AQME'10 System Description

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What is a quantified Boolean formula?

Consider a Boolean formula, e.g.,

$$(x_1 \vee x_2) \wedge (\neg x_1 \vee x_2)$$

Adding existential "$\exists$" and universal "$\forall$" quantifiers, e.g.,

$$\forall x_1 \exists x_2 (x_1 \vee x_2) \wedge (\neg x_1 \vee x_2)$$

yields a quantified Boolean formula (QBF).

What is the meaning of a QBF?

A QBF, e.g.,

$$\forall x_1 \exists x_2 (x_1 \vee x_2) \wedge (\neg x_1 \vee x_2)$$

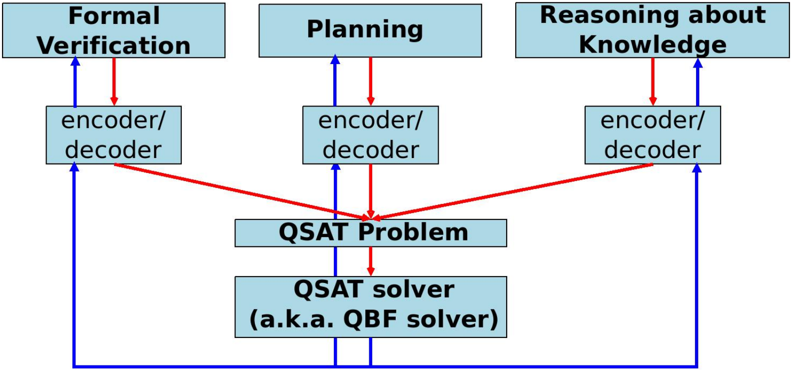
is true if and only if

for every value of x_1 there exist a value of x_2 such that $(x_1 \vee x_2) \wedge (\neg x_1 \vee x_2)$ is propositionally satisfiable

Given any QBF ψ:

- if $\psi = \forall x \varphi$ then ψ is true iff $\varphi_{|_{x=0}} \wedge \varphi_{|_{x=1}}$ is true
- if $\psi = \exists x \varphi$ then ψ is true iff $\varphi_{|_{x=0}} \vee \varphi_{|_{x=1}}$ is true

QBFs as a logic "assembly" language



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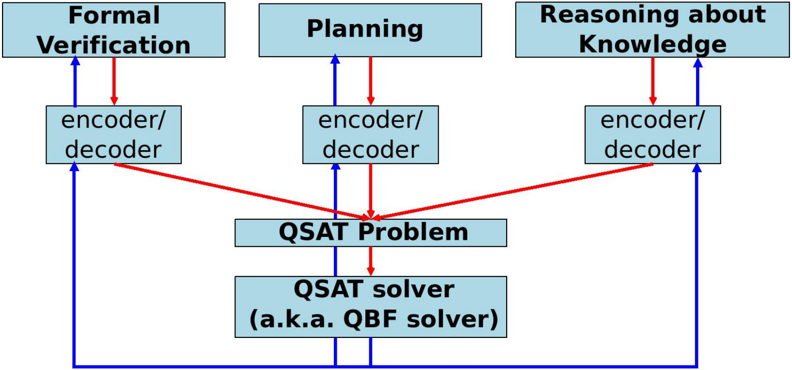
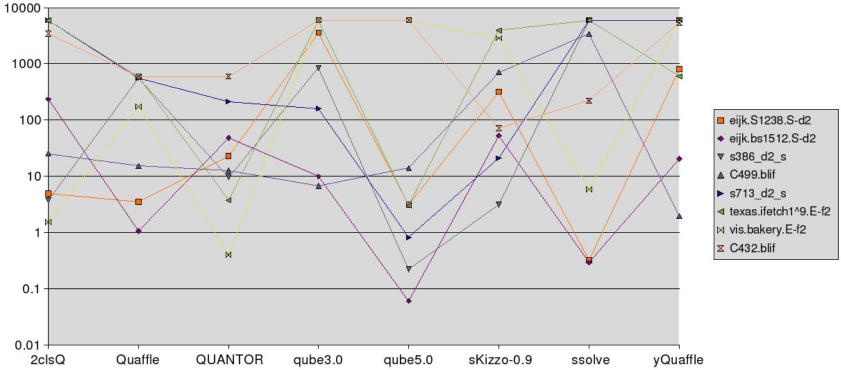


This approach works fine as long as QBF solvers are robust!

Are state-of-the-art QBF solvers robust?



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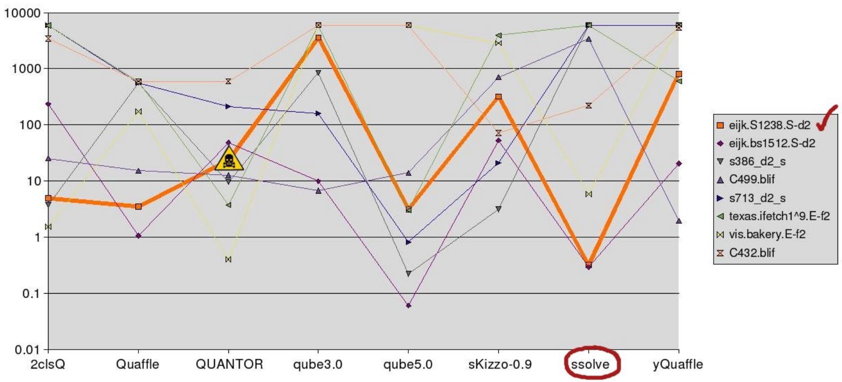

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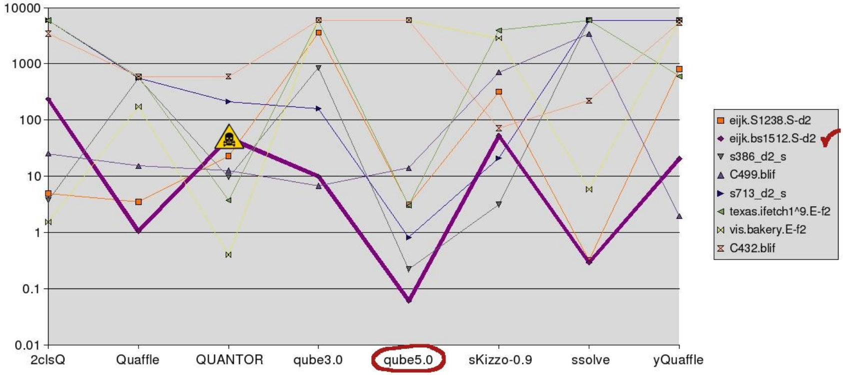

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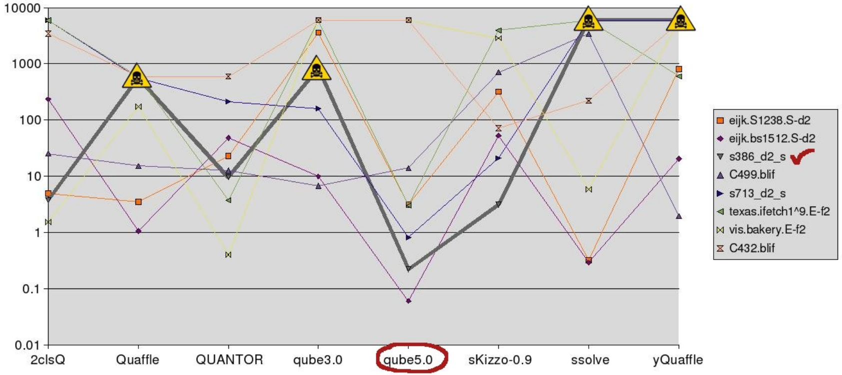

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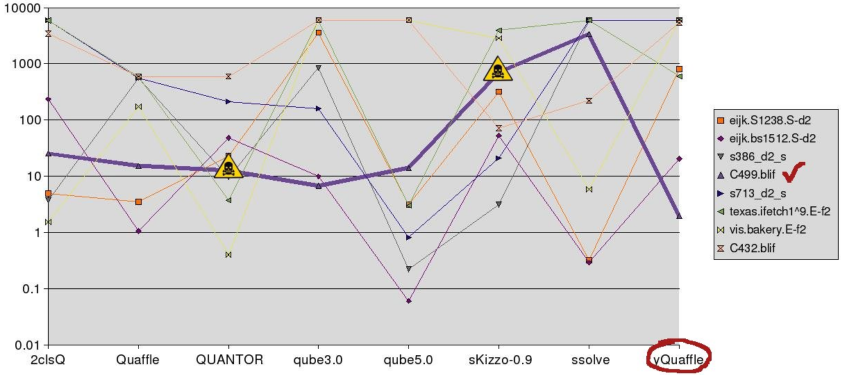

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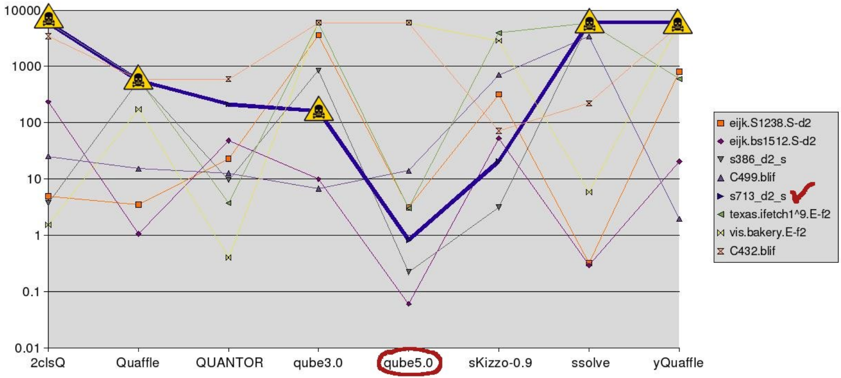

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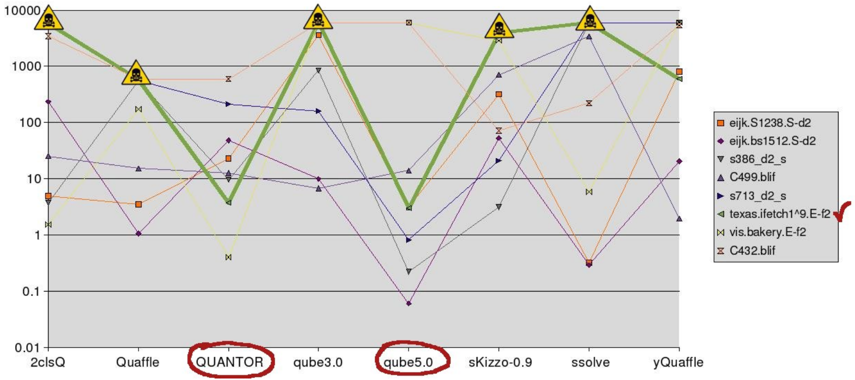

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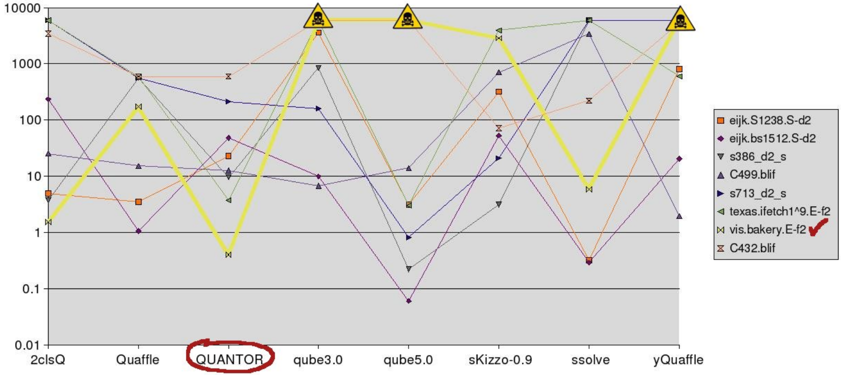

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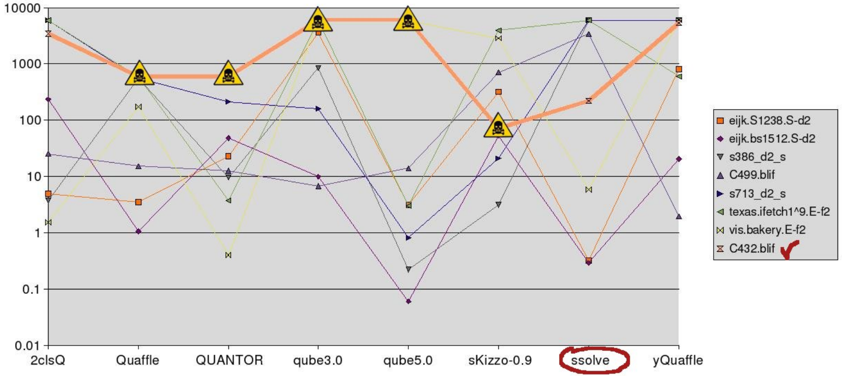
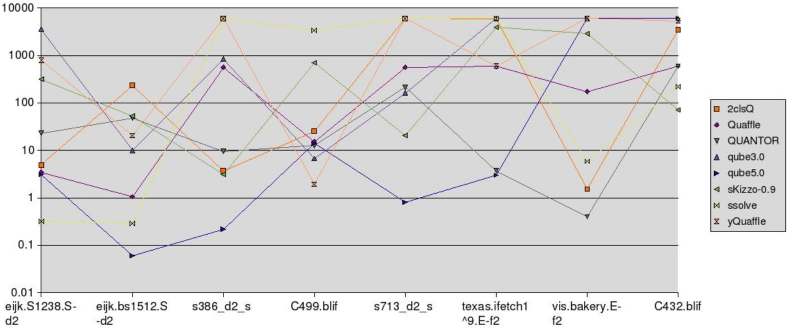


Are state-of-the-art QBF solvers robust?

NOT REALLY...

Goal: a robust QBF solver



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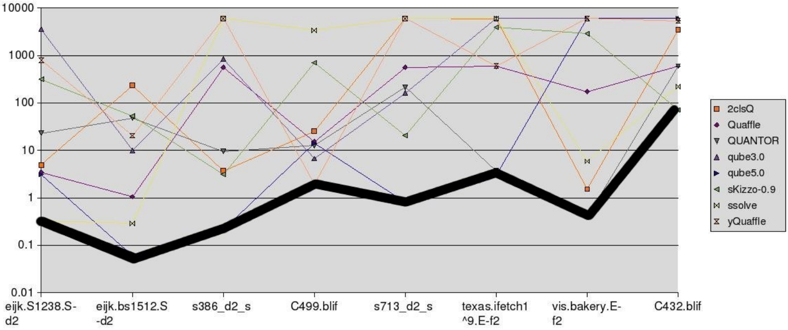

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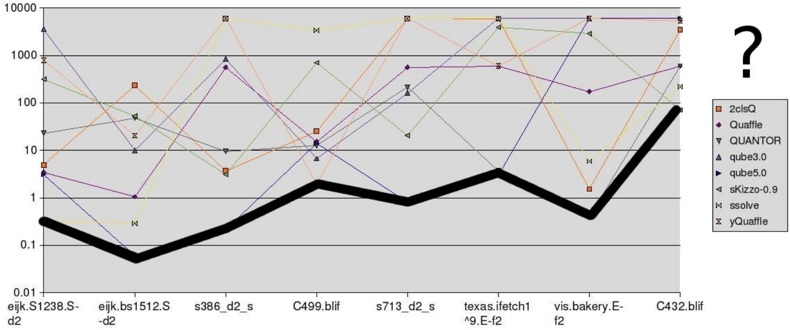

Outline

1. Engineering a robust QBF solver
2. Designing a self-adaptive multi-engine
3. Experiments
4. Conclusions & future work

Outline

Two approaches to yield a robust solver

Brute force

Given *m* QSAT instances and *n* solvers (engines)

1. Run each engine on a separate machine.
2. Stop all the engines as soon as one solves the instance, or all the engines exhaust resources.
3. Continue with the next instance (if any).

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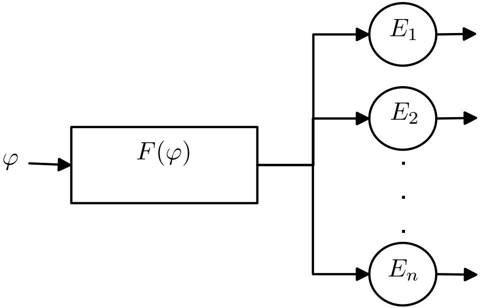
Intelligence

Understand which engine is best for which QBFs

- Fairly old idea: asset allocation in economics.
- Looking for dynamically adaptive policies.
- Algorithm portfolios: SAT, SMT, QBFs (see related work).

Intelligence = Learning (to choose engines)



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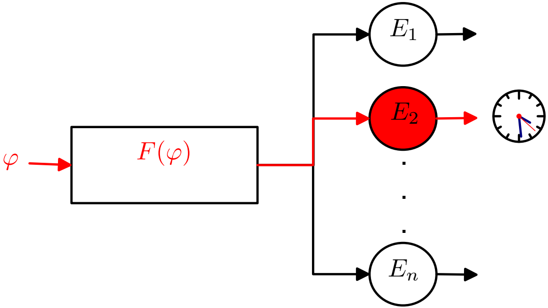

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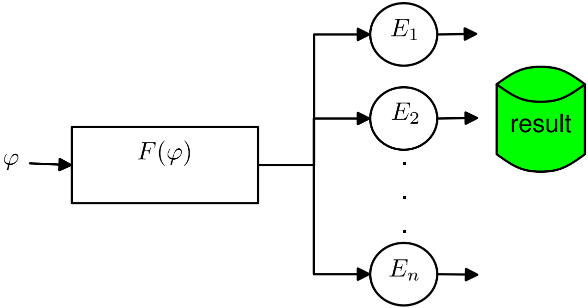

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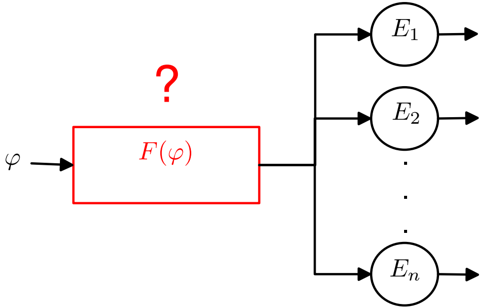

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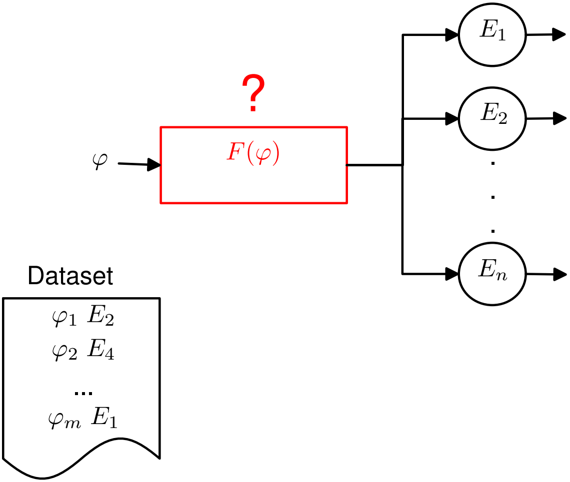

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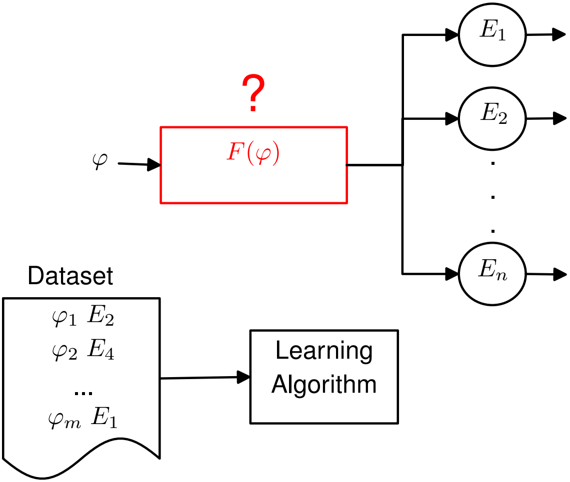

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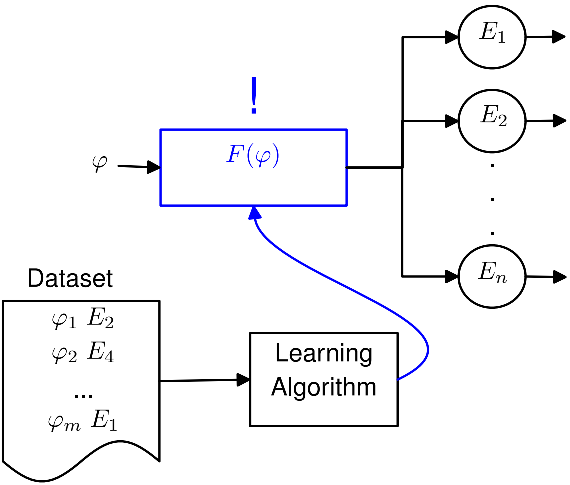

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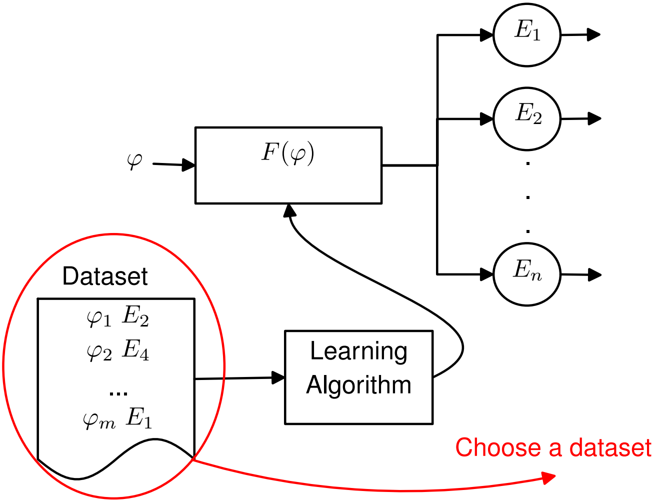

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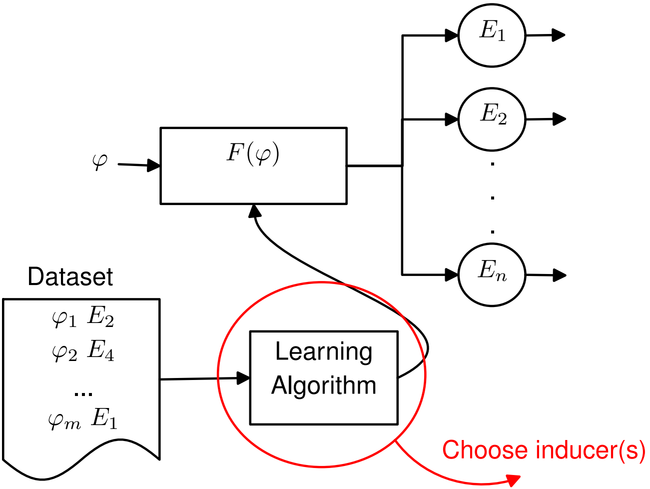

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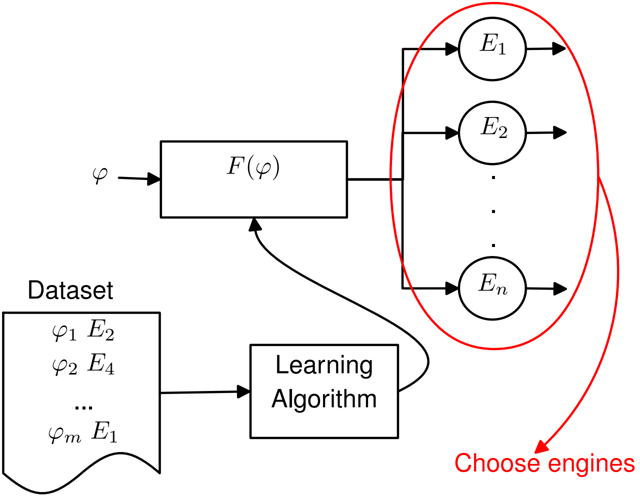

Choosing datasets

- QBFLIB (`www.qbflib.org`), a repository of QBFs
  - More than 15K formulas in a standard format.
  - Artificially generated, toy problems, realistic encodings, challenge problems, ...
- QBF solvers competitions (`www.qbfeval.org`)
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Our choice in AQME'10

The whole QBFEVAL'08 dataset (3326 fixed structured formulas).

Representing QBFs

Basic features regarding:

- Clauses: total number, number of Horn clauses, . . .
- Variables: total number, existential and universal, . . .
- Quantifiers: alternations, . . .
- Literals: total number, average per clause, . . .
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Combined features: ratios/products between basic features.

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109 cheap syntactic features for each QBF.

Choice of inductive models

Our desiderata:

- Deal with numerical attributes (QBF features) and multiple class labels (engines).
- No assumptions of normality or (in)dependence among the features.
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Nearest-neighbour (1-NN)

- We also implemented multivariate logistic regression, decision trees, and decision rules.
- We select 1-NN for its robustness w.r.t. the inductive models above (see [Pulina and Tacchella, CP-DP'08]).

Choosing reasoning engines

- QBFEVALs reveal major differences between
  - Heuristic search based solvers.
  - Hybrid solvers mainly based on other techniques (e.g., resolution, skolemization), but possibly including search.
- Which solvers to choose as basic engines?
  - Only the best “search” and “hybrid”?
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- Hybrid: QUANTOR2.11, and SKIZZO-0.9-STD.

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"Vintage engines" offer us a baseline to compare the current progress in the development of QBF solvers.

Outline

Designing a self-adaptive multi-engine

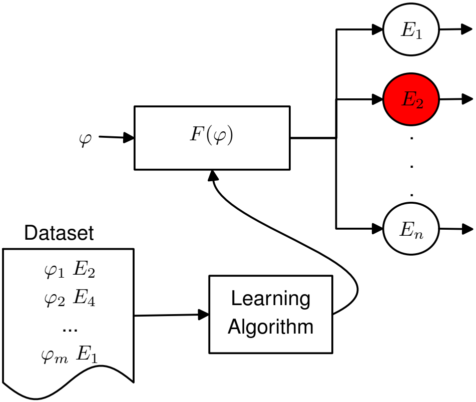
How could AQME'10 learn by its incorrect predictions?

Designing a self-adaptive multi-engine

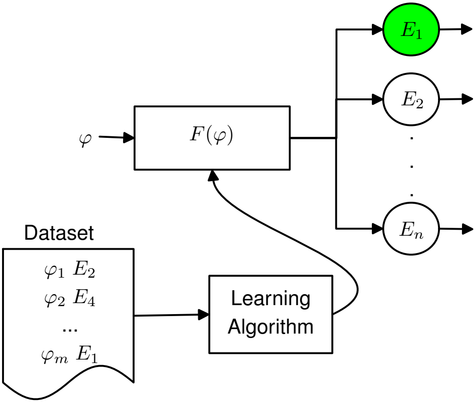
How could AQME'10 learn by its incorrect predictions?

Retraining: adaptation schema applied to engine selection policies whenever they fail to give good predictions.

Retraining


φ
$F(\varphi)$
E_1
E_2
E_n
Dataset
φ_1 E_2
φ_2 E_4
...
φ_m E_1
Learning Algorithm

Retraining



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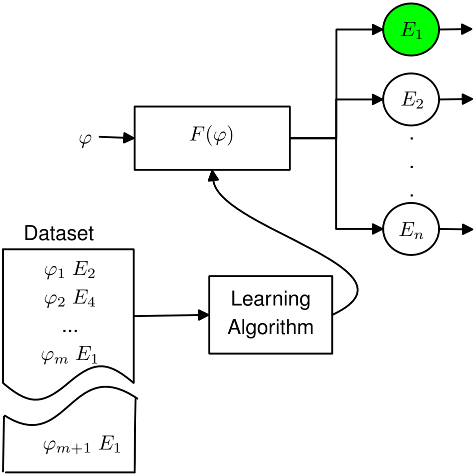
E_1
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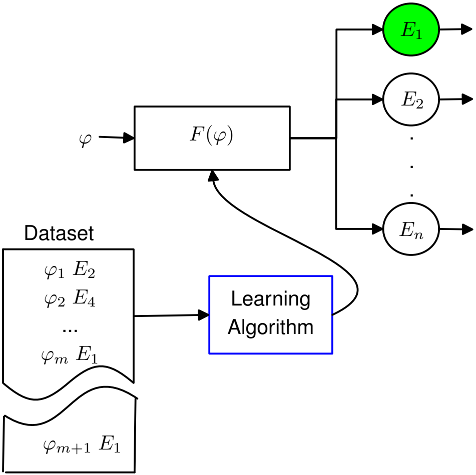
Learning Algorithm
φ_{m+1} E_1

Retraining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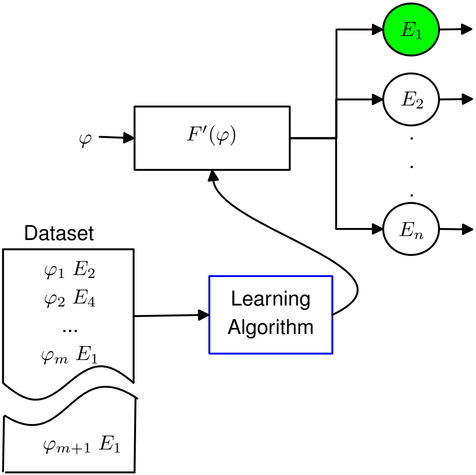

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Retraining policies

Critical points for AQME'10 performances:

- How much CPU time is granted to each engine.
- Which engine is called for retraining.

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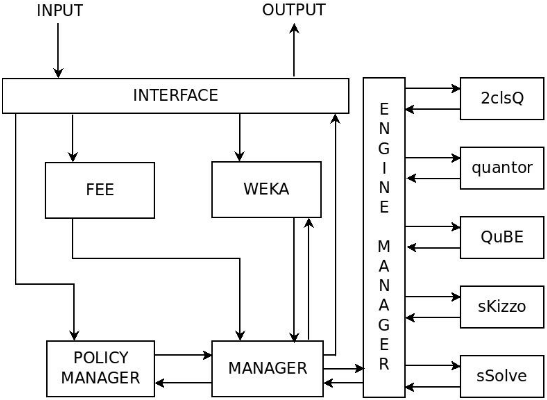
- Which engine is called for retraining.

Policies in AQME'10

- **Granted CPU time**: "Trust the Predicted Engine"
  - A fixed amount of CPU time is granted to the predicted solver.
  - If it fails, another engine is called (following the engine selection policy), with a granted amount of CPU time until the solver solves the input formula.
  - If the formula is not solved, the originally predicted engine is fired, with the time limit assigned to the remaining time.
- **Engine selection**: The engine to fire is selected according to the QBFEVAL'06 ranking.

AQME'10 architecture



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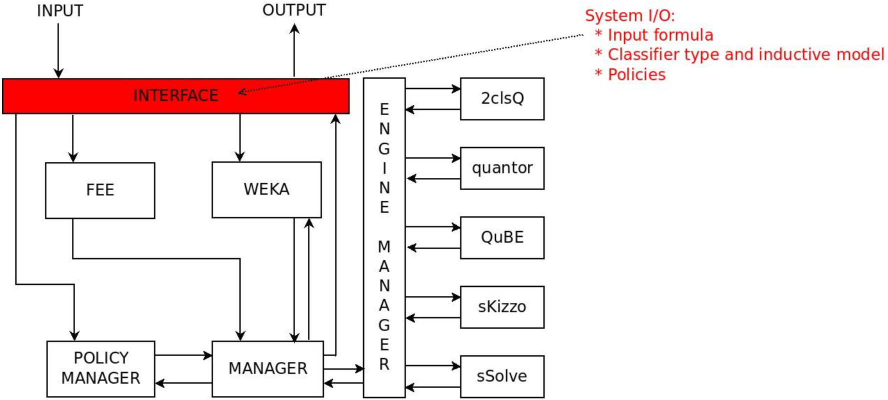

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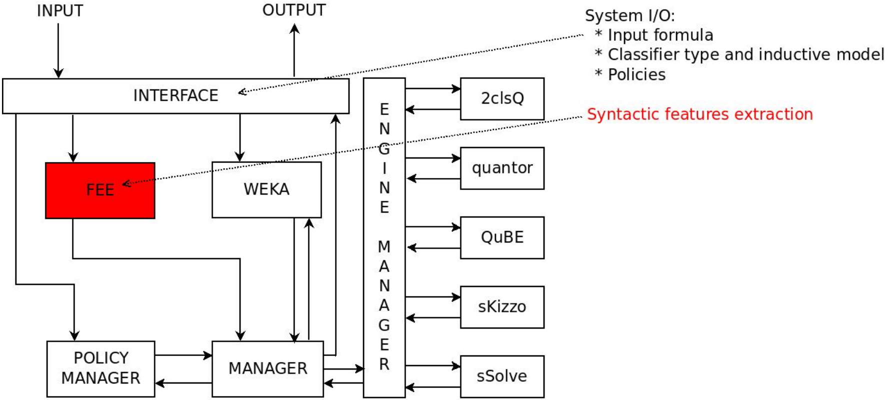

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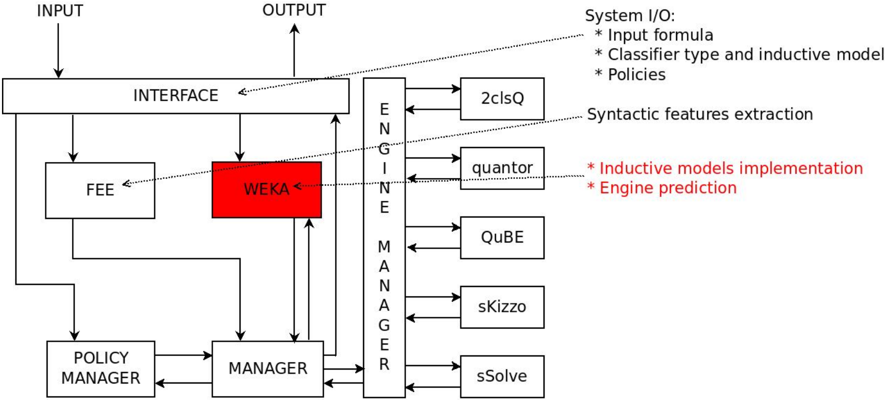

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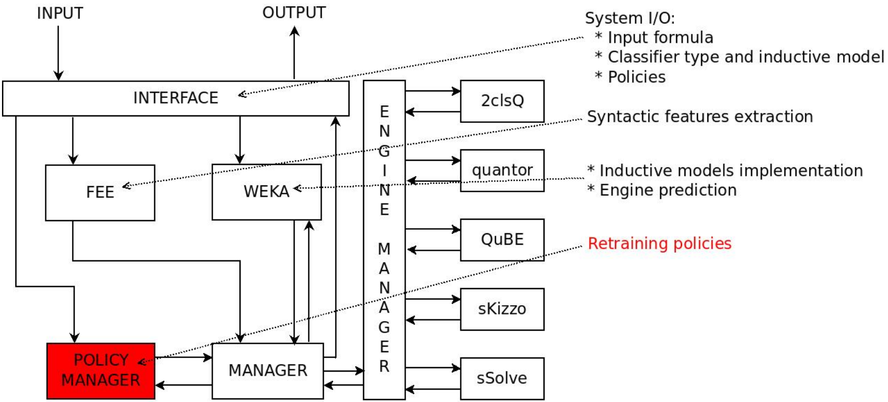

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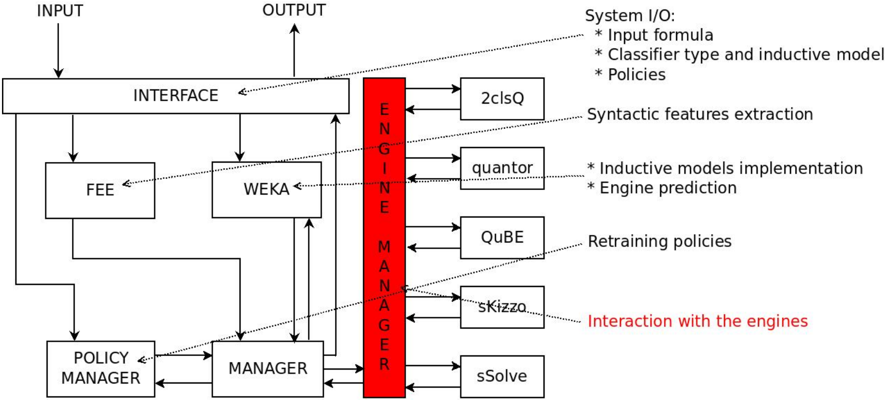

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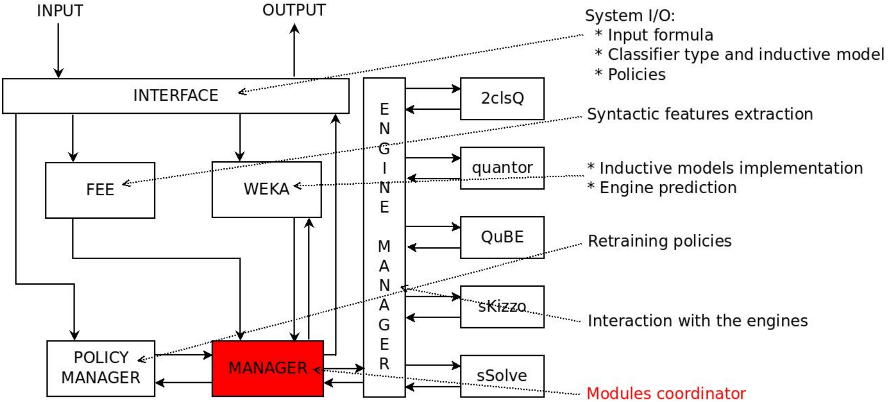


Outline

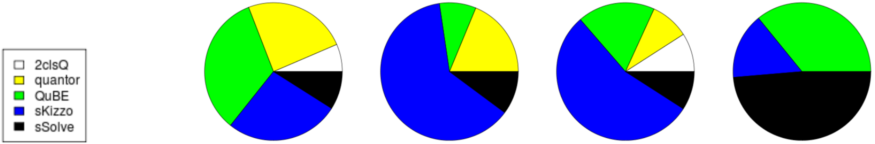
AQME'10@QBFEVAL'10

Solver	MAIN		2QBF		SH		RND	
	#	Time	#	Time	#	Time	#	Time
AIGSOLVE	329	22786.60	NA	NA	**37**	1140.01	NA	NA
AQME'10	**434**	33346.60	128	2323.11	11	30132.40	**407**	20078.90
DEPQBF	370	21515.30	24	690.42	4	41448.00	342	12895.10
DEPQBF-PRE	356	18995.90	51	877.02	4	33371.90	343	9438.62
NENOFEX	225	13786.90	50	3545.65	3	30194.20	149	34502.80
QMAIGA	361	43058.10	NA	NA	NA	NA	NA	NA
QUANTOR3.1	205	6711.37	48	3689.30	5	57960.90	134	2830.97
STRUQS'10	240	32839.70	**132**	1399.30	5	26257.30	117	15480.40

- Best[1] solver in MAIN and RND tracks.
- Good performance in 2QBF and SH tracks.

[1] In the sense of numbers of problems solved within the CPU time limit

Looking inside AQME'10



	MAIN	2QBF	SH	RND
2CLSQ	28	–	1	–
QUANTOR2.11	106	24	1	–
QUBE3.1	**145**	11	2	146
SKIZZO	116	**80**	**6**	63
SSOLVE-UT	39	13	1	**198**
Retrainings	22	3	–	15

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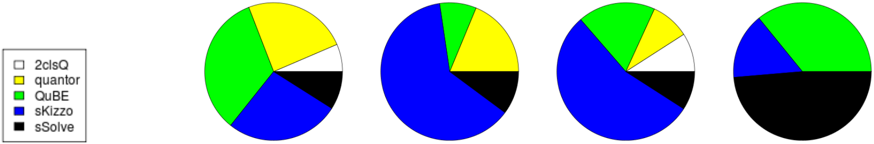

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Self-adaptation based on the characteristics of the test set.

Outline

Conclusions

- A multiengine solver is a robust alternative to current state-of-the-art QBF solvers.
- Good performance achieved also using engines date back 2006.
- Retraining algorithm increases the performances in terms of number of solved formula.
- Performances “limited” by the **State-of-the-art solver**, i.e., the ideal solver that always fares the best time among all the considered solvers.

Future work

- Mechanism for the automatic integration of new engines.
- Implementation of new learning algorithms (see, e.g., D. Stern et al., AAAI 2010).
- Integration between different algorithms, not black-box engines (see, e.g., Pulina and Tacchella, FROCOS 2009).

Thank you!