Introducton to COIN-OR Tools for Optimization

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Outline

1. Introduction to COIN
2. Overview of Projects
3. Using COIN
   - Optimization Services
   - CHiPPS
   - DECOMP
4. Conclusion

Brief History of COIN-OR

- The Common Optimization Interface for Operations Research Initiative was an initiative launched by IBM at ISMP in 2000.
- IBM seeded an open source repository with four initial projects and created a Web site.
- The goal was to develop the project and then hand it over to the community.
- The project has now grown to be self-sustaining and was spun off as a nonprofit educational foundation in the U.S. several years ago.
- The name was also changed to the Computational Infrastructure for Operations Research to reflect a broader mission.

What is COIN-OR Today?

The COIN-OR Foundation

- A non-profit foundation promoting the development and use of interoperable, open-source software for operations research.
- A consortium of researchers in both industry and academia dedicated to improving the state of computational research in OR.
- A venue for developing and maintaining standards.
- A forum for discussion and interaction between practitioners and researchers.

The COIN-OR Repository

- A collection of interoperable software tools for building optimization codes, as well as a few stand alone packages.
- A venue for peer review of OR software tools.
- A development platform for open source projects, including a wide range of project management tools.

The COIN-OR Foundation

- The foundation has been up and running for several years.
- We have two boards.
  - A strategic board to set overall direction
  - A technical board to advise on technical issues
- The boards are composed of members from both industry and academia, as well as balanced across disciplines.
- Membership in the foundation is available to both individuals and institutions.
- The foundation Web site and repository are hosted by INFORMS.

What You Can Do With COIN

- We currently have 40+ projects and more are being added all the time.
- Most projects are now licensed under the EPL (very permissive).
- COIN has solvers for most common optimization problem classes.
  - Linear programming
  - Nonlinear programming
  - Mixed integer linear programming
  - Mixed integer nonlinear programming (convex and nonconvex)
  - Stochastic linear programming
  - Semidefinite programming
  - Graph problems
  - Combinatorial problems (VRP, TSP, SPP, etc.)
- COIN has various utilities for reading/building/manipulating/preprocessing optimization models and getting them into solvers.
- COIN has overarching frameworks that support implementation of broad algorithm classes.
  - Parallel search
  - Branch and cut (and price)
  - Decomposition-based algorithms

COIN-OR Projects Overview: Linear Optimization

- Clp: COIN LP Solver

  Project Manager: ??

- Cbc: COIN Branch and Cut

  Project Manager: Ted Ralphs

- SYMPHONY: a flexible integer programming package that supports shared and distributed memory parallel processing, biobjective optimization, warm starting, sensitivity analysis, application development, etc.

  Project Manager: Ted Ralphs

- BLIS: Parallel IP solver built to test the scalability of the CHiPPS framework.

  Project Manager: Ted Ralphs

COIN-OR Projects Overview: Nonlinear Optimization

- Ipopt: Interior Point OPTimizer implements interior point methods for solving nonlinear optimization problems.

  Project Manager: Andreas Wächter

- Bonmin: Basic Open-source Nonlinear Mixed INteger programming is for (convex) nonlinear integer programming.

  Project Manager: Pierre Bonami

- Couenne: Solver for nonconvex nonlinear integer programming problems.

  Project Manager: Pietro Belotti

COIN-OR Projects Overview: Modeling and Interfaces

- Osi: Open solver interface is a generic API for linear and mixed integer linear programs.

  Project Manager: Matthew Saltzman

- GAMSlinks: Allows you to use the GAMS algebraic modeling language and call COIN-OR solvers.

  Project Manager: Stefan Vigerske

- FLOPC++: An open-source modeling system.

  Project Manager: Tim Hultberg

- CoinMP: A callable library that wraps around CLP and CBC, providing an API similar to CPLEX, XPRESS, Gurobi, etc.

  Project Manager: Bjarni Kristjansson

- Optimization Services: A framework defining data interchange formats and providing tools for calling solvers locally and remotely through Web services.

  Project Managers: Jun Ma, Gus Gassmann, and Kipp Martin

COIN-OR Projects Overview: Frameworks

- Bcp: A generic framework for implementing branch, cut, and price algorithms.

  Project Manager: Laci Ladanyi

- CHiPPS: A framework for developing parallel tree search algorithms.

  Project Manager: Ted Ralphs

- DECOMP: A framework for implementing decomposition-based algorithms for integer programming, including Dantzig-Wolfe, Lagrangian relaxation, cutting plane, and combinations.

  Project Manager: Ted Ralphs

COIN-OR Projects Overview: Miscellaneous

- CppAD: a package for doing algorithmic differentiation, a key ingredient in modern nonlinear optimization codes.

  Project Manager: Brad Bell

- CSDP: A solver for semi-definite programs

  Project Manager: Brian Borchers

- DFO: An algorithm for derivative free optimization.

  Project Manager: Katya Scheinburg

CoinAll, CoinBinary, BuildTools, and TestTools

- Many of the tools mentioned interoperate by using the configuration and build utilities provided by the `BuildTools` project.
- The `BuildTools` includes autoconf macros and scripts that allow PMs to smoothly integrate code from other projects into their own.
- The `CoinAll` project is an über-project that includes a set of mutually interoperable projects and specifies specific sets of versions that are compatible.
- The `TestTools` project is the focal point for testing of COIN code.
- The `CoinBinary` project is a long-term effort to provide pre-built binaries for popular platforms.
  - Installers for Windows
  - RPMs for Linux
  - .debs for Linux
- You can download `CoinAll` (source and/or binaries) here:

  http://projects.coin-or.org/svn/CoinBinary/CoinAll/

  http://www.coin-or.org/download/binary/CoinAll

Building CoinAll

- For MSVC++, there are project files provided.
- In *nix environments (Linux, Solaris, AIX, CYGWIN, MSys, etc.)

Installing CoinAll

```
svn co http://projects.coin-or.org/svn/CoinBinary/CoinAll/releases/1.3.0 \
     CoinAll-1.3.0
cd CoinAll-1.3.0
./get.AllThirdParty
mkdir build
cd build
../configure --enable-gnu-packages -C [--prefix=/path/to/install/location]
make -j 2
make test
make install
```

Optimization Services (OS)

Optimization Services (OS) integrates numerous COIN-OR projects. The OS project provides:

- A set of XML based standards for representing optimization instances (`OSiL`), optimization results (`OSrL`), and optimization solver options (`OSoL`).
- A uniform API for constructing optimization problems (linear, nonlinear, discrete) and passing them to solvers.
- A command line executable `OSSolverService` for reading problem instances in several formats and calling a solver either locally or remotely.
- Utilities that convert AMPL nl and MPS files into the OSiL format.
- Client side software for creating Web Services SOAP packages with OSiL instances and contact a server for solution.
- Standards that facilitate the communication between clients and solvers using Web Services.
- Server software that works with Apache Tomcat.

Solving a Problem on the Command Line

- The OS project provides an single executable `OSSolverService` that can be used to call most COIN solvers.
- To solve a problem in MPS format

```
OSSolverService -mps ../../data/mpsFiles/parinc.mps
```

- The solver also accepts AMPL nl and OSiL formats.
- You can display the results in raw XML, but it's better to print to a file to be parsed.

```
OSSolverService -osil ../../data/osilFiles/parincLinear.osil
    -osrl result.xml
```

- You can then display the solution in a browser using XSLT.
  - Copy the stylesheets to your output directory.
  - Open in your browser

Specifying a Solver

```
OSSolverService -osil ../../data/osilFiles/p0033.osil
      -solver cbc
```

To solve a **linear program** set the solver options to:

- `clp`
- `dylp`

To solve a **mixed integer linear program** set the solver options to:

- `cbc`
- `symphony`

To solve a **continuous nonlinear program** set the solver options to:

- `ipopt`

To solve a **mixed integer nonlinear program** set the solver options to:

- `bonmin`
- `couenne`

Calling a Solver Remotely

You can use the OSSolverService to call a solver remotely using Web services.

```
OSSolverService -osil ../../data/osilFiles/p0033.osil
      -solver cbc
      -serviceLocation
       http://webdss.ise.ufl.edu:2646/OSServer/services/OSSolverService
```

Getting a Model into the Solver

- What is the point of the OSiL format?
  - Provides a single interchange standard for all classes of mathematical programs.
  - Makes it easy to use existing tools for defining Web services, etc.
  - Generally, however, one would not build an OSiL file directly.
- To construct a model and pass it to a COIN solver, there are several routes.
  - Use a modeling language—AMPL, GAMS, MPL, and AIMMS all work with COIN-OR solvers.
  - Use FlopC++.
  - Build the instance in memory using COIN-OR utilities.

Using AMPL with OS

To use OS to call solvers in AMPL, you specify the `OSAmplClient` as the solver.

```
model hs71.mod;
# tell AMPL that the solver is OSAmplClient
option solver OSAmplClient;

# now tell OSAmplClient to use Ipopt
option OSAmplClient_options "solver ipopt";

# now solve the problem
solve;
```

In order to call a remote solver service, set the solver `service` option to the address of the remote solver service.

```
option ipopt_options
  "service http://webdss.ise.ufl.edu:2646/OSServer/services/OSSolverService";
```

Building a Model in Memory using OS

Step 1: Construct an instance in a solver-independent format using the OS API.
Step 2: Create a solver object

```
CoinSolver *solver = new CoinSolver();
solver->sSolverName = "clp";
```

Step 3: Feed the solver object the instance created in Step 1.

```
solver->osinstance = osinstance;
```

Step 4: Build solver-specific model instance

```
solver->buildSolverInstance();
```

Step 5: Solve the problem.

```
solver->solve();
```

Building an OS Instance

The `OSInstance` class provides an API for constructing models and getting those models into solvers.

- `set()` and `add()` methods for creating models.
- `get()` methods for getting information about a problem.
- `calculate()` methods for finding gradient and Hessians using algorithmic differentiation.

Building an OS Instance (cont.)

- Create an `OSInstance` object.

```
OSInstance *osinstance =  new OSInstance();
```

- Put some variables in

```
osinstance->setVariableNumber( 2);
osinstance->addVariable(0, "x0", 0, OSDBL_MAX, 'C', OSNAN, "");
osinstance->addVariable(1, "x1", 0, OSDBL_MAX, 'C', OSNAN, "");
```

- There are methods for constructing
  - the objective function
  - constraints with all linear terms
  - quadratic constraints
  - constraints with general nonlinear terms

Other Options for Linear Problems

- `CoinUtils` has a number of utilities for constructing instances.
  - `PackedMatrix` and `PackedVector` classes.
  - `CoinBuild`
  - `CoinModel`
- `Osi` provides an interface for building models and getting them into solvers for linear probes.

Quick Introduction to CHiPPS

- CHiPPS stands for COIN-OR High Performance Parallel Search.
- CHiPPS is a set of C++ class libraries for implementing tree search algorithms for both sequential and parallel environments.

CHiPPS Components (Current)

ALPS (Abstract Library for Parallel Search)
- is the search-handling layer (parallel and sequential).
- provides various search strategies based on node priorities.

BiCePS (Branch, Constrain, and Price Software)
- is the data-handling layer for relaxation-based optimization.
- adds notion of variables and constraints.
- assumes iterative bounding process.

BLIS (BiCePS Linear Integer Solver)
- is a concretization of BiCePS.
- specific to models with linear constraints and objective function.

ALPS: Design Goals

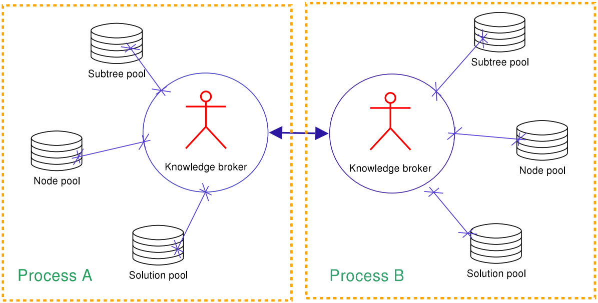
- Intuitive object-oriented class structure.
  - `AlpsModel`
  - `AlpsTreeNode`
  - `AlpsNodeDesc`
  - `AlpsSolution`
  - `AlpsParameterSet`
- Minimal algorithmic assumptions in the base class.
  - Support for a wide range of problem classes and algorithms.
  - Support for constraint programming.
- Easy for user to develop a custom solver.
- Design for *parallel scalability*, but operate effective in a sequential environment.
- Explicit support for *memory compression* techniques (packing/differencing) important for implementing optimization algorithms.

ALPS: Overview of Features

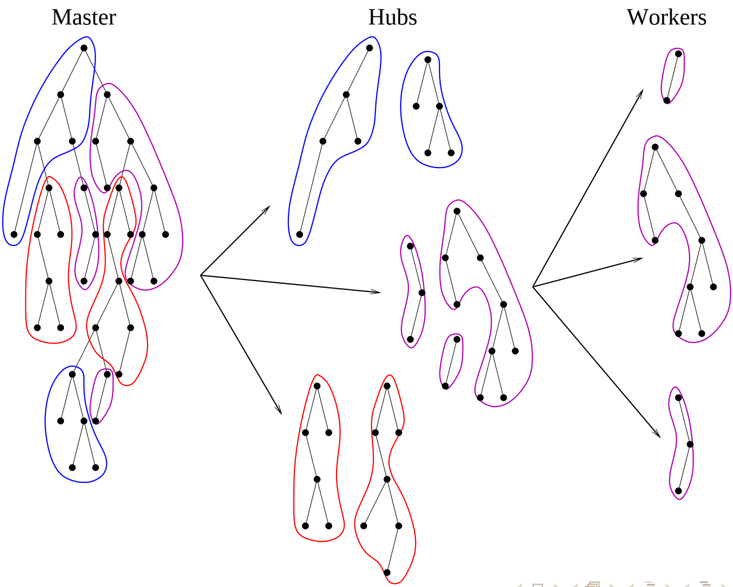
- The design is based on a very general concept of *knowledge*.
- Knowledge is shared asynchronously through *pools* and *brokers*.
- Management overhead is reduced with the *master-hub-worker* paradigm.
- Overhead is decreased using dynamic task granularity.
- Two static load balancing techniques are used.
- Three dynamic load balancing techniques are employed.
- Uses asynchronous messaging to the highest extent possible.
- A scheduler on each process manages tasks like
  - node processing,
  - load balaning,
  - update search states, and
  - termination checking, etc.

Knowledge Sharing

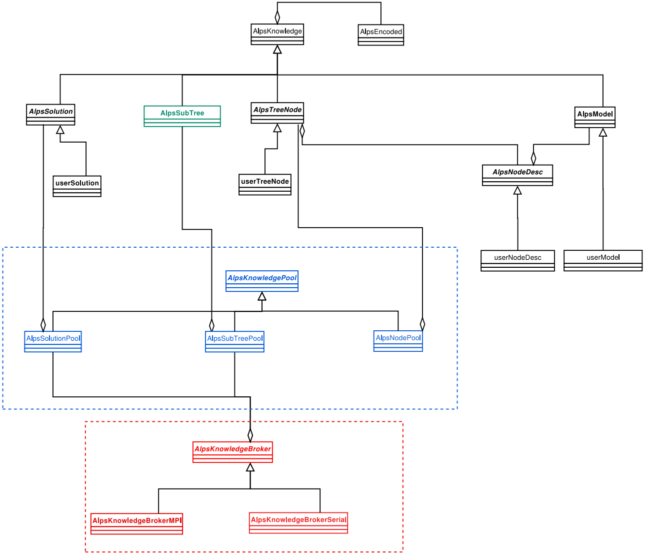
- All knowledge to be shared is derived from a single base class and has an associated *encoded form*.
- Encoded form is used for identification, storage, and communication.
- Knowledge is maintained by one or more *knowledge pools*.
- The knowledge pools communicate through *knowledge brokers*.



Master-Hub-Worker Paradigm



Alps Class Hierarchy



Using ALPS: A Knapack Solver

The formulation of the binary knapsack problem is

$$\max\{\sum_{i=1}^{m} p_i x_i : \sum_{i=1}^{m} s_i x_i \leq c, x_i \in \{0,1\}, i = 1, 2, \ldots, m\}, \tag{1}$$

We derive the following classes:

- `KnapModel` (from `AlpsModel`) : Stores the data used to describe the knapsack problem and implements `readInstance()`
- `KnapTreeNode` (from `AlpsTreeNode`) : Implements `process()` (bound) and `branch()`
- `KnapNodeDesc` (from `AlpsNodeDesc`) : Stores information about which variables/items have been fixed by branching and which are still free.
- `KnapSolution` (from `AlpsSolution`) Stores a solution (which items are in the knapsack).

Using ALPS: A Knapack Solver

Then, supply the main function.

```
int main(int argc, char* argv[])
{
    KnapModel model;

#if defined(SERIAL)
    AlpsKnowledgeBrokerSerial broker(argc, argv, model);
#elif defined(PARALLEL_MPI)
    AlpsKnowledgeBrokerMPI broker(argc, argv, model);
#endif

    broker.search();
    broker.printResult();
    return 0;
}
```

BiCePS: Support for Relaxation-based Optimization

- Adds notion of *modeling objects* (variables and constraints).
- Models are built from sets of such objects.
- Bounding is an iterative process that produces new objects.
- A differencing scheme is used to store the difference between the descriptions of a child node and its parent.

```
struct BcpsObjectListMod
{
    int  numRemove;
    int* posRemove;
    int  numAdd;
    BcpsObject **objects;
    BcpsFieldListMod<double> lbHard;
    BcpsFieldListMod<double> ubHard;
    BcpsFieldListMod<double> lbSoft;
    BcpsFieldListMod<double> ubSoft;
};
```

```
template<class T>
struct BcpsFieldListMod
{
    bool relative;
    int  numModify;
    int  *posModify;
    T    *entries;
};
```

BLIS: A Generic Solver for MILP

MILP

$$\min \quad c^T x \tag{2}$$
$$s.t. \quad Ax \leq b \tag{3}$$
$$x_i \in \mathbb{Z} \quad \forall\, i \in I \tag{4}$$

where $(A, b) \in \mathbb{R}^{m \times (n+1)}, c \in \mathbb{R}^n$.

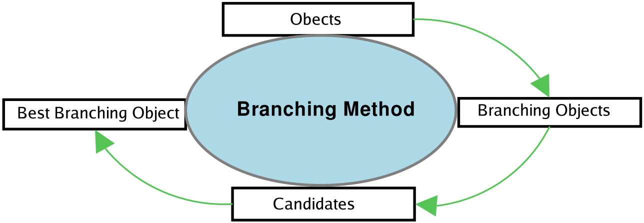
Basic Algorithmic Components

- Bounding method.
- Branching scheme.
- Object generators.
- Heuristics.

BLIS: Branching Scheme

BLIS Branching scheme comprise three components:

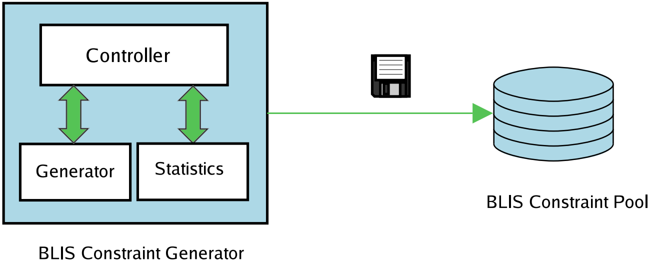
- Object: has feasible region and can be branched on.
- Branching Object:
  - is created from objects that do not lie in they feasible regions or objects that will be beneficial to the search if branching on them.
  - contains instructions for how to conduct branching.
- Branching method:
  - specifies how to create a set of candidate branching objects.
  - has the method to compare objects and choose the best one.



BLIS: Constraint Generators

BLIS constraint generator:

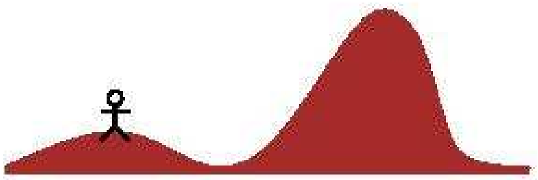
- provides an interface between BLIS and the algorithms in COIN/Cgl.
- provides a base class for deriving specific generators.
- has the ability to specify rules to control generator:
  - where to call: root, leaf?
  - how many to generate?
  - when to activate or disable?
- contains the statistics to guide generating.



BLIS: Heuristics

BLIS primal heuristic:

- defines the functionality to search for solutions.
- has the ability to specify rules to control heuristics.
  - where to call: before root, after bounding, at solution?
  - how often to call?
  - when to activate or disable?
- collects statistics to guide the heuristic.
- provides a base class for deriving specific heuristics.



BLIS Applications

BLIS can be customized easily by deriving the base C++ classes.

Sample Applications (Scott DeNegre, Ted Ralphs, Yan Xu, and others)

- Vehicle Routing Problem (VRP)
- Traveling Salesman Problem (TSP)
- Mixed Integer Bilevel Programming (MiBS)

BLIS Applications: VRP Formulation

$$min \sum_{e \in E} c_e x_e$$

$$\sum_{e=\{0,j\} \in E} x_e = 2k, \tag{5}$$

$$\sum_{e=\{i,j\} \in E} x_e = 2 \quad \forall i \in N, \tag{6}$$

$$\sum_{\substack{e=\{i,j\} \in E \\ i \in S, j \notin S}} x_e \geq 2b(S) \quad \forall S \subset N, \ |S| > 1, \tag{7}$$

$$0 \leq x_e \leq 1 \quad \forall e = \{i,j\} \in E, \ i,j \neq 0, \tag{8}$$

$$0 \leq x_e \leq 2 \quad \forall e = \{i,j\} \in E, \tag{9}$$

$$x_e \in \mathbb{Z} \quad \forall e \in E. \tag{10}$$

BLIS Applications: VRP

First, derive a few subclasses to specify the algorithm and model

- `VrpModel` (from `BlisModel`),
- `VrpSolution` (from `BlisSolution`),
- `VrpCutGenerator` (from `BlisConGenerator`),
- `VrpHeurTSP` (from `BlisHeuristic`),
- `VrpVariable` (from `BlisVariable`), and
- `VrpParameterSet` (from `AlpsParameterSet`).

BLIS Applications: VRP (cont.)

```
int main(int argc, char* argv[])
{
    OsiClpSolverInterface lpSolver;
    VrpModel model;
    model.setSolver(&lpSolver);
#ifdef  COIN_HAS_MPI
    AlpsKnowledgeBrokerMPI broker(argc, argv, model);
#else
    AlpsKnowledgeBrokerSerial broker(argc, argv, model);
#endif
    broker.search(&model);
    broker.printBestSolution();
    return 0;
}
```

Shameless Self-Promotion

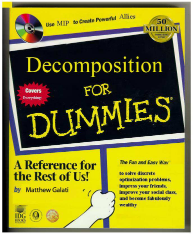
In October, 2007, the VRP/TSP solver won the Open Contest of Parallel Programming at the 19th International Symposium on Computer Architecture and High Performance Computing.

DECOMP Framework: Motivation

DECOMP Framework

DECOMP is a software framework that provides a virtual sandbox for testing and comparing various decomposition-based bounding methods.

- It's difficult to compare variants of decomposition-based algorithms.
- The method for separation/optimization over a given relaxation is the primary custom component of any of these algorithms.
- DECOMP abstracts the common, generic elements of these methods.
  - Key: The user defines methods in the space of the compact formulation.
  - The framework takes care of reformulation and implementation for all variants.



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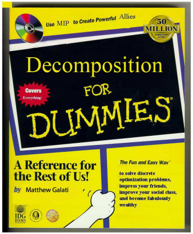

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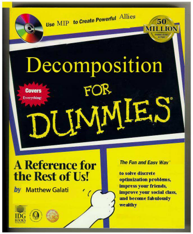
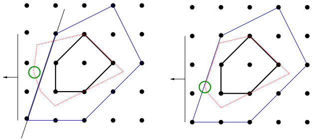


Traditional Decomposition Methods

The Cutting Plane Method (CP) iteratively builds an *outer* approximation of $\mathcal{P}'$ by solving a cutting plane generation subproblem.



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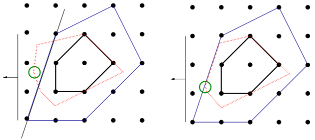
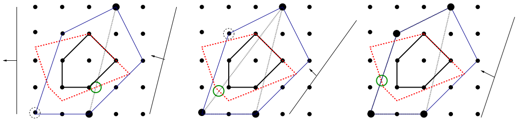


The Dantzig-Wolfe Method (DW) iteratively builds an *inner* approximation of $\mathcal{P}'$ by solving a column generation subproblem.



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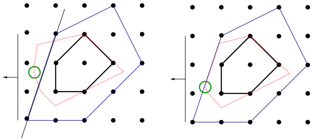

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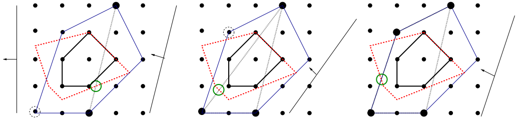
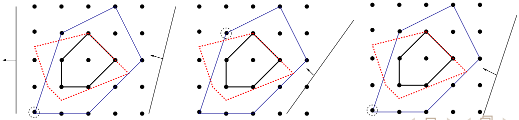
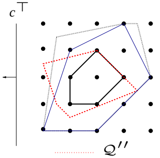


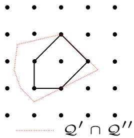
The Lagrangian Method (LD) iteratively solves a Lagrangian relaxation subproblem.



Common Threads

- The LP bound is obtained by optimizing over the intersection of two explicitly defined polyhedra.
$$z_{LP} = \min_{x \in \mathbb{R}^n} \{c^\top x \mid x \in \mathcal{Q}' \cap \mathcal{Q}''\}$$
- The decomposition bound is obtained by optimizing over the intersection of one explicitly defined polyhedron and one implicitly defined polyhedron.
$$z_{CP} = z_{DW} = z_{LD} = z_D = \min_{x \in \mathbb{R}^n} \{c^\top x \mid x \in \mathcal{P}' \cap \mathcal{Q}''\} \geq z_{LP}$$
- Traditional decomposition-based bounding methods contain two primary steps
  - **Master Problem:** Update the primal/dual solution information.
  - **Subproblem:** Update the approximation of $\mathcal{P}'$: $SEP(x, \mathcal{P}')$ or $OPT(c, \mathcal{P}')$.
- Integrated decomposition methods further improve the bound by considering two implicitly defined polyhedra whose descriptions are iteratively refined.
  - Price and Cut (PC)
  - Relax and Cut (RC)
  - Decompose and Cut (DC)





Common Threads

- The LP bound is obtained by optimizing over the intersection of two explicitly defined polyhedra.

$$z_{LP} = \min_{x \in \mathbb{R}^n} \{c^\top x \mid x \in \mathcal{Q}' \cap \mathcal{Q}''\}$$

- The decomposition bound is obtained by optimizing over the intersection of one explicitly defined polyhedron and one implicitly defined polyhedron.

$$z_{CP} = z_{DW} = z_{LD} = z_D = \min_{x \in \mathbb{R}^n} \{c^\top x \mid x \in \mathcal{P}' \cap \mathcal{Q}''\} \geq z_{LP}$$

- Traditional decomposition-based bounding methods contain two primary steps
  - **Master Problem:** Update the primal/dual solution information.
  - **Subproblem:** Update the approximation of $\mathcal{P}'$: $SEP(x, \mathcal{P}')$ or $OPT(c, \mathcal{P}')$.
- Integrated decomposition methods further improve the bound by considering two implicitly defined polyhedra whose descriptions are iteratively refined.
  - Price and Cut (PC)
  - Relax and Cut (RC)
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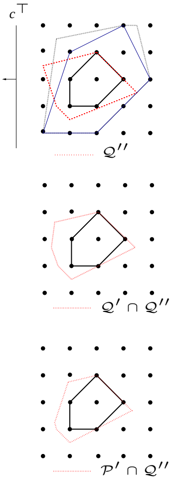

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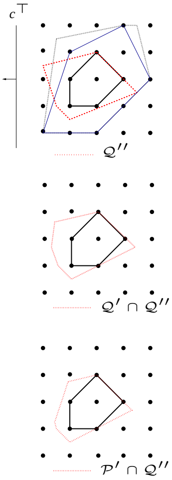

DECOMP Framework

- The DECOMP framework, written in C++, is accessed through two user interfaces:
  - Applications Interface: `DecompApp`
  - Algorithms Interface: `DecompAlgo`
- DECOMP provides the bounding method for branch and bound.
- ALPS (Abstract Library for Parallel Search) provides the framework for parallel tree search.
  - `AlpsDecompModel : public AlpsModel`
    - a wrapper class that calls (data access) methods from `DecompApp`
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COIN needs your help!

- Contribute a project
- Help develop an existing project
- Use projects and report bugs
- Volunteer to review new projects
- Develop documentation
- Develop Web site
- Chair a committee

Questions? & Thank You!