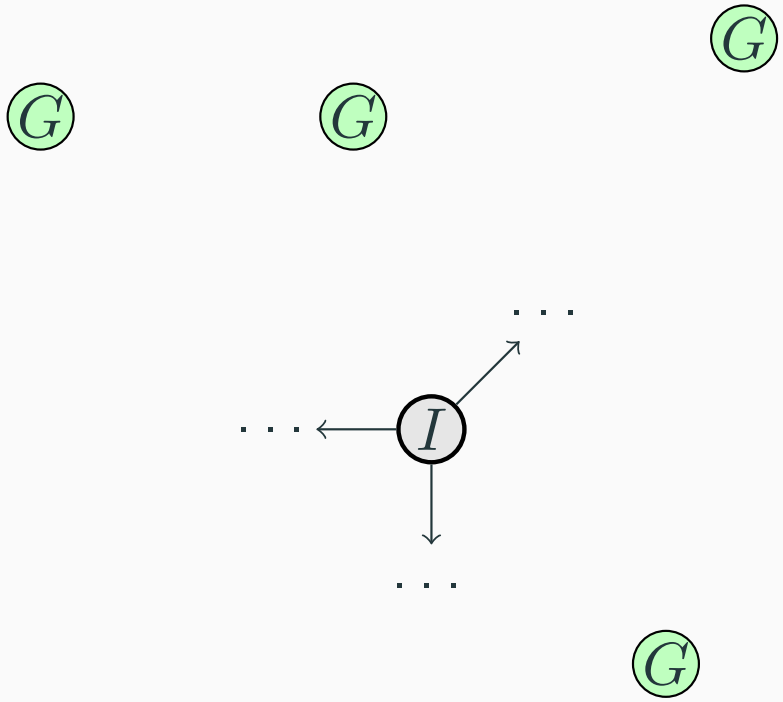
Bounded-Cost Search Using Estimates of Uncertainty

Maximilian Fickert, Tianyi Gu, Wheeler Ruml

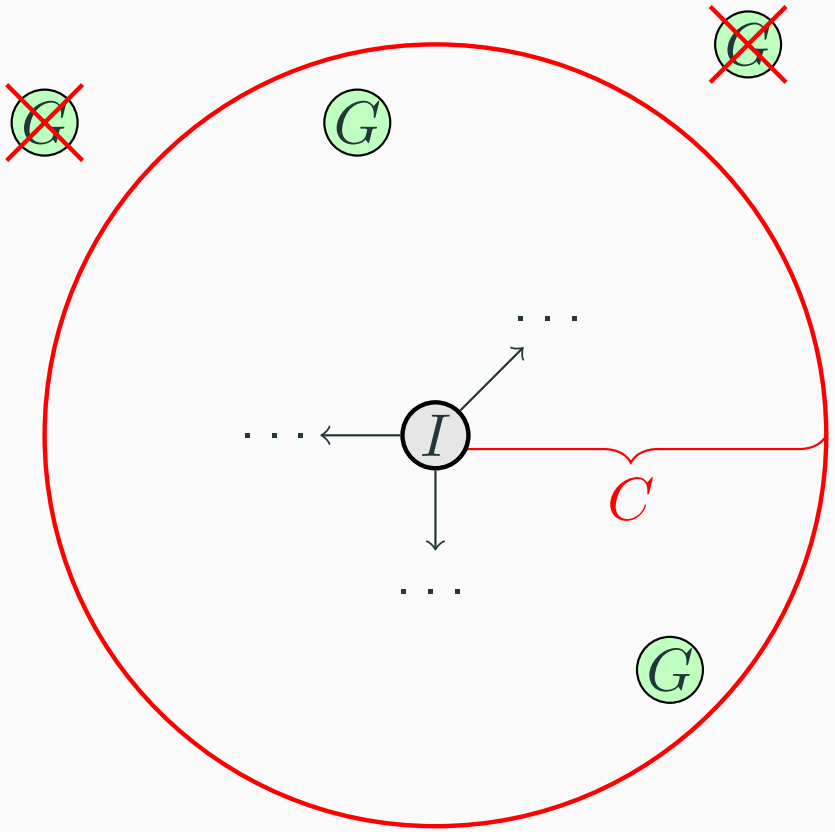
SAARLAND UNIVERSITY
SAARBRÜCKEN GRADUATE SCHOOL OF COMPUTER SCIENCE

University of New Hampshire

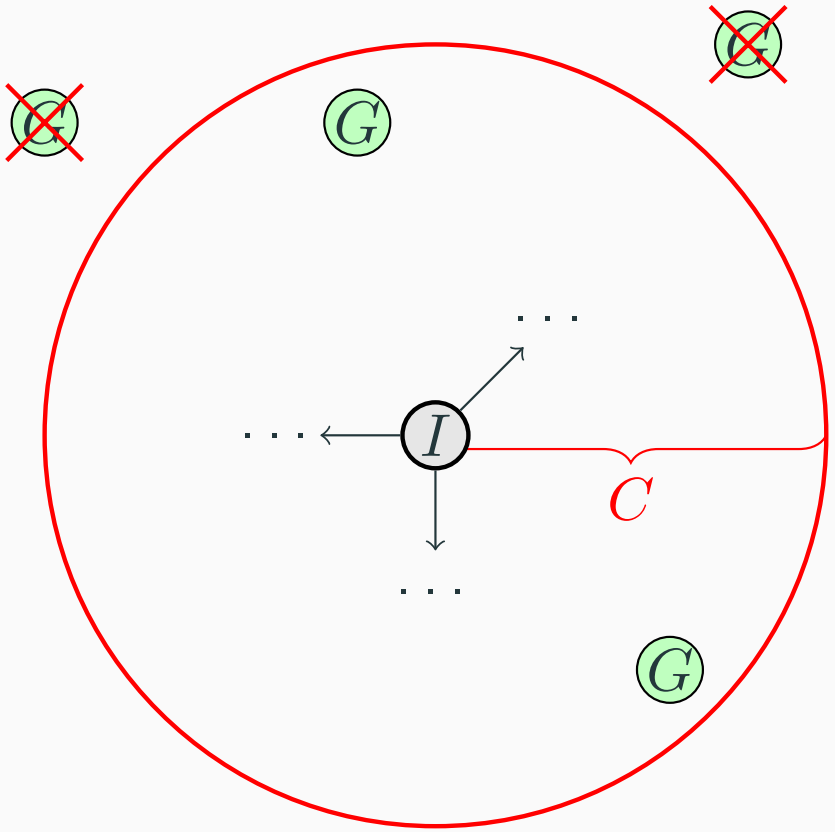
Bounded-Cost Search



Bounded-Cost Search



Bounded-Cost Search



Objective: Find a plan with cost at most C as fast as possible.

Previous Approaches

- Standard Heuristic Search with Pruning on C
- Potential Search (PTS)[1]
  $\rightarrow$ best-first search on $\frac{h}{C-g}$
- Bounded-cost Explicit Estimation Search (BEES)[2]
  $\rightarrow$ focal search:
  - *open* sorted by f, only nodes with $g + h \leq C$
  - *focal* sorted by d, only nodes with $g + \hat{h} \leq C$
    ($\hat{h}$ is corrected for the observed heuristic error[3])

[1] Stern, Puzis, and Felner 2011.
[2] Thayer et al. 2012.
[3] Thayer, Dionne, and Ruml 2011.

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

[4] First suggested by Dobson and Haslum (HSDIP'17).

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

$T = 10$
$p = 0.5$

$T = 6$
$p = 0.25$

[4] First suggested by Dobson and Haslum (HSDIP'17).

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

n_1 $\quad T = 10,\ p = 0.5 \quad \rightsquigarrow 20$

n_2 $\quad T = 6,\ p = 0.25 \quad \rightsquigarrow 24$

[4] First suggested by Dobson and Haslum (HSDIP'17).

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

n_1 $T = 10$, $p = 0.5$ $\rightsquigarrow 20$

n_2 $T = 6$, $p = 0.25$ $\rightsquigarrow 24$

How to obtain T?

How to obtain p?

[4] First suggested by Dobson and Haslum (HSDIP'17).

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

n_1 $T = 10$, $p = 0.5$ $\rightsquigarrow 20$

n_2 $T = 6$, $p = 0.25$ $\rightsquigarrow 24$

How to obtain T?

$\rightarrow$ just use d

How to obtain p?

[4] First suggested by Dobson and Haslum (HSDIP'17).

Expected Effort Search (XES)

Best-first search on the expected effort:[4] $\frac{T}{p}$

- $T(n)$: search effort to find a solution under n
- $p(n)$: probability that n leads to a solution within C

n_1 $T = 10$, $p = 0.5$ $\rightsquigarrow 20$

n_2 $T = 6$, $p = 0.25$ $\rightsquigarrow 24$

How to obtain T?

$\rightarrow$ just use d

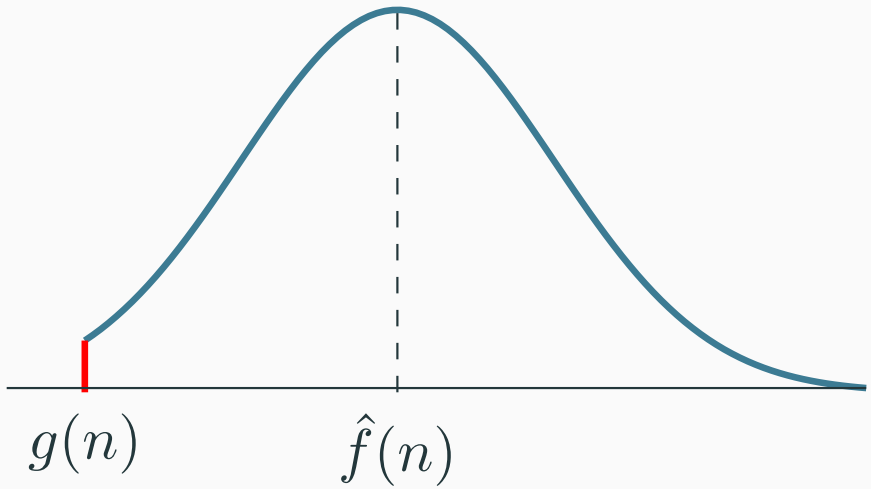
How to obtain p?

$\rightarrow$ approximate from $\hat{h}$ distribution

[4] First suggested by Dobson and Haslum (HSDIP'17).

Obtaining p from Belief Distributions

Nancy[5] belief distributions based on heuristic error observations[6]:

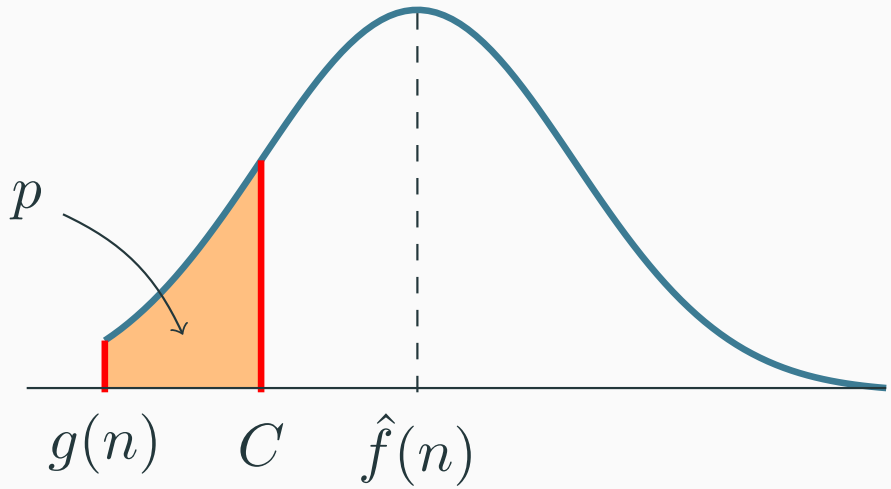


[5] Mitchell et al. 2019.

[6] Thayer, Dionne, and Ruml 2011.

Obtaining p from Belief Distributions

Nancy[5] belief distributions based on heuristic error observations[6]:



[5] Mitchell et al. 2019.

[6] Thayer, Dionne, and Ruml 2011.

Theoretical Analysis

XES optimizes search effort, assuming

1. the search explores one subtree at a time,
2. subtrees are independent, and
3. subtrees are abandoned after spending $T(n)$ time.

Using p in BEES

BEES95:

- *open* sorted by f, only nodes with $g + h \leq C$
- *focal* sorted by d, only nodes with ~~$g + \hat{h} \leq C$~~ $p(n) > 95\%$

Experiments

Planning Domains:

- Implementation in Fast Downward[7]
- Benchmarks:
  - IPC'18 cost-bounded track
  - Previous IPC domains with bounds from Planning.Domains[8]

Search Domains:

- Sliding-Tile Puzzle, Vacuum World, Pancake, Racetrack

[7] Helmert 2006.
[8] Muise 2016.

IPC'18 Bounded-Cost Track

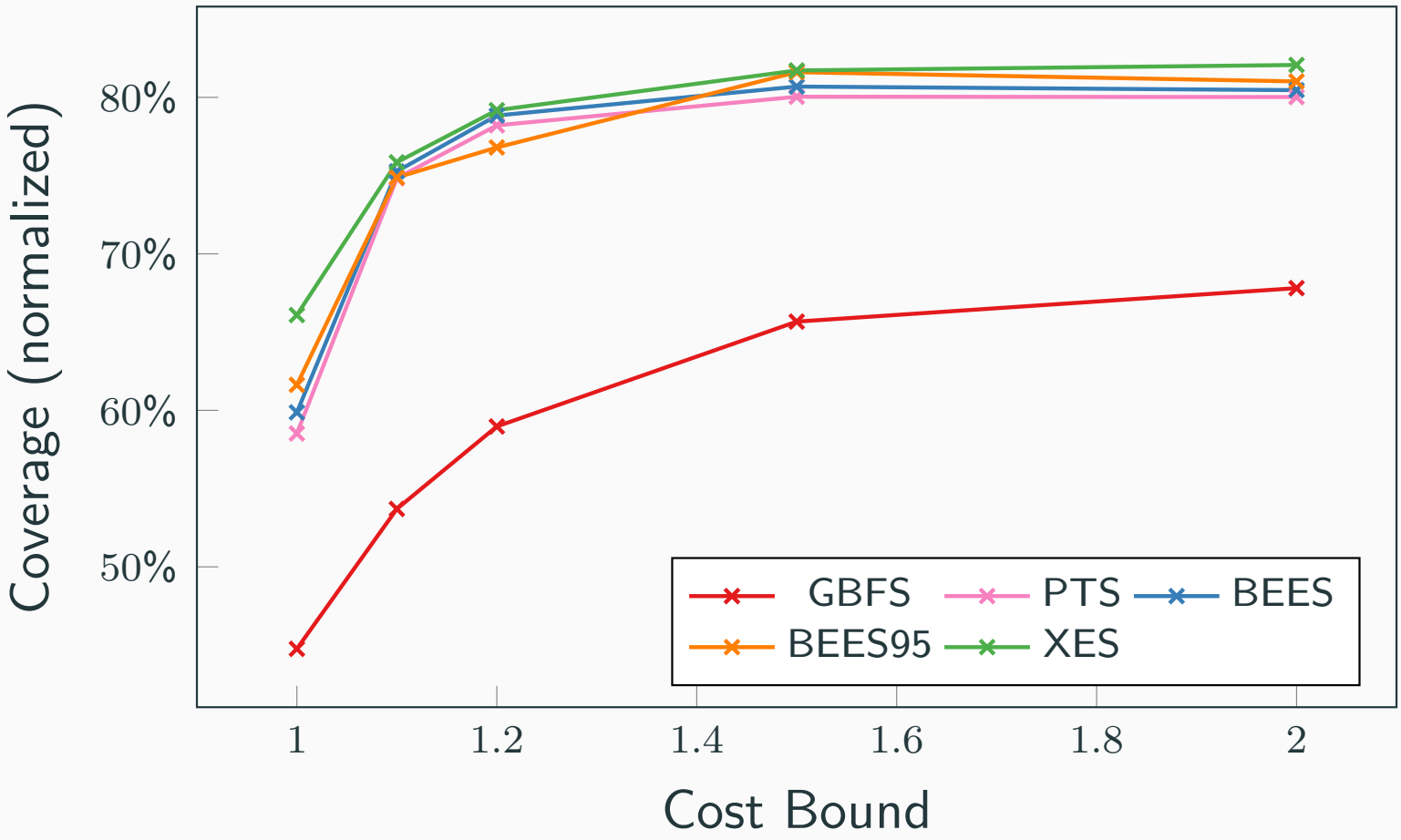
Coverage	GBFS	PTS	BEES	BEES95	XES
Agricola (20)	**1**	0	0	0	0
Caldera (20)	8	10	10	12	**13**
Caldera-split (20)	**4**	2	2	2	2
DataNetwork (20)	2	0	3	3	**4**
Nurikabe (20)	4	10	10	**11**	9
Settlers (20)	4	5	10	**11**	**11**
Snake (20)	4	**5**	4	4	**5**
Spider (20)	7	**11**	10	10	9
Termes (20)	11	9	11	11	**13**
Sum (180)	45	52	60	64	**66**
Expansions ($*10^3$)	1.93	3.93	2.10	2.25	**1.77**

IPC'18 Bounded-Cost Track

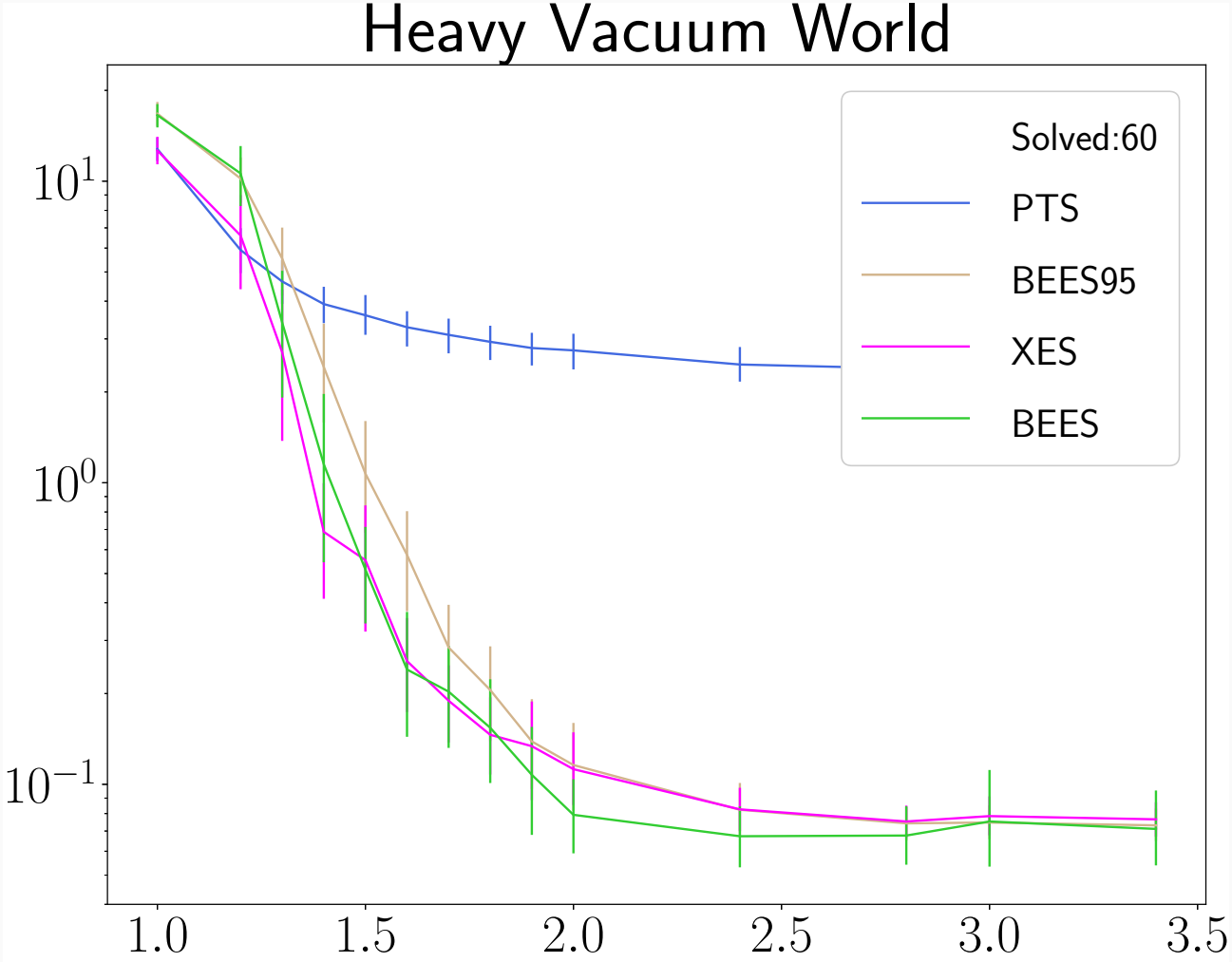
Coverage	GBFS	PTS	BEES	BEES95	XES
Agricola (20)	**1**	0	0	0	0
Caldera (20)	8	10	10	12	**13**
Caldera-split (20)	**4**	2	2	2	2
DataNetwork (20)	2	0	3	3	**4**
Nurikabe (20)	4	10	10	**11**	9
Settlers (20)	4	5	10	**11**	**11**
Snake (20)	4	**5**	4	4	**5**
Spider (20)	7	**11**	10	10	9
Termes (20)	11	9	11	11	**13**
Sum (180)	45	52	60	64	**66**
Expansions ($*10^3$)	1.93	3.93	2.10	2.25	**1.77**

$\rightarrow$ Cost-bounded algorithms dominate GBFS; XES is best overall.

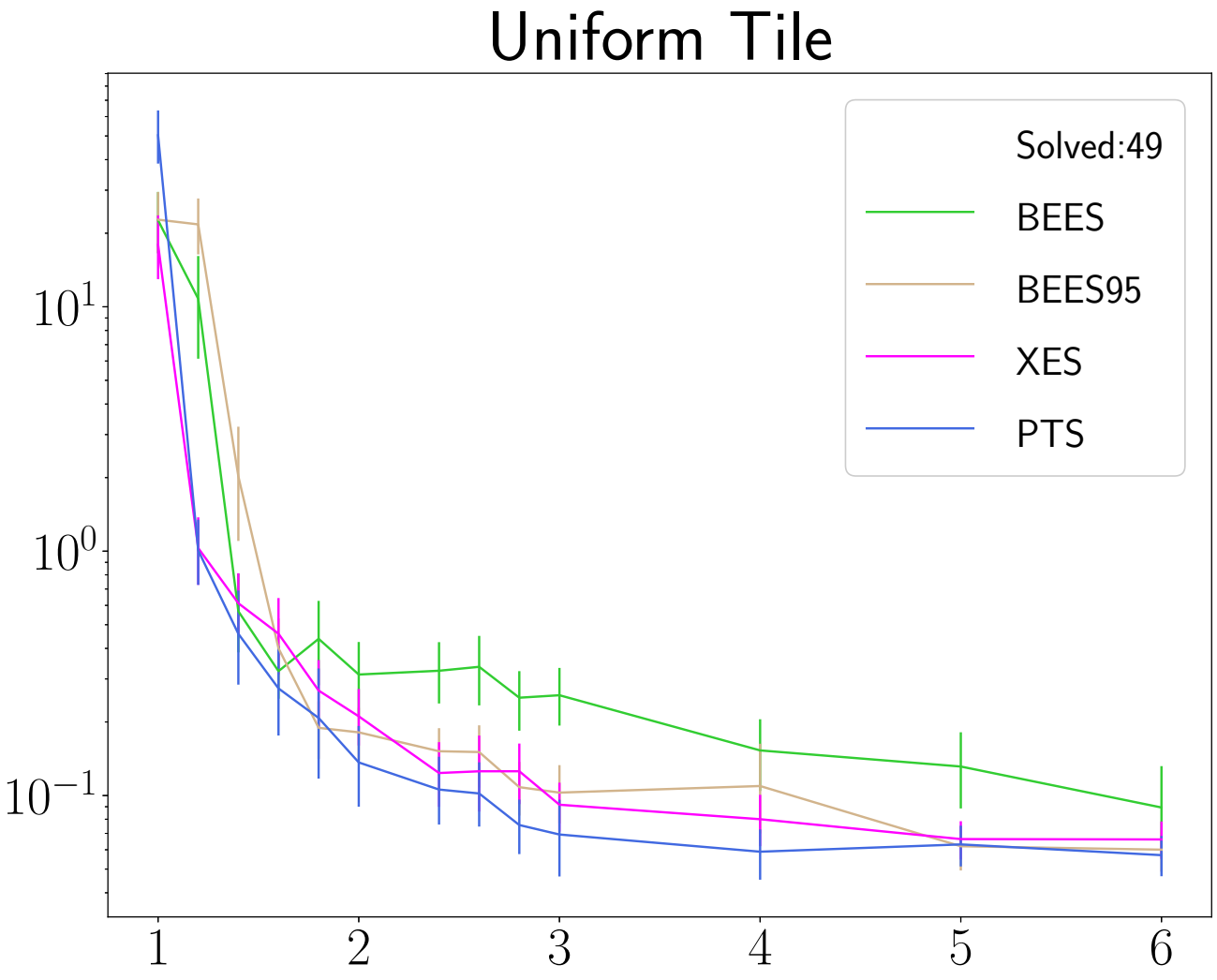
Pre-2018 IPC Domains



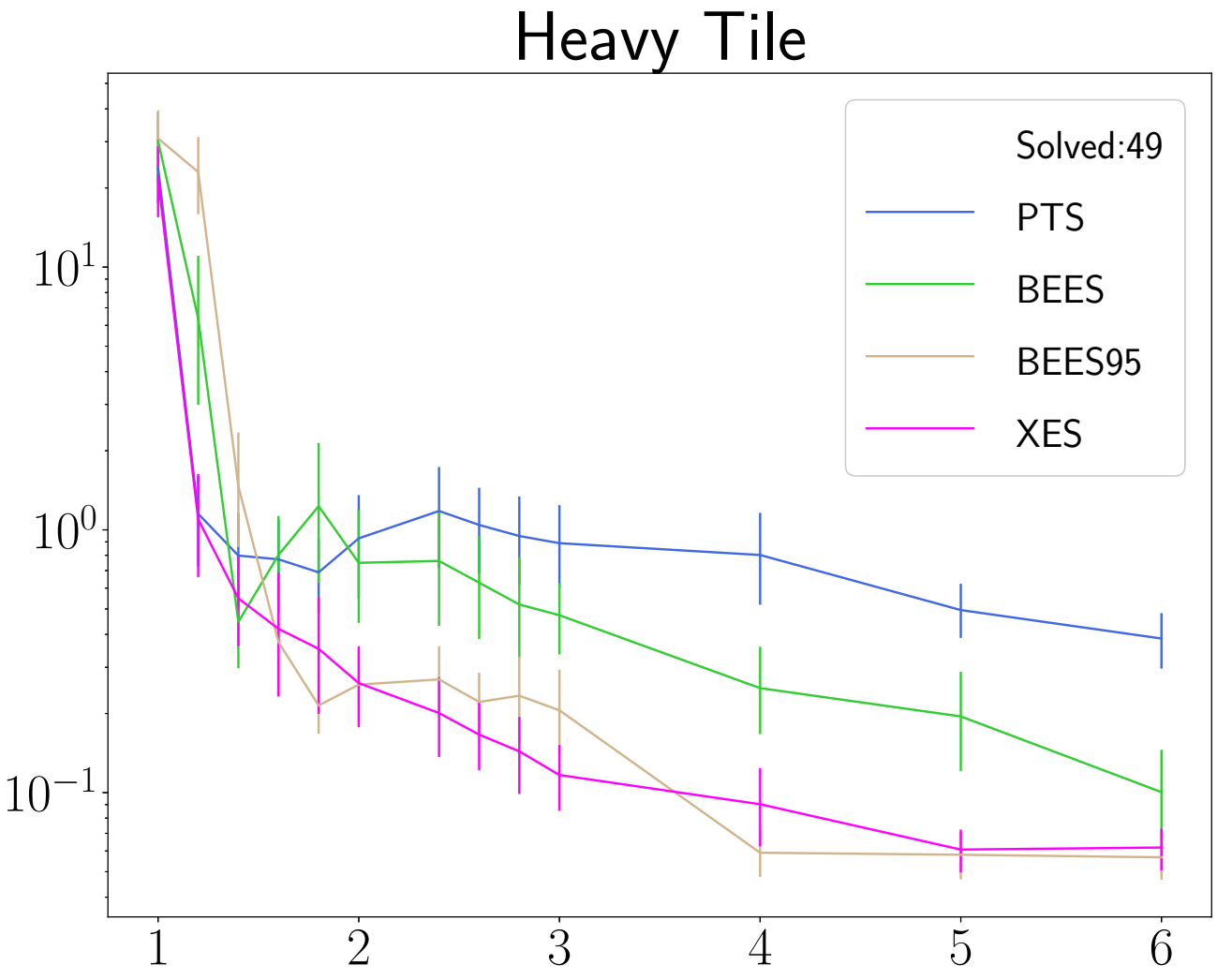
Search Domains: Heavy Vacuum World



Search Domains



Search Domains



Conclusion

Expected Effort Search (XES):

- Optimizes search effort in a simplified model.
- Superior robustness and performance to comparable algorithms.

$\rightarrow$ Advances the trend of leveraging distributional information in deterministic heuristic search.