It's a Bird... It's a Plane... It's SMS++

Antonio Frangioni

Dipartimento di Informatica, Università di Pisa

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Outline

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- Programming is hard, good programming is harder, optimization is hard, good programming for optimization is extremely hard
- Typically done early on in the career (you)
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- Selfish version of the altruistic reason: if all this work was readily available decomposition would make a lot more sense, and my own work would be more useful

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Decomposition-aware modelling systems

- Decomposition is complex, but so is any Branch-and-X
- Need general-purpose efficient decomposition software:
  - Cplex does Benders', structure automatic or user hints
  - SCIP[1] does B&C&P (one-level D-W), pricing & reformulation up to the user (plugins)
  - GCG[1] extends SCIP with automatic and user-defined (one-level) D-W and recently also a generic (one-level) Benders' approach[2]
  - D-W approaches for two-stage stochastic programs are implemented in DDSIP[3] and PIPS[4], the latter interfaced with StructJuMP[5]
  - The BaPCoD B&C&P code has been used to develop Coluna.jl[6], doing one-level D-W and (alpha) Benders', multi-level planned
- No multi-level C++, so we started one

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[1] https://scipopt.org, https://gcg.or.rwth-aachen.de

[2] Maher "Implementing the Branch-and-Cut approach for a general purpose Benders' decomposition framework" *EJOR*, 2021

[3] https://github.com/RalfGollmer/ddsip

[4] https://github.com/Argonne-National-Laboratory/PIPS

[5] https://github.com/StructJuMP/StructJuMP.jl

[6] https://github.com/atoptima/Coluna.jl

Outline

https://gitlab.com/smspp/smspp-project

Open source (LGPL3)

Public as of February 8, but some 8+ years in the making

What SMS++ is

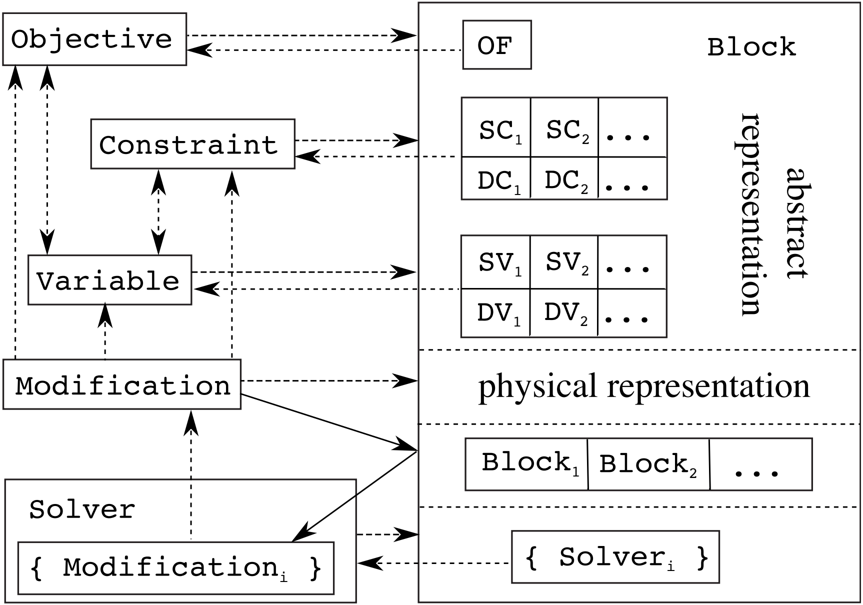
- A core set of C++-17 classes implementing a modelling system that:
  - explicitly supports the notion of Block ≡ nested structure
  - separately provides "semantic" information from "syntactic" details (list of constraints/variables ≡ one specific formulation among many)
  - allows exploiting specialised Solver on Block with specific structure
  - manages any dynamic change in the Block beyond "just" generation of constraints/variables
  - supports reformulation/restriction/relaxation of Block
  - has built-in parallel processing capabilities
  - should be able to deal with almost anything (bilevel, PDE, . . .)
- An hopefully growing set of specialized Block and Solver
- In perspective an ecosystem fostering collaboration and code sharing

What SMS++ is not

- An algebraic modelling language: `Block` / `Solver` are C++ code (although it provides some modelling-language-like functionalities)
- For the faint of heart: primarily written for algorithmic experts (although users may benefit from having many pre-defined `Block`)
- Stable: only version 0.4, lots of further development ahead, significant changes in interfaces not ruled out, actually expected (although current `Block` / `Solver` very thoroughly tested)
- Interfaced with many solvers: only `Cplex`, `SCIP`, `MCFClass`, `StOpt` (although the list should hopefully grow)

Outline

A Crude Schematic



Block

- Block = abstract class representing the general concept of "a (part of a) mathematical model with a well-understood identity"
- Each :Block a model with specific structure (e.g., MCFBlock:Block = a Min-Cost Flow problem)
- Physical representation of a Block: whatever data structure is required to describe the instance (e.g., G, b, c, u)
- Possibly alternative abstract representation(s) of a Block:
  - one Objective (but possibly vector-valued)
  - any # of groups of (static) Variable
  - any # of groups of std::list of (dynamic) Variable
  - any # of groups of (static) Constraint
  - any # of groups of std::list of (dynamic) Constraint

  groups of Variable/Constraint can be single (std::list) or std::vector (...) or boost::multi_array
- Any # of sub-Blocks (recursively), possibly of specific type (e.g., Block::MMCFBlock has k Block::MCFBlock inside)

Variable

- Abstract concept, thought to be extended (a matrix, a function, . . .)
- Does not even have a value
- Knows which `Block` it belongs to
- Can be fixed and unfixed to/from its current value (whatever that is)
- Influences a set of `Constraint`/`Objective`/`Function` (actually, a set of `ThinVarDepInterface`)
- Fundamental design decision: “name” of a `Variable` = its memory address $\Longrightarrow$ copying a `Variable` makes a different `Variable` $\Longrightarrow$ dynamic `Variables` always live in `std::lists`
- `VariableModification:Modification` (fix/unfix)

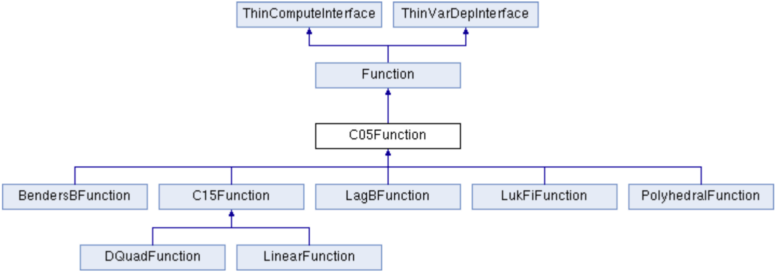
Constraint

- Abstract concept, thought to be extended (any algebraic constraint, a matrix constraint, a PDE constraint, bilevel program, ...)
- Depends from a set of `Variable` (`:ThinVarDepInterface`)
- Either satisfied or not by the current value of the `Variable`, checking it possibly costly (`:ThinComputeInterface`)
- Knows which `Block` it belongs to
- Can be relaxed and enforced
- Fundamental design decision: "name" of a `Constraint` = its memory address $\Longrightarrow$ copying a `Constraint` makes a different `Constraint` $\Longrightarrow$ dynamic `Constraint`s always live in `std::list`s
- `ConstraintModification:Modification` (relax/enforce)

Objective

- Abstract concept, does not specify its return value (vector, set, ...)
- Either minimized or maximized
- Depends from a set of `Variable` (`:ThinVarDepInterface`)
- Must be evaluated w.r.t. the current value of the `Variable`, possibly a costly operation (`:ThinComputeInterface`)
- `RealObjective:Objective` implements "value is an extended real"
- Knows which `Block` it belongs to
- Same fundamental design decision ...
  (but there is no such thing as a dynamic `Objective`)
- `ObjectiveModification:Modification` (change verse)

Function



- Real-valued `Function`
- Depends from a set of `Variable` (`:ThinVarDepInterface`)
- Must be evaluated w.r.t. the current value of the `Variable`, possibly a costly operation (`:ThinComputeInterface`)
- Approximate computation supported in a quite general way[56] (since `:ThinComputeInterface`, and that does)
- `FunctionModification[Variables]` for "easy" changes $\Longrightarrow$ reoptimization (shift, adding/removing "quasi separable" `Variable`)

C05Function and C15Function

- C05Function/C15Function deal with $1^{st}/2^{nd}$ order information (not necessarily continuous)
- General concept of "linearization" (gradient, convex/concave subgradient, Clarke subgradient, ...)
- Multiple linearizations produced at each evaluation (local pool)
- Global pool of linearizations for reoptimization:
  - convex combination of linearizations
  - "important linearization" (at optimality)
- C05FunctionModification[Variables/LinearizationShift] for "easy" changes $\Longrightarrow$ reoptimization (linearizations shift, some linearizations entries changing in simple ways)
- C15Function supports (partial) Hessians
- Arbitrary hierarchy of :Function possible/envisioned, any one that makes sense for application and/or solution method

Closer to the ground

- `ColVariable:Variable`: "value = one single real" (possibly $\in \mathbb{Z}$)
- `RowConstraint:Constraint`: "$l \leq$ a real $\leq u$" $\Longrightarrow$ has dual variable (single real) attached to it
- `OneVarConstraint:RowConstraint`: "a real" = a single `ColVariable` $\equiv$ bound constraints
- `FRowConstraint:RowConstraint`: "a real" given by a `Function`
- `FRealObjective:RealObjective`: "value" given by a `Function`
- `LinearFunction:Function`: a linear form in `ColVariable`
- `DQuadFunction:Function`: a separable quadratic form
- Many things missing (`AlgebraicFunction`, `DenseLinearFunction`, `Matrix/VectorVariable`, ...)

Block and Solver

- Any # of Solver attached to a Block to solve it
- :Solver for a specific :Block can use the physical representation
  $\Longrightarrow$ no need for explicit Constraint
  $\Longrightarrow$ abstract representation of Block only constructed on demand
- However, Variable are always present to interface with Solver (this may change thanks to methods factory)
- A general-purpose Solver uses the abstract representation
- Dynamic Variable/Constraint can be generated on demand (user cuts/lazy constraints/column generation)
- For a Solver attached to a Block:
  - Variable not belonging to the Block are constants
  - Constraint not belonging to the Block are ignored

  (belonging = declared there or in any sub-Block recursively)
- Objective of sub-Blocks summed to that of father Block if has same verse, otherwise min/max

Solver

- Solver = interface between a Block and algorithms solving it
- Each Solver attached to a single Block, from which it picks all the data, but any # of Solver can be attached to the same Block
- Solutions are written directly into the Variable of the Block
- Individual Solver can be attached to sub-Block of a Block
- Tries to cater for all the important needs:
  - optimal and sub-optimal solutions, provably unbounded/unfeasible
  - time/resource limits for solutions, but restarts (reoptimization)
  - any # of multiple solutions produced on demand
  - lazily reacts to changes in the data of the Block via Modification
- Slanted towards RealObjective (≈optimality = up/low bounds)
- CDASolver:Solver is "Convex Duality Aware": bounds are associated to dual solutions (possibly, multiple)
- Provides general events mechanism (ThinComputeInterface does)

Block and Modification

- Most Block components can change, but not all:
  - set of sub-Block
  - # and shape of groups of Variable/Constraint
- Any change is communicated to each interested Solver (attached to the Block or any of its ancestor) via a Modification object
- anyone_there() $\equiv \exists$ interested Solver (Modification needed)
- However, two different kinds of Modification (what changes):
  - physical Modification, only specialized Solver concerned
  - abstract Modification, only Solver using it concerned
- Abstract Modification used to keep both representations in sync
  $\Longrightarrow$ a single change may trigger more than one Modification
  $\Longrightarrow$ concerns_Block() mechanism to avoid this to repeat
  $\Longrightarrow$ parameter in changing methods to avoid useless Modification
- Specialized Solver disregard abstract Modification and vice-versa
- A Block may refuse to support some changes (explicitly declaring it)

Modification

- Almost empty base class, then everything has its own derived ones
- Heavy stuff can be attached to a `Modification` (e.g., added/deleted dynamic `Variable`/`Constraint`)
- Each `Solver` has the responsibility of cleaning up its list of `Modification` (smart pointers → memory eventually released)
- `Solver` supposedly reoptimize to improve efficiency, which is easier if you can see all list of changes at once (lazy update)
- `GroupModification` to (recursively) pack many `Modification` together ⟹ different "channels" in `Block`
- `Modification` processed in the arrival order to ensure consistency
- A `Solver` may optimize the changes (`Modifications` may cancel each outer out . . .), but its responsibility

Support to (coarse-grained) Parallel Computation

- `Block` can be (r/w) `lock()`-ed and `read_lock()`-ed
- `lock()`-ing a `Block` automatically `lock()`s all inner `Block`
- `lock()` (but not `read_lock()`) sets an owner and records its `std::thread::id`; other `lock()` from the same thread fail (`std::mutex` would not work there)
- Similar mechanism for `read_lock()`, any # of concurrent reads
- Write starvation not handled yet
- A `Solver` can be "lent an ID" (solving an inner `Block`)
- The list of `Modification` of `Solver` is under an "active guard" (`std::atomic`)
- Distributed computation under development, can exploit general serialize/deserialize `Block` capabilities, Cray/HPE "Fugu" framework

Solution

- Block produces Solution object, possibly using its sub-Blocks'
- Solution can read() its own Block and write() itself back
- Solution is Block-specific rather than Solver-specific
- Solution may save dual information
- Solution may save only a specific subset of primal/dual information
- Linear combination of Solution supported $\Longrightarrow$ "less general" Solution may (automatically) convert in "more general" ones
- Like Block, Solution are tree-structured complex objects
- ColVariableSolution:Solution uses the abstract representation of any Block that only have (std::vector or boost::multi_array of) (std::list of) ColVariables to read/write the solution
- RowConstraintSolution:Solution same for dual information (RowConstraint), ColRowSolution for both

Configuration

- Block a tree-structured complex object $\Longrightarrow$ Configuration for them a (possibly) tree-structured complex object
- But also SimpleConfiguration<T>:Configuration (T an int, a double, a std::pair<>, ...)
- [C/O/R]BlockConfiguration:Configuration set [recursively]:
  - which dynamic Variable/Constraint are generated, how (Solver, time limit, parameters ...)
  - which Solution is produced (what is saved)
  - the ComputeConfiguration:Configuration of any Constraint/Objective that needs one
  - a bunch of other Block parameters
- [R]BlockSolverConfiguration:Configuration set [recursively] which Solver are attached to the Block and their ComputeConfiguration:Configuration
- Can be clear()-ed for cleanup

R^3Block

- Often reformulation crucial, but also relaxation or restriction: get_R3_Block() produces one, possibly using sub-Blocks'
- Obvious special case: copy (clone) should always work
- Available R^3Blocks :Block-specific, a :Configuration needed
- R^3Block completely independent (new Variable/Constraint), useful for algorithmic purposes (branch, fix, solve, ...)
- Solution of R^3Block useful to Solver for original Block: map_back_solution() (best effort in case of dynamic Variable)
- Sometimes keeping R^3Block in sync with original necessary: map_forward_Modification(), task of original Block
- map_forward_solution() and map_back_Modification() useful, e.g., dynamic generation of Variable/Constraint in the R^3Block
- :Block is in charge of all this, thus decides what it supports

A lot of other support stuff

- All tree-structured complex objects (`Block`, `Configuration`, . . .) and `Solver` have an (almost) automatic factory
- All tree-structured complex objects (. . .) have methods to serialize/deserialize themselves to `netCDF` files
- A methods factory for changing the physical representation without knowing of which `:Block` it exactly is (standardised interface)
- `AbstractBlock` for constructing a model a-la algebraic language, can be derived for "general `Block` + specific part"
- `PolyhedralFunction[Block]`, very useful for decomposition
- `AbstractPath` for indexing any `Constranit`/`Variable` in a `Block`
- `FakeSolver:Solver` stashes away all `Modification`, `UpdateSolver:Solver` immediately forwards/R^{3}Bs them
- . . .

Outline

Main Existing :Block

- MCFBlock/MMCFBlock: single/multicommodity flow (p.o.c.)
- UCBlock for UC, abstract UnitBlock with several concrete (ThermalUnitBlock, HydroUnitBlock, ...), abstract NetworkBlock with a few concrete (DCNetworkBlock)
- LagBFunction:{C05Function,Block} transforms any Block (with appropriate Objective) into its dual function
- BendersBFunction:{C05Function,Block} transforms any Block (with appropriate Constraint) into its value function
- StochasticBlock implements realizations of scenarios into any Block (using methods factory)
- SDDPBlock represents multi-stage stochastic programs suitable for Stochastic Dual Dynamic Programming

Main "Basic" :Solver

- MCFSolver: templated p.o.c. wrapper to MCFClass[7] for MCFBlock
- DPSolver for ThermalUnitBlock (still needs serious work)
- MILPSolver: constructs matrix-based representation of any "LP" Block: ColVariable, FRowConstraint, FRealObjective with LinearFunction or DQuadFunction
- CPXMILPSolver:MILPSolver and SCIPMILPSolver:MILPSolver wrappers for Cplex and SCIP (to be improved)
- BundleSolver:CDASolver: SMS++-native version of[8] (still shares some code, dependency to be removed), optimizes any (sum of) C05Function, several (but not all) state-of-the-art tricks
- SDDPSolver: wrapper for SDDP solver StOpt[9] using StochasticBlock, BendersBFunction and PolyhedralFunction
- SDDPGreedySolver: greedy forward simulator for SDDPBlock

[7] https://github.com/frangio68/Min-Cost-Flow-Class

[8] https://gitlab.com/frangio68/ndosolver_fioracle_project

[9] https://gitlab.com/stochastic-control/StOpt

Our Masterpiece: LagrangianDualSolver

- Works for any Block with natural block-diagonal structure: no Objective or Variable, all Constraint linking the inner Block
- Using LagBFunction stealthily constructs the Lagrangian Dual w.r.t. linking Constraint, R^3B-ing or "stealing" the inner Block
- Solves the Lagrangian Dual with appropriate CDASolver (e.g., but not necessarily, BundleSolver), provides dual and "convexified" solution in original Block
- Can attach LagrangianDualSolver and (say) :MILPSolver to same Block, solve in parallel!
- Weeks of work in days/hours (if Block of the right form already)
- Hopefully soon BendersDecompositionSolver (crucial component BendersBFunction existing and tested)
- Multilevel nested parallel heterogeneous decomposition by design (but I'll believe it when I'll see it running)

Outline

The many things that we do not have (yet)

- A relaxation-agnostic Branch-and-X `Solver` (could recycle `OOBB`?)
- Many other forms of (among many other things):
  - `Variable` (`Vector/MatrixVariable`, `FunctionVariable`, ...)
  - `Constraint` (`SOCConstraint`, `SDPConstraint`, `PDEConstraint`, `BilevelConstraint`, `EquilibriumConstraint`, ...)
  - `Objective` (`RealVectorObjective`, ...)
  - `Function` (`AlgebraicFunction`, ...)
- Better handling of many things (groups of stuff, `Modification`, ...)
- Interfaces with many other general-purpose solvers (`GuRoBi`, `OSISolverInterface`, `Couenne`, OR-tools `CP-SAT Solver`, ...)
- Many many many more `:Block` and their specialised `:Solver`
- Translation layers from real modelling languages (AMPL, JuMP, ...)
- In a word: users/mindshare – chicken-and-egg problem

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- Lots of fun to be had, all contributions welcome

[10] F., Perez Sanchez "Transforming Mathematical Models Using Declarative Reformulation Rules" *LNCS*, 2011

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