D = 1;
int M = 2; int S = 3;

int Formation[Positions] = [ 1, 2, 3, 1 ]; // The formation for
                                           // which we optimize

tuple Player {                // Players we need to schedule
    string name;
    {int} play;
};
{Player} Players = {
  <"Josh",   {S, M}>,  <"Simon",  {S}>,  <"Jordy",  {S}>,
  <"Chris",  {M, D}>,  <"Andy",   {M}>,  <"Richie", {M, D}>,
  <"Tritto", {D}>,     <"Guy",    {D}>,  <"Neil",   {M}>,
  <"Justin", {M}>,     <"Steve",  {D}>,  <"Cory",   {G}>
};
float avg = card(Periods) * nplayers / card(Players);

// Decision variables
dvar float+ eplus[Players];
dvar float+ eminus[Players];
dvar boolean x[Periods][player in Players][p in Positions] in 0..((p in player.play) ? 1 : 0);

minimize sum(p in Players) (eplus[p] + eminus[p]);

subject to {
  // Each player can play at most one position
  forall (player in Players)
    forall (period in Periods)
      sum(p in Positions) x[period][player][p] <= 1;

  // Correct number of players for each position
  forall (p in Positions) forall (period in Periods)
     sum (player in Players : p in player.play)
       x[period][player][p] == Formation[p];

  // Calculates minutes above/below average
  forall (player in Players) {
    sum (p in player.play) sum (period in Periods) x[period][player][p] - avg == eplus[player] - eminus[player];
  }
}
```

# `docplex`

## Most recent addition

- https://pypi.python.org/pypi/docplex
- pure Python modeling API (no native code)
- open source (`pypi`, `github`)
- prepared to connect to local or cloud CPLEX

→ write your model in Python
→ hook up with the whole Python software ecosystem

# docplex

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## For example

- Equitable Coach Problem
- list of players from the internet (web service)
- graphical display of solution

→ use `iPython/Jupyter` notebook and Python libraries

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