Lecture slides for

Automated Planning: Theory and Practice

Chapter 10
Control Rules in Planning

Dana S. Nau

University of Maryland

Fall 2009

Motivation

- Often, planning can be done much more efficiently if we have domain-specific information
- Example:
  - classical planning is EXPSPACE-complete
  - block-stacking can be done in time $O(n^3)$
- But we don't want to have to write a new domain-specific planning system for each problem!
- *Domain-configurable* planning algorithm
  - Domain-independent search engine (usually a forward state-space search)
  - Input includes domain-specific information that allows us to avoid a brute-force search
    - » Prevent the planner from visiting unpromising states

Motivation (Continued)

- If we're at some state s in a state space, sometimes a domain-specific test can tell us that
  - s doesn't lead to a solution, or
  - for any solution below s, there's a better solution along some other path
- In such cases we can to prune s immediately

```
Abstract-search(u)
    if Terminal(u) then return(u)
    u ← Refine(u)          ;;  refinement step
    B ← Branch(u)          ;;  branching step
    B′ ← Prune(B)          ;;  pruning step
    if B′ = ∅ then return(failure)
    nondeterministically choose v ∈ B′
    return(Abstract-search(v))
end
```

- Rather than writing the domain-dependent test as low-level computer code, we'd prefer to talk directly about the planning domain
- One approach:
  - Write logical formulas giving conditions that states must satisfy; prune states that don't satisfy the formulas
- Presentation similar to the chapter, but not identical
  - Based partly on TLPlan [Bacchus & Kabanza 2000]

Quick Review of First Order Logic

- First Order Logic (FOL):
  - constant symbols, function symbols, predicate symbols
  - logical connectives (∨, ∧, ¬, ⇒, ⇔), quantifiers (∀, ∃), punctuation
  - Syntax for formulas and sentences $on(A,B) \wedge on(B,C)$
    $\exists x\ on(x,A)$
    $\forall x\ (ontable(x) \Rightarrow clear(x))$
- First Order Theory T:
  - "Logical" axioms and inference rules – encode logical reasoning in general
  - Additional "nonlogical" axioms – talk about a particular domain
  - Theorems: produced by applying the axioms and rules of inference
- Model: set of objects, functions, relations that the symbols refer to
  - For our purposes, a model is some state of the world s
  - In order for s to be a model, all theorems of T must be true in s
  - $s \models on(A,B)$ read "s satisfies $on(A,B)$" or "s models $on(A,B)$"
    - » means that $on(A,B)$ is true in the state s

Linear Temporal Logic

- Modal logic: FOL plus *modal operators*
  to express concepts that would be difficult to express within FOL
- Linear Temporal Logic (LTL):
  - Purpose: to express a limited notion of time
    - An infinite sequence $\langle 0, 1, 2, \ldots \rangle$ of time instants
    - An infinite sequence $M = \langle s_0, s_1, \ldots \rangle$ of states of the world
  - Modal operators to refer to the states in which formulas are true:

    $\bigcirc f$ - *next f* - f holds in the next state, e.g., $\bigcirc\ on(A,B)$

    $\Diamond f$ - *eventually f* - f either holds now or in some future state

    $\Box f$ - *always f* - f holds now and in all future states

    $f_1 \cup f_2$ - f_1 *until* f_2 - f_2 either holds now or in some future state, and f_1 holds until then
  - Propositional constant symbols TRUE and FALSE

Linear Temporal Logic (continued)

- Quantifiers cause problems with computability
  - Suppose $f(x)$ is true for infinitely many values of x
  - Problem evaluating truth of $\forall x \ f(x)$ and $\exists x \ f(x)$

- Bounded quantifiers
  - Let $g(x)$ be such that $\{x : g(x)\}$ is finite and easily computed

    $\forall[x{:}g(x)]\, f(x)$
    - means $\forall x\ (g(x) \Rightarrow f(x))$
    - expands into $f(x_1) \wedge f(x_2) \wedge \ldots \wedge f(x_n)$

    $\exists[x{:}g(x)]\, f(x)$
    - means $\exists x\ (g(x) \wedge f(x))$
    - expands into $f(x_1) \vee f(x_2) \vee \ldots \vee f(x_n)$

Models for LTL

- A model is a triple (M, s_i, v)
  - $M = \langle s_0, s_1, \ldots \rangle$ is a sequence of states
  - s_i is the i'th state in M,
  - v is a *variable assignment* function
    - » a substitution that maps all variables into constants

- Write $(M,s_i,v) \models f$

  to mean that $v(f)$ is true in s_i

- Always require that

$$(M,\ s_i, v) \models \text{TRUE}$$

$$(M,\ s_i, v) \models \neg\text{FALSE}$$

Examples

- Suppose $M = \langle s_0, s_1, \ldots \rangle$

  $(M,s_0,v) \models \bigcirc\bigcirc\, on(A,B)$ means A is on B in s_2

- Abbreviations:

  $(M,s_0) \models \bigcirc\bigcirc\, on(A,B)$ no free variables, so v is irrelevant:

  $M \models \bigcirc\bigcirc\, on(A,B)$ if we omit the state, it defaults to s_0

- Equivalently,

  $(M,s_2,v) \models on(A,B)$ same meaning with no modal operators

  $s_2 \models on(A,B)$ same thing in ordinary FOL

- $M \models \Box\neg holding(C)$
  - in every state in M, we aren't holding C

- $M \models \Box(on(B, C) \Rightarrow (on(B, C) \cup on\ (A, B)))$
  - whenever we enter a state in which B is on C, B remains on C until A is on B.

Where We're Going

- Basic idea:
  - TLPLan does a forward search, using LTL to do pruning tests
  - Input includes a current state *s*, and a **control formula** *f* written in LTL
    - » If *f* isn't satisfied, then *s* is unacceptable => backtrack
    - » Else keep going
- We'll need to augment LTL to include a way to refer to goal states
  - Include a GOAL operator such that GOAL(*f*) means *f* is true in every goal state
  - $((M,s_i,V),g) \models \text{GOAL}(f)$ iff $(M,s_i,V) \models f$ for every $s_i \in g$
- Next, some examples of control formulas

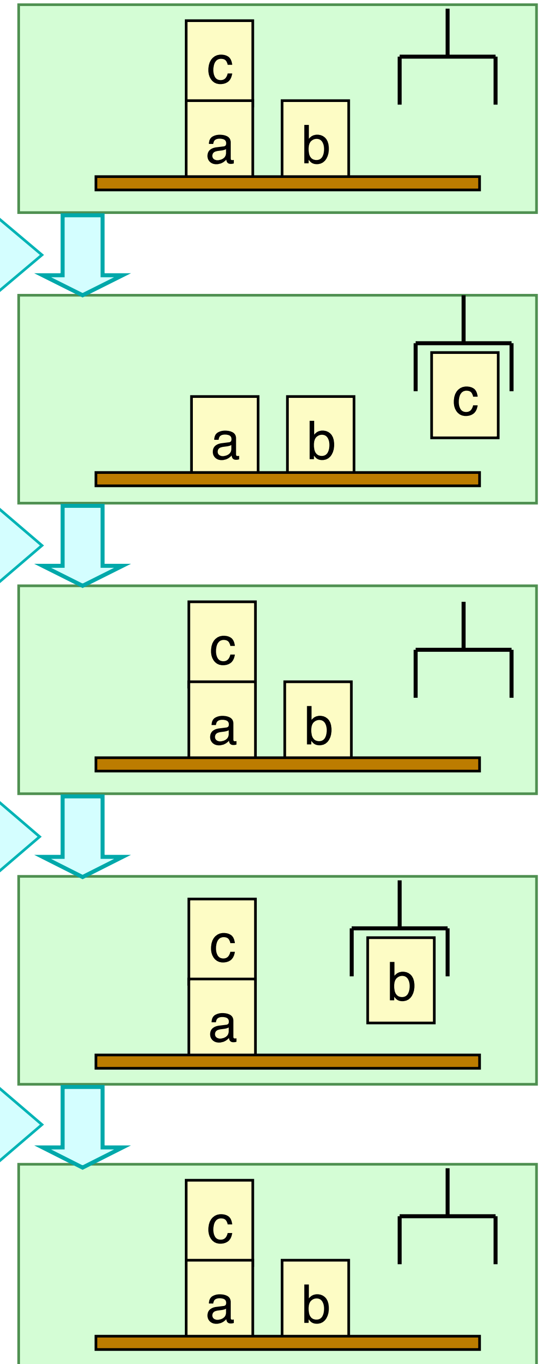
Example: Blocks World

unstack(x,y)
Precond: on(x,y), clear(x), handempty
Effects: ¬on(x,y), ¬clear(x), ¬handempty, holding(x), clear(y)

stack(x,y)
Precond: holding(x), clear(y)
Effects: ¬holding(x), ¬clear(y), on(x,y), clear(x), handempty

pickup(x)
Precond: ontable(x), clear(x), handempty
Effects: ¬ontable(x), ¬clear(x), ¬handempty, holding(x)

putdown(x)
Precond: holding(x)
Effects: ¬holding(x), ontable(x), clear(x), handempty



Supporting Axioms

- Want to define conditions under which a stack of blocks will never need to be moved
- If x is the top of a stack of blocks, then we want *goodtower*(x) to hold if
  - x doesn't need to be anywhere else
  - None of the blocks below x need to be anywhere else
- Definitions to support this:
  - $goodtower(x) \Leftrightarrow clear(\mathrm{x}) \wedge \neg \mathrm{GOAL}(holding(x)) \wedge goodtowerbelow(x)$
  - $goodtowerbelow(x) \Leftrightarrow$

$$[ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))]]$$

$$\vee\ \exists[y{:}on(x,y)]\ \{\neg\mathrm{GOAL}(ontable(x)) \wedge \neg\mathrm{GOAL}(holding(y))$$

$$\wedge\ \neg\mathrm{GOAL}(clear(y)) \wedge \forall[z{:}\mathrm{GOAL}(on(x,z))]\ (z = y)$$

$$\wedge\ \forall[z{:}\mathrm{GOAL}(on(z,y))]\ (z = x) \wedge goodtowerbelow(y)\}$$

  - $badtower(x) \Leftrightarrow clear(x) \wedge \neg goodtower(x)$

Blocks World Example (continued)

Three different control formulas:

(1) Every goodtower must always remain a goodtower:

$$\Box\Big(\forall[x{:}clear(x)]\ goodtower(x) \Rightarrow \bigcirc(clear(x) \lor \exists[y{:}on(y,x)]\ goodtower(y))\Big)$$

(2) Like (1), but also says never to put anything onto a badtower:

$$\Box\Big(\forall[x{:}clear(x)]\ goodtower(x) \Rightarrow \bigcirc(clear(x) \lor \exists[y{:}on(y,x)]\ goodtower(y)) \\ \land\ badtower(x) \Rightarrow \bigcirc(\neg\exists[y{:}on(y,x)]\ )\Big)$$

(3) Like (2), but also says never to pick up a block from the table unless you can put it onto a goodtower:

$$\Box\Big(\forall[x{:}clear(x)]\ goodtower(x) \Rightarrow \bigcirc(clear(x) \lor \exists[y{:}on(y,x)]\ goodtower(y)) \\ \land\ badtower(x) \Rightarrow \bigcirc(\neg\exists[y{:}on(y,x)]\ ) \\ \land\ (ontable(x) \land \exists[y{:}\mathrm{GOAL}(on(x,y))]\ \neg goodtower(y)) \\ \Rightarrow \bigcirc(\neg holding(x))\Big)$$

Outline of How TLPlan Works

- Recall that TLPLan's input includes a current state *s,* and a control formula *f* written in LTL
  - How can TLPLan determine whether there exists a sequence of states *M* beginning with *s,* such that $M \models f$?

- We can compute a formula f^+ such that for every sequence $M = \langle s, s^+, s^{++},\ldots\rangle$,
  - $M \models f^+$ iff $M^+ = \langle s^+, s^{++},\ldots\rangle$ satisfies f^+
  - f^+ is called the **progression** of *f* through *s*

- If f^+ = FALSE then no M^+ can satisfy f^+
  - Thus no *M* can satisfy *f*, so TLPLan can backtrack
- Otherwise, need to determine whether there is an M^+ that satisfies f^+
  - For every child s^+ of *s,* call TLPLan recursively on s^+ and f^+

- How to compute the progression of *f* through *s*?

Procedure Progress(f, s)

Case

1. f contains no temporal operators: $f^+ :=$ TRUE if $s \models f$, FALSE otherwise.
2. $f = f_1 \wedge f_2$: $f^+ :=$ Progress$(f_1, s) \wedge$ Progress(f_2, s)
3. $f = \neg f_1$: $f^+ := \neg$Progress(f_1, s)
4. $f = \bigcirc f_1$: $f^+ := f_1$
5. $f = f_1 \cup f_2$: $f^+ :=$ Progress$(f_2, s) \vee$ (Progress$(f_1, s) \wedge f$)
6. $f = \Diamond f_1$: $f^+ :=$ Progress$(f_1, s) \vee f$
7. $f = \Box f_1$: $f^+ :=$ Progress$(f_1, s) \wedge f$
8. $f = \forall[x{:}\gamma(x)]\, f_1$: $f^+ := \bigwedge_{i=1,\ldots,n}$ Progress(f_i, s)
9. $f = \exists[x{:}\gamma(x)]\, f_1$: $f^+ := \bigvee_{i=1,\ldots,n}$ Progress(f_i, s)

where $\{c_1, \ldots, c_n\} = \{x : s \models \gamma(x)\}$, and $f_i = f$ with x replaced by c_i

Boolean simplification rules:

1. $[\text{FALSE} \wedge \phi | \phi \wedge \text{FALSE}] \mapsto \text{FALSE}$,
2. $[\text{TRUE} \wedge \phi | \phi \wedge \text{TRUE}] \mapsto \phi$,
3. $\neg\text{TRUE} \mapsto \text{FALSE}$,
4. $\neg\text{FALSE} \mapsto \text{TRUE}$.

Examples

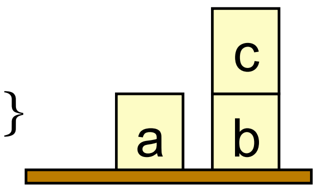
- Suppose $f = \Box$ on(a,b)
  - $f^+ = \text{Progress}(on(\text{a,b}), s) \wedge \Box\, on(\text{a,b})$
  - If on(a,b) is true in s then
    - » $f^+ = \text{TRUE} \wedge \Box\, on(\text{a,b})$
    - » simplifies to $\Box\, on(\text{a,b})$
  - If on(a,b) is false in s then
    - » $f^+ = \text{FALSE} \wedge \Box\, on(\text{a,b})$
    - » simplifies to FALSE

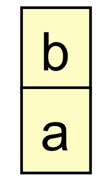
- Summary:
  - $\Box$ generates a test on the current state
  - If the test succeeds, $\Box$ propagates it to the next state

Examples (continued)

- Suppose $f = \Box(on(\text{a,b}) \Rightarrow \bigcirc clear(\text{a}))$
  - $f^+ = \text{Progress}[\Box(on(\text{a,b}) \Rightarrow \bigcirc clear(\text{a})), s]$
  - $\quad = \text{Progress}[\text{on(a,b)} \Rightarrow \bigcirc clear(\text{a}), s] \wedge \Box(on(\text{a,b}) \Rightarrow \bigcirc clear(\text{a}))$
  - If $on(\text{a,b})$ is true in s, then
    - » $f^+ = \text{clear(a)} \wedge \Box(on(\text{a,b}) \Rightarrow \bigcirc clear(\text{a}))$
      - Since $on(\text{a,b})$ is true in s,
        s^+ must satisfy $clear(\text{a})$
      - The "always" constraint is propagated to s^+
  - If $on(\text{a,b})$ is false in s, then
    - » $f^+ = \Box(on(\text{a,b}) \Rightarrow \bigcirc clear(\text{a}))$
      - The "always" constraint is propagated to s^+

Example





- $s = \{ontable(\mathsf{a}), ontable(\mathsf{b}), clear(\mathsf{a}), clear(\mathsf{c}), on(\mathsf{c},\mathsf{b})\}$
- $g = \{on(\mathsf{b}, \mathsf{a})\}$
- $f = \Box\forall[x{:}clear(x)]\ \{(ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))]) \Rightarrow \bigcirc\neg holding(x)\}$
  - never pick up a block x if x is not required to be on another block y

- $f^{+} = \mathrm{Progress}(f,s) \wedge f$

- $\mathrm{Progress}(f,s)$

  $= \mathrm{Progress}(\ \forall[x{:}clear(x)]$
  $\{(ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))]) \Rightarrow \bigcirc\neg holding(x)\}, s)$

  $= \mathrm{Progress}((ontable(\mathsf{a}) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(\mathsf{a},y))]) \Rightarrow \bigcirc\neg holding(\mathsf{a})\}, s)$
  $\wedge\ \mathrm{Progress}((ontable(\mathsf{b}) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(\mathsf{b},y))]) \Rightarrow \bigcirc\neg holding(\mathsf{b})\}, s)$

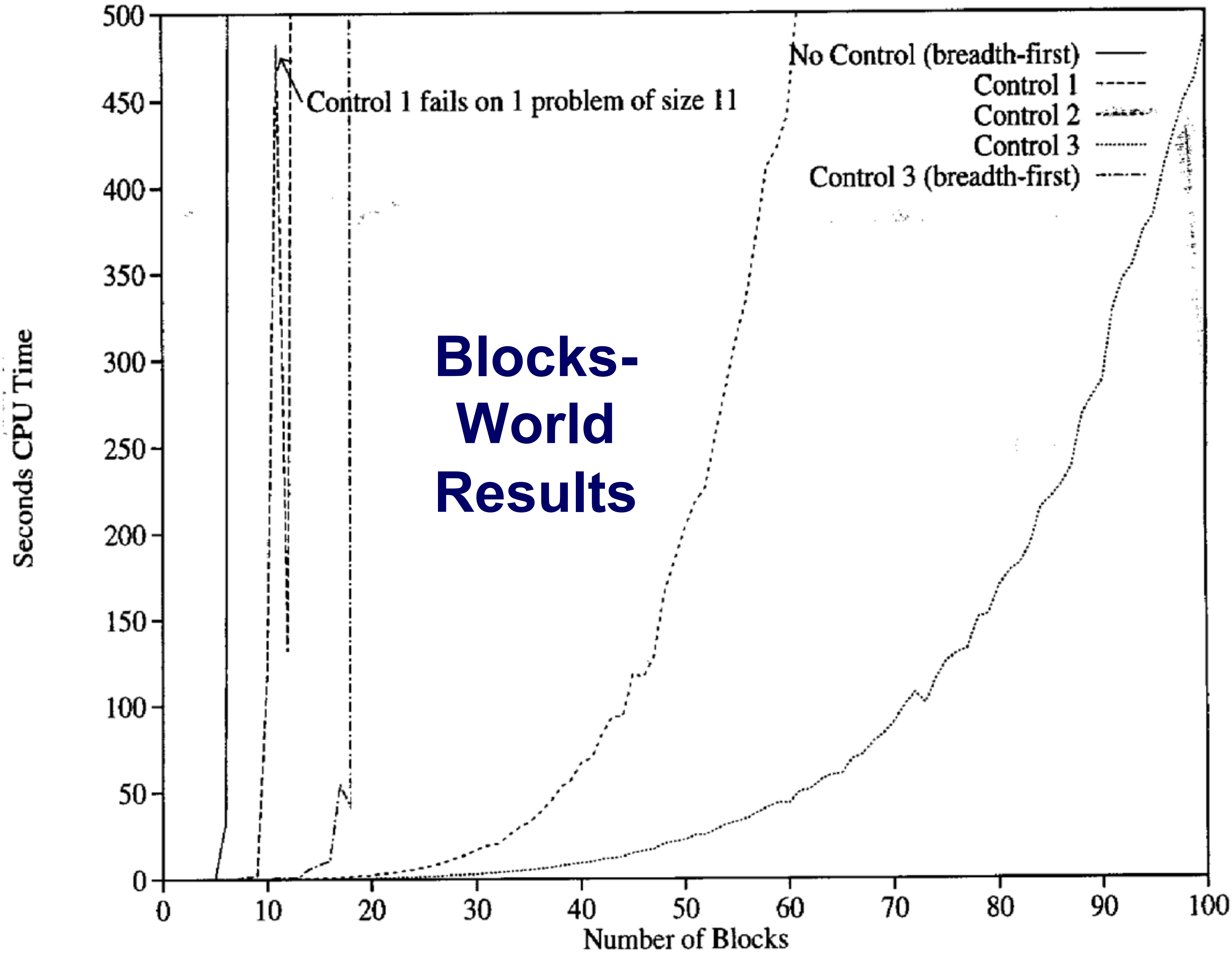
  $= \neg holding(\mathsf{a}) \wedge \mathrm{TRUE}$

- $f^{+} = \neg holding(\mathsf{a}) \wedge \mathrm{TRUE} \wedge f$
  $= \neg holding(\mathsf{a}) \wedge$
  $\Box\forall[x{:}clear(x)]\ \{(ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))]) \Rightarrow \bigcirc\neg holding(x)\}$

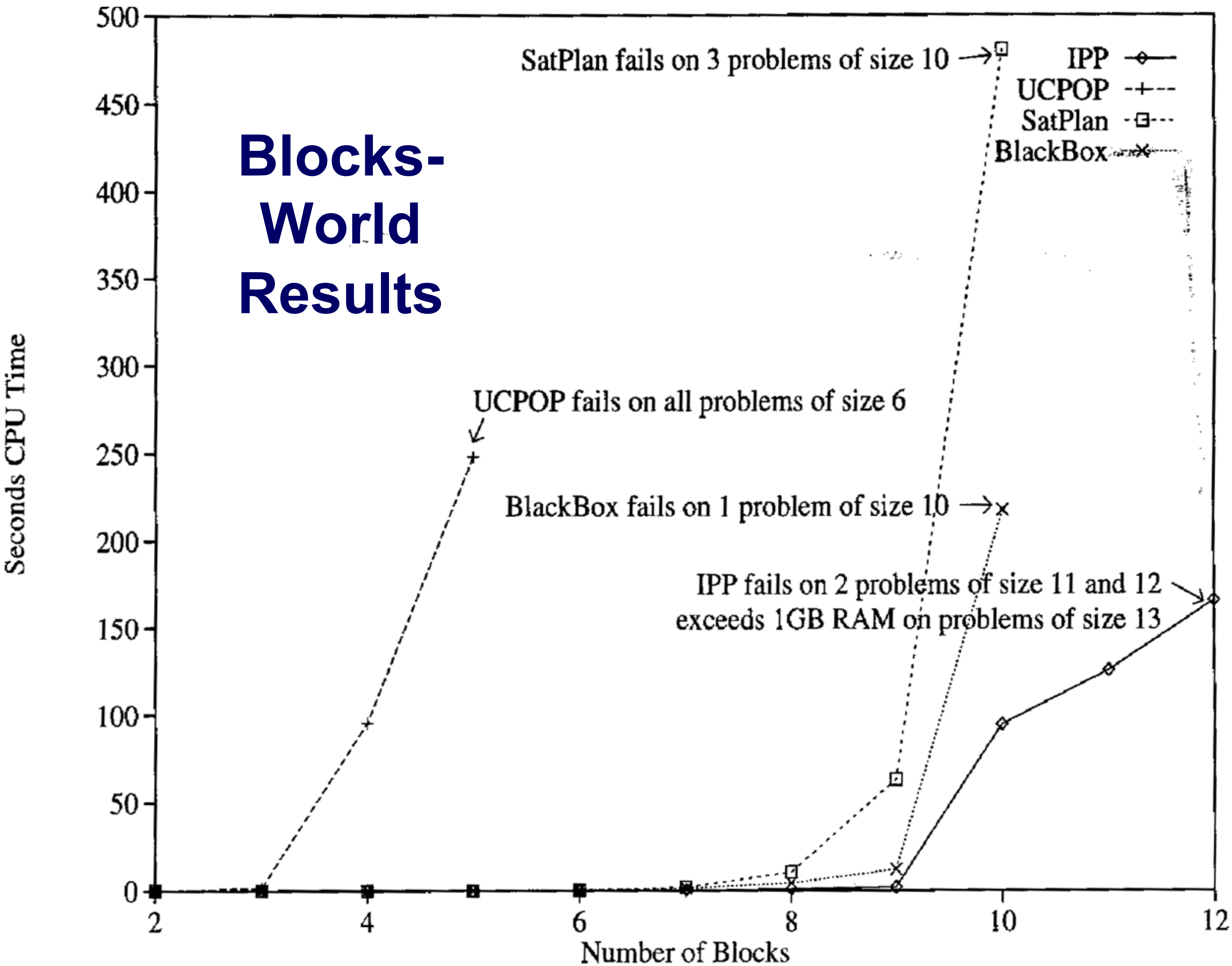
Pseudocode for TLPlan

- Nondeterministic forward search
  - Input includes a control formula f for the current state s
  - When we expand a state s, we progress its formula f through s
  - If the progressed formula is false, s is a dead-end
  - Otherwise the progressed formula is the control formula for s's children

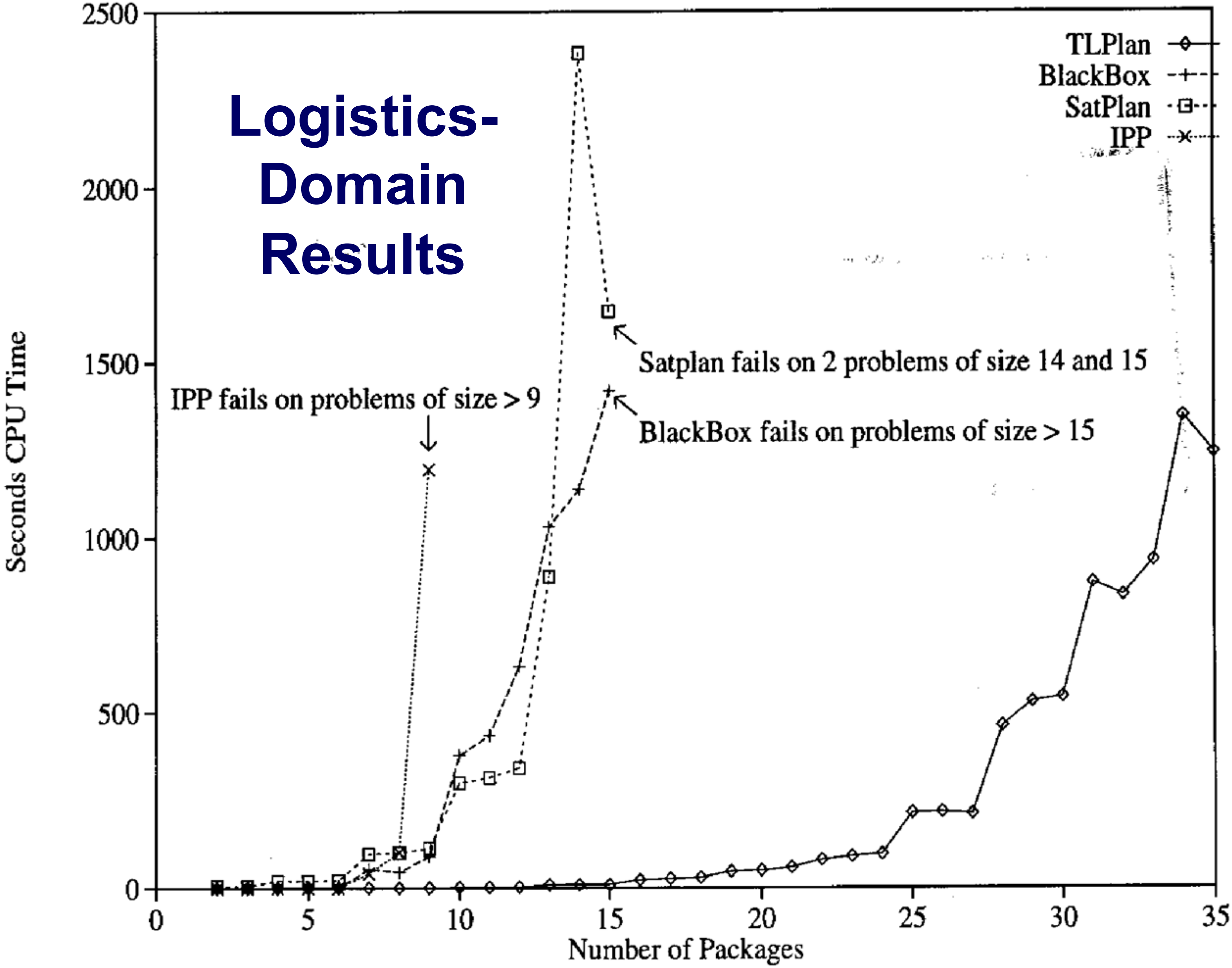
```
Procedure TLPlan (s, f, g, π)
        f⁺ ← Progress (f, s)
        if f⁺ = FALSE then return failure
        if s satisfies g then return π
        A ← {actions applicable to s}
        if A = empty then return failure
        nondeterministically choose a ∈ A
        s⁺ ← γ(s,a)
        return TLPlan (s⁺, f⁺, g, π.a)
```


Blocks-World Results
500
450
400
350
300
250
200
150
100
50
0
Seconds CPU Time
0
10
20
30
40
50
60
70
80
90
100
Number of Blocks
No Control (breadth-first)
Control 1
Control 2
Control 3
Control 3 (breadth-first)
Control 1 fails on 1 problem of size 11

Blocks-World Results



Logistics-Domain Results



Discussion

- 2000 International Planning Competition
  - TALplanner: same kind of algorithm, different temporal logic
    - » received the top award for a “hand-tailored” (i.e., domain-configurable) planner
- TLPlan won the same award in the 2002 International Planning Competition
- Both of them:
  - Ran several orders of magnitude faster than the “fully automated” (i.e., domain-independent) planners
    - » especially on large problems
  - Solved problems on which the domain-independent planners ran out of time/memory