Engineering a Heuristic Search Planner

Gabriele Röger Malte Helmert

University of Basel, Switzerland

ICAPS Tutorial
11 June 2013

Introduction

About this Tutorial

We will talk about Fast Downward. (That's what we know.)

- Part 1: high-level picture, architecture
- Part 2: in-depth look: efficient FF heuristic implementation

work in progress $\rightsquigarrow$ what do you want from such a tutorial?

Why this Tutorial?

Why did we propose this tutorial?

- efficiency often a stumbling block
- experience with large (and painful!) code integration efforts
- not/barely covered in papers

$\rightsquigarrow$ communicate lessons learned

Fast Downward Overview & History

Fast Downward

Three components of Fast Downward:

1. Translator

- implemented in Python
- takes PDDL input, produces finite-domain representation
- main jobs: invariants, grounding

Preprocessor ("Knowledge Compilation")

- implemented in C++
- augments translator output
- main jobs: relevance analysis, successor generator

Search

- implemented in C++
- various search algorithms and heuristics

Demo

```
$ hg clone ssh://hg.fast-downward.org downward
$ cd downward/src
$ ./build_all -j4
$ ./plan PROBLEM_FILE --search 'astar(lmcut())'
```

Where to Find More Details

If you want to read up on this:

- translator:
  M. Helmert. Concise finite-domain representations for PDDL planning tasks.
  AIJ 173(5–6):503–535, 2009.
- preprocessor:
  Malte Helmert. The Fast Downward Planning System.
  JAIR 26:191–246, 2006.
- search:
  all over the place

Code History

Fast Downward 2004

Translator	3082 lines
Preprocessor	1871 lines
Search	2966 lines

Code History

Fast Downward 2004

Translator	3082 lines
Preprocessor	1871 lines
Search	2966 lines

Fast Downward 2013

Translator	4941 lines
Preprocessor	2161 lines
Search	23990 lines

With Great Variety Comes Great Mess

- 2004:
  - 1 search algorithm (lazy greedy BFS)
  - 2 heuristics (CG and FF)
  - 4 switches (cCfF)

With Great Variety Comes Great Mess

- 2004:
  - 1 search algorithm (lazy greedy BFS)
  - 2 heuristics (CG and FF)
  - 4 switches (cCfF)
- 2005–2009:
  - two more search algorithms (eager greedy BFS, A*)
  - more heuristics (M&S, h^{cea}, landmarks, ...)
  - many more switches (cCyYfFakziwmhdspLDbuARS)

Command Lines: Then

Pop quiz: What does `Dyu` do in Fast Downward 2009?

Command Lines: Then

Pop quiz: What does `Dyu` do in Fast Downward 2009?

Run eager search with alternation between context-enhanced additive heuristic and LM-cut heuristic, using preferred operators from the additive heuristic.

Command Lines: Then

Pop quiz: What does `Dyu` do in Fast Downward 2009?

Run eager search with alternation between context-enhanced additive heuristic and LM-cut heuristic, using preferred operators from the additive heuristic.

For extra credit:

Command Lines: Then

Pop quiz: What does `Dyu` do in Fast Downward 2009?

Run eager search with alternation between context-enhanced additive heuristic and LM-cut heuristic, using preferred operators from the additive heuristic.

For extra credit: Why??

Command Lines: Now

Today (theatre cut)

```
./plan PROBLEM_FILE
  --heuristic 'h1=cea()'
  --heuristic 'h2=lmcut()'
  --heuristic 'h3=add()'
  --search 'eager_greedy([h1, h2], preferred=[h3])'
```

which is actually syntactic sugar for. . .

Command Lines: Now

Today (director's cut)

```
./plan PROBLEM_FILE
      --heuristic 'h1=cea(cost_type=NORMAL)'
      --heuristic 'h2=lmcut(cost_type=NORMAL)'
      --heuristic 'h3=add(cost_type=NORMAL)'
      --search 'eager(open=alt(sublists=[
          single(h1), single(h1, pref_only=true),
          single(h2), single(h2, pref_only=true)],
                                 boost=0),
                      reopen_closed=false,
                      pathmax=false,
                      preferred=[h3],
                      cost_type=NORMAL,
                      bound=2147483647)
```

Another Command Line Example

Pop quiz: What is this?

If all actions are unit cost, run:

```
./plan PROBLEM_FILE
  --heuristic 'hlm,hff=lm_ff_syn(lm_rhw(
      reasonable_orders=true,lm_cost_type=2,cost_type=2))'
  --search 'iterated([
      lazy_greedy([hff,hlm],preferred=[hff,hlm]),
      lazy_wastar([hff,hlm],preferred=[hff,hlm],w=5),
      lazy_wastar([hff,hlm],preferred=[hff,hlm],w=3),
      lazy_wastar([hff,hlm],preferred=[hff,hlm],w=2),
      lazy_wastar([hff,hlm],preferred=[hff,hlm],w=1)],
      repeat_last=true,continue_on_fail=true)'
```

Another Command Line Example

Pop quiz: What is this?

Otherwise, run:

```
./plan PROBLEM_FILE
  --heuristic 'hlm1,hff1=lm_ff_syn(lm_rhw(
      reasonable_orders=true,lm_cost_type=1,cost_type=1))'
  --heuristic 'hlm2,hff2=lm_ff_syn(lm_rhw(
      reasonable_orders=true,lm_cost_type=2,cost_type=2))'
  --search 'iterated([
      lazy_greedy([hff1,hlm1],preferred=[hff1,hlm1],
                  cost_type=1,reopen_closed=false),
      lazy_greedy([hff2,hlm2],preferred=[hff2,hlm2],
                  reopen_closed=false),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=5),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=3),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=2),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=1)],
      repeat_last=true,continue_on_fail=true)'
```

Another Command Line Example

Pop quiz: What is this?

Otherwise, run:

```
./plan PROBLEM_FILE
  --heuristic 'hlm1,hff1=lm_ff_syn(lm_rhw(
      reasonable_orders=true,lm_cost_type=1,cost_type=1))'
  --heuristic 'hlm2,hff2=lm_ff_syn(lm_rhw(
      reasonable_orders=true,lm_cost_type=2,cost_type=2))'
  --search 'iterated([
      lazy_greedy([hff1,hlm1],preferred=[hff1,hlm1],
                  cost_type=1,reopen_closed=false),
      lazy_greedy([hff2,hlm2],preferred=[hff2,hlm2],
                  reopen_closed=false),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=5),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=3),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=2),
      lazy_wastar([hff2,hlm2],preferred=[hff2,hlm2],w=1)],
      repeat_last=true,continue_on_fail=true)'
```

$\rightsquigarrow$ LAMA 2011

Plug-In Architecture

Why All These Long Options?

problems with the old way of handling things:

- running out of letters
- options for heuristics/search algorithms painful
- not very flexible
- merge conflicts

Idea:

- small core
- plug-ins for heuristics etc.
- no code changes to add/remove plug-ins

Search Component: Codebase

planner.cc axioms.cc causal_graph.cc combining_evaluator.cc domain_transition_graph.cc eager_search.cc enforced_hill_climbing_search.cc exact_timer.cc g_evaluator.cc globals.cc heuristic.cc ipc_max_heuristic.cc iterated_search.cc lazy_search.cc legacy_causal_graph.cc max_evaluator.cc operator.cc operator_cost.cc option_parser.cc pref_evaluator.cc relaxation_heuristic.cc rng.cc search_engine.cc search_node_info.cc search_progress.cc search_space.cc state.cc successor_generator.cc sum_evaluator.cc timer.cc utilities.cc weighted_evaluator.cc additive_heuristic.cc blind_search_heuristic.cc cea_heuristic.cc cg_heuristic.cc cg_cache.cc ff_heuristic.cc goal_count_heuristic.cc hm_heuristic.cc lm_cut_heuristic.cc max_heuristic.cc

open_lists/alternation_open_list.cc .../open_list_buckets.cc .../pareto_open_list.cc .../standard_scalar_open_list.cc .../tiebreaking_open_list.cc

merge_and_shrink/abstraction.cc .../label_reducer.cc .../merge_and_shrink_heuristic.cc .../shrink_bisimulation.cc .../shrink_bucket_based.cc .../shrink_fh.cc .../shrink_random.cc .../shrink_strategy.cc .../variable_order_finder.cc

landmarks/exploration.cc .../h_m_landmarks.cc .../lama_ff_synergy.cc .../landmark_cost_assignment.cc .../landmark_count_heuristic.cc .../landmark_status_manager.cc .../landmark_graph_merged.cc .../landmark_graph.cc .../landmark_factory.cc .../landmark_factory_rpg_exhaust.cc .../landmark_factory_rpg_sasp.cc .../landmark_factory_zhu_givan.cc .../util.cc

learning/AODE.cc .../classifier.cc .../composite_feature_extractor.cc .../feature_extractor.cc .../maximum_heuristic.cc .../naive_bayes_classifier.cc .../PDB_state_space_sample.cc .../probe_state_space_sample.cc .../selective_max_heuristic.cc .../state_space_sample.cc .../state_vars_feature_extractor.cc

pdbs/canonical_pdbs_heuristic.cc .../dominance_pruner.cc .../match_tree.cc .../max_cliques.cc .../pattern_generation_edelkamp.cc .../pattern_generation_haslum.cc .../pdb_heuristic.cc .../util.cc .../zero_one_pdbs_heuristic.cc

Search Component: Codebase

planner.cc axioms.cc causal_graph.cc ~~combining_evaluator.cc~~ domain_transition_graph.cc ~~eager_search.cc~~ ~~enforced_hill_climbing_search.cc~~ ~~exact_timer.cc~~ ~~g_evaluator.cc~~ globals.cc heuristic.cc ~~ipc_max_heuristic.cc~~ ~~iterated_search.cc~~ ~~lazy_search.cc~~ legacy_causal_graph.cc ~~max_evaluator.cc~~ operator.cc operator_cost.cc option_parser.cc ~~pref_evaluator.cc~~ ~~relaxation_heuristic.cc~~ rng.cc search_engine.cc search_node_info.cc search_progress.cc search_space.cc state.cc successor_generator.cc ~~sum_evaluator.cc~~ timer.cc utilities.cc ~~weighted_evaluator.cc~~ ~~additive_heuristic.cc~~ ~~blind_search_heuristic.cc~~ ~~cea_heuristic.cc~~ ~~cg_heuristic.cc~~ ~~cg_cache.cc~~ ~~ff_heuristic.cc~~ ~~goal_count_heuristic.cc~~ ~~hm_heuristic.cc~~ ~~lm_cut_heuristic.cc~~ ~~max_heuristic.cc~~

~~open_lists/alternation_open_list.cc~~ ~~.../open_list_buckets.cc~~ ~~.../pareto_open_list.cc~~ ~~.../standard_scalar_open_list.cc~~ ~~.../tiebreaking_open_list.cc~~

~~merge_and_shrink/abstraction.cc~~ ~~.../label_reducer.cc~~ ~~.../merge_and_shrink_heuristic.cc~~ ~~.../shrink_bisimulation.cc~~ ~~.../shrink_bucket_based.cc~~ ~~.../shrink_fh.cc~~ ~~.../shrink_random.cc~~ ~~.../shrink_strategy.cc~~ ~~.../variable_order_finder.cc~~

~~landmarks/exploration.cc~~ ~~.../h_m_landmarks.cc~~ ~~.../lama_ff_synergy.cc~~ ~~.../landmark_cost_assignment.cc~~ ~~.../landmark_count_heuristic.cc~~ ~~.../landmark_status_manager.cc~~ ~~.../landmark_graph_merged.cc~~ ~~.../landmark_graph.cc~~ ~~.../landmark_factory.cc~~ ~~.../landmark_factory_rpg_exhaust.cc~~ ~~.../landmark_factory_rpg_sasp.cc~~ ~~.../landmark_factory_zhu_givan.cc~~ ~~.../util.cc~~

~~learning/AODE.cc~~ ~~.../classifier.cc~~ ~~.../composite_feature_extractor.cc~~ ~~.../feature_extractor.cc~~ ~~.../maximum_heuristic.cc~~ ~~.../naive_bayes_classifier.cc~~ ~~.../PDB_state_space_sample.cc~~ ~~.../probe_state_space_sample.cc~~ ~~.../selective_max_heuristic.cc~~ ~~.../state_space_sample.cc~~ ~~.../state_vars_feature_extractor.cc~~

~~pdbs/canonical_pdbs_heuristic.cc~~ ~~.../dominance_pruner.cc~~ ~~.../match_tree.cc~~ ~~.../max_cliques.cc~~ ~~.../pattern_generation_edelkamp.cc~~ ~~.../pattern_generation_haslum.cc~~ ~~.../pdb_heuristic.cc~~ ~~.../util.cc~~ ~~.../zero_one_pdbs_heuristic.cc~~

small core $\rightsquigarrow$ no need to understand the other code

Demo

- $\rightsquigarrow$ demo: minimal codebase
- $\rightsquigarrow$ demo: add a search algorithm and a heuristic

How do the plug-ins work?

Plug-in mechanism for heuristics (and other things):

- factory function that creates heuristic object from (parsed) parameter string
- global object that registers the factory function with the option parser for a certain keyword

$\rightsquigarrow$ demo: a simple plug-in

$\rightsquigarrow$ demo: a plug-in with options

Tools for Organizing Development

Tools We Use

Tools making our life easier, in roughly historical order:

Tools We Use

Tools making our life easier, in roughly historical order:

- version control (!!!)

Tools We Use

Tools making our life easier, in roughly historical order:

- version control (!!!)
- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`

Tools We Use

Tools making our life easier, in roughly historical order:

- version control (!!!)

- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`
- experiment infrastructure (!!!)
  $\rightsquigarrow$ `https://bitbucket.org/jendrikseipp/lab`

Tools We Use

Tools making our life easier, in roughly historical order:

- distributed version control (!!!!!)
  $\rightsquigarrow$ `http://hg.fast-downward.org`
- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`
- experiment infrastructure (!!!)
  $\rightsquigarrow$ `https://bitbucket.org/jendrikseipp/lab`

Tools We Use

Tools making our life easier, in roughly historical order:

- distributed version control (!!!!!)
  $\rightsquigarrow$ `http://hg.fast-downward.org`
- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`
- experiment infrastructure (!!!)
  $\rightsquigarrow$ `https://bitbucket.org/jendrikseipp/lab`
- wiki
  $\rightsquigarrow$ `http://www.fast-downward.org`

Tools We Use

Tools making our life easier, in roughly historical order:

- distributed version control (!!!!!)
  $\rightsquigarrow$ http://hg.fast-downward.org
- issue tracker (!!!)
  $\rightsquigarrow$ http://issues.fast-downward.org
- experiment infrastructure (!!!)
  $\rightsquigarrow$ https://bitbucket.org/jendrikseipp/lab
- wiki
  $\rightsquigarrow$ http://www.fast-downward.org
- buildbot
  $\rightsquigarrow$ http://buildbot.fast-downward.org

Tools We Use

Tools making our life easier, in roughly historical order:

- distributed version control (!!!!!)
  $\rightsquigarrow$ `http://hg.fast-downward.org`
- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`
- experiment infrastructure (!!!)
  $\rightsquigarrow$ `https://bitbucket.org/jendrikseipp/lab`
- wiki
  $\rightsquigarrow$ `http://www.fast-downward.org`
- buildbot
  $\rightsquigarrow$ `http://buildbot.fast-downward.org`
- public mailing list
  $\rightsquigarrow$ `http://groups.google.com/group/fast-downward/`

Tools We Use

Tools making our life easier, in roughly historical order:

- distributed version control (!!!!!)
  $\rightsquigarrow$ `http://hg.fast-downward.org`
- issue tracker (!!!)
  $\rightsquigarrow$ `http://issues.fast-downward.org`
- experiment infrastructure (!!!)
  $\rightsquigarrow$ `https://bitbucket.org/jendrikseipp/lab`
- wiki
  $\rightsquigarrow$ `http://www.fast-downward.org`
- buildbot
  $\rightsquigarrow$ `http://buildbot.fast-downward.org`
- public mailing list
  $\rightsquigarrow$ `http://groups.google.com/group/fast-downward/`
- internal mailing list

Relaxation Heuristics

Relaxation Heuristics

- heuristics derived from delete relaxation of task
- delete relaxation ignores negative effects
- often taught by means of relaxed planning graph

Rest of this section:

- brief reminder of relaxed planning graph, additive heuristic, and FF heuristic
- efficient implementation of the heuristics by means of exploration queues

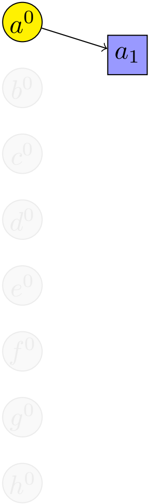
Illustrative Example

Variables V, initial state I, goal propositions G, actions A

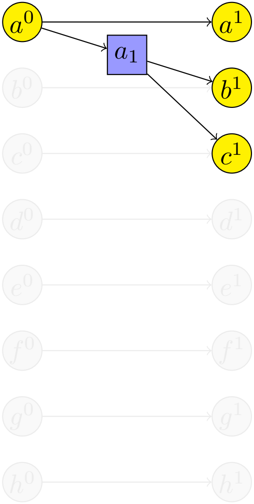
$$
\begin{aligned}
V &= \{a, b, c, d, e, f, g, h\} \\
I &= \{a\} \\
G &= \{c, d, e, f, g\} \\
A &= \{a_1, a_2, a_3, a_4, a_5, a_6\} \\
a_1 &= \langle a \rightarrow b, c \rangle_3 \\
a_2 &= \langle a, c \rightarrow d \rangle_1 \\
a_3 &= \langle b, c \rightarrow e \rangle_1 \\
a_4 &= \langle b \rightarrow f \rangle_1 \\
a_5 &= \langle d \rightarrow e, f \rangle_1 \\
a_6 &= \langle d \rightarrow g \rangle_1
\end{aligned}
$$

Illustrative Example: Relaxed Planning Graph

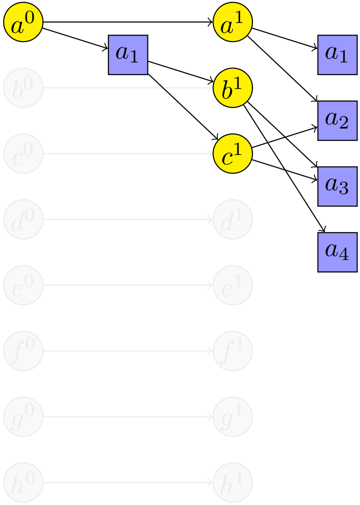
Illustrative Example: Relaxed Planning Graph



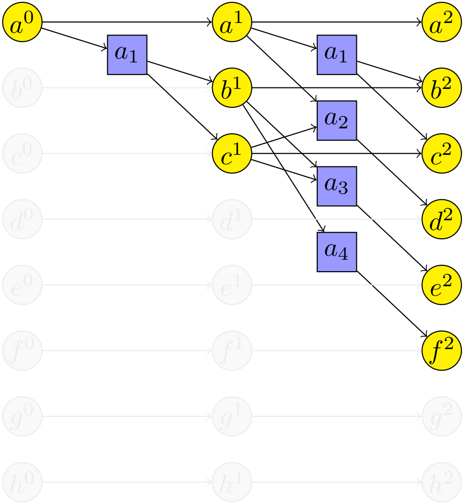
Illustrative Example: Relaxed Planning Graph



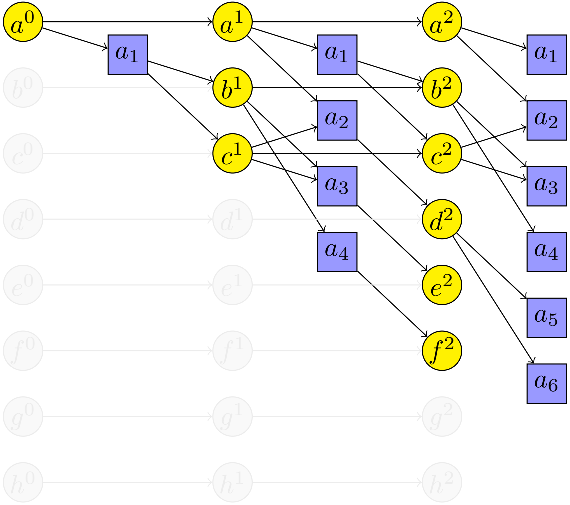
Illustrative Example: Relaxed Planning Graph



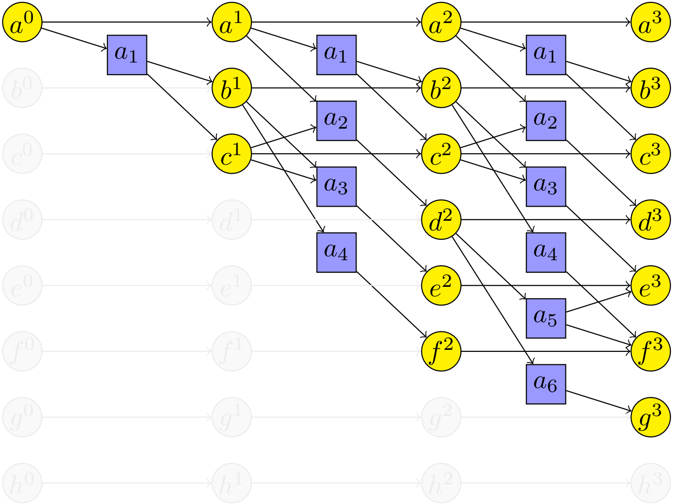
Illustrative Example: Relaxed Planning Graph



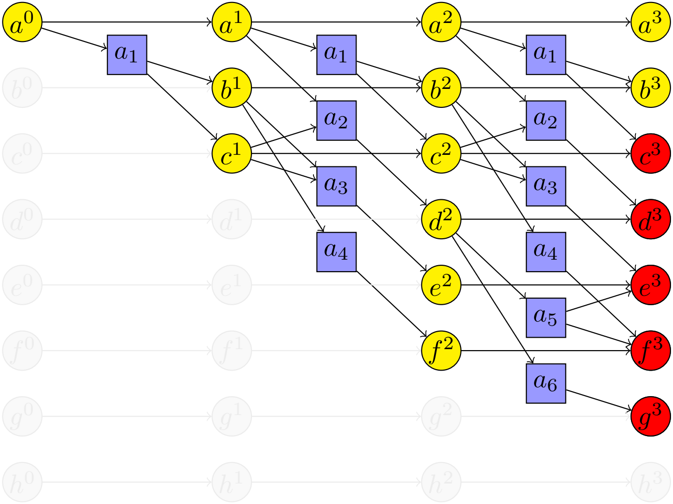
Illustrative Example: Relaxed Planning Graph



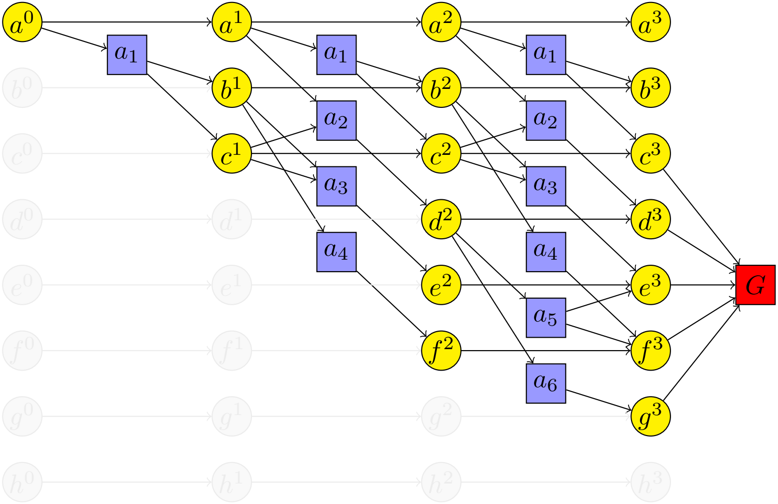
Illustrative Example: Relaxed Planning Graph



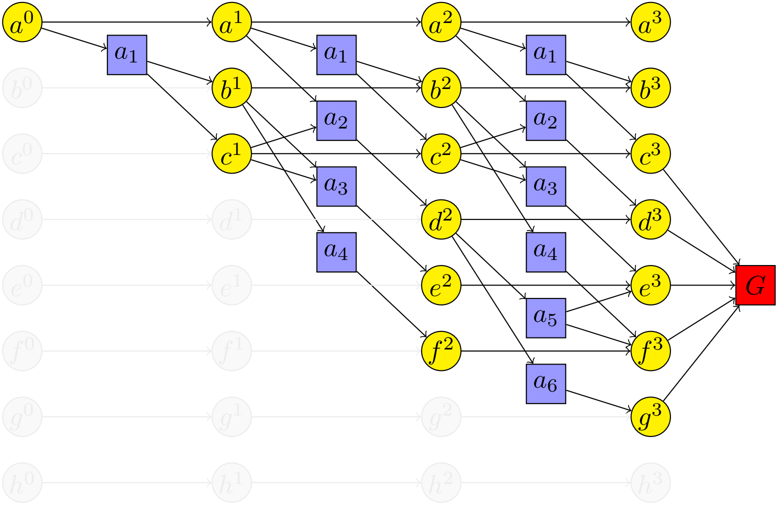
Illustrative Example: Relaxed Planning Graph



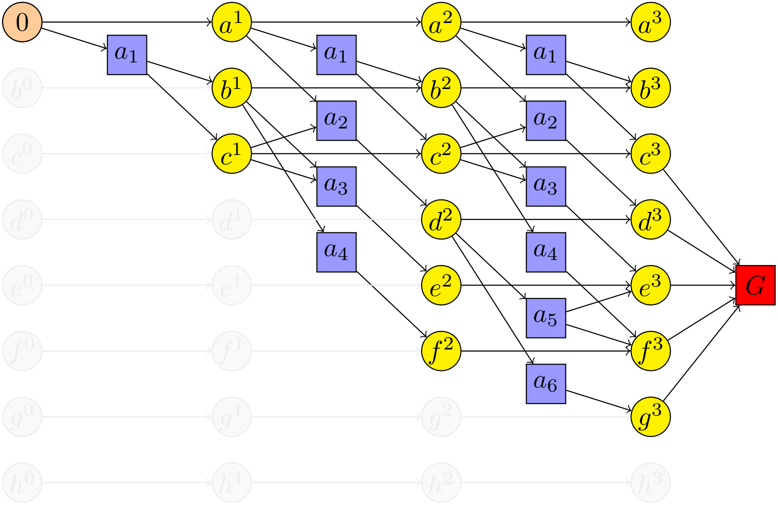
Illustrative Example: Relaxed Planning Graph



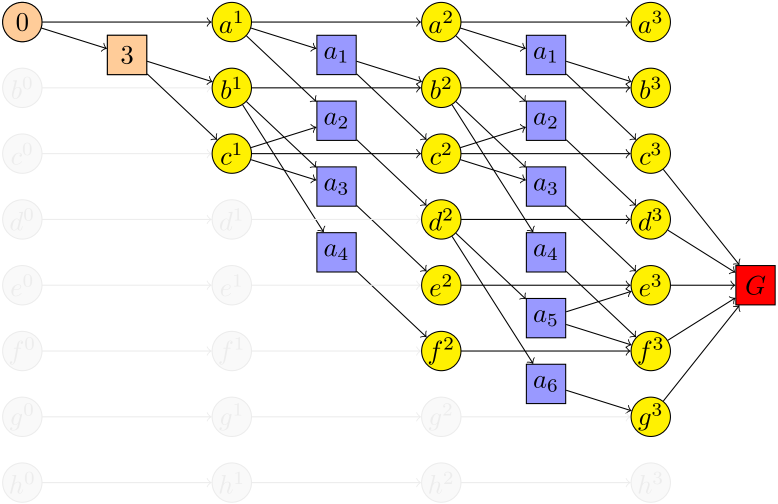
Illustrative Example: Additive Heuristic h^{add}



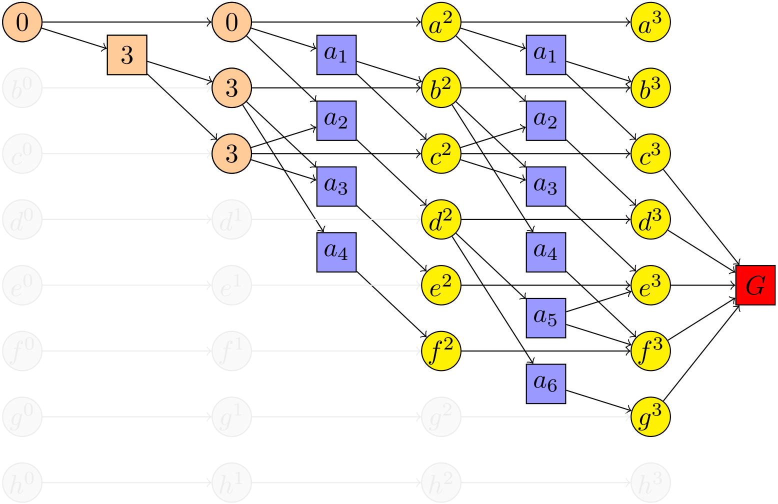
Illustrative Example: Additive Heuristic h^{add}



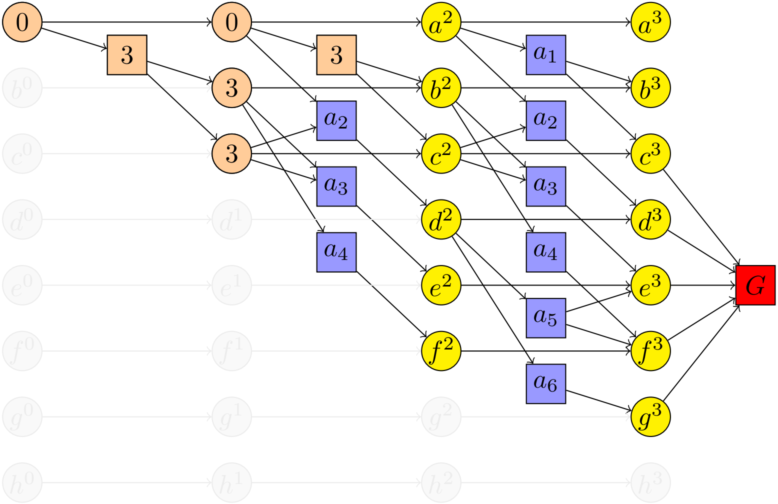
Illustrative Example: Additive Heuristic h^{add}



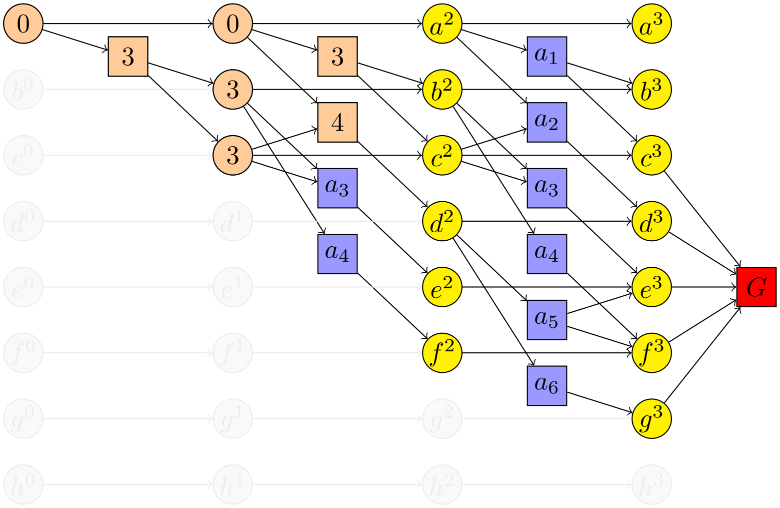
Illustrative Example: Additive Heuristic h^{add}



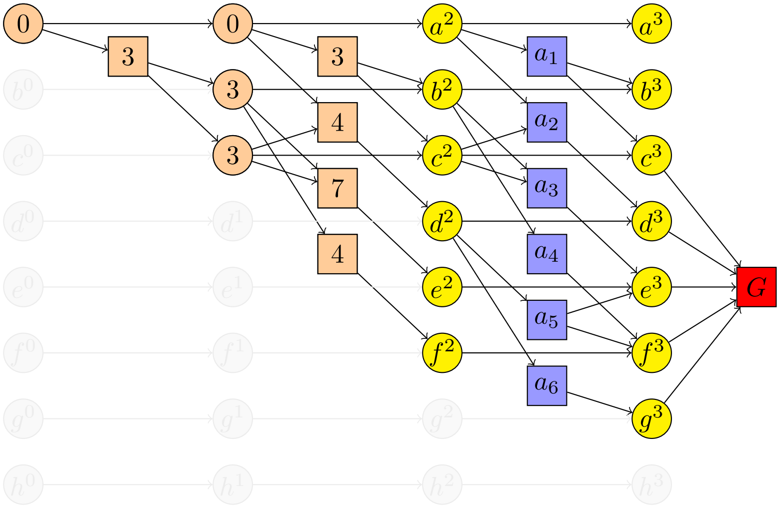
Illustrative Example: Additive Heuristic h^{add}



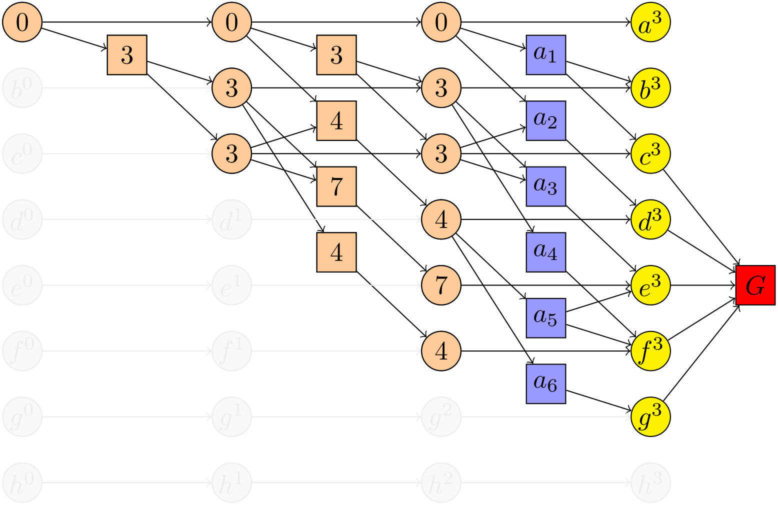
Illustrative Example: Additive Heuristic h^{add}



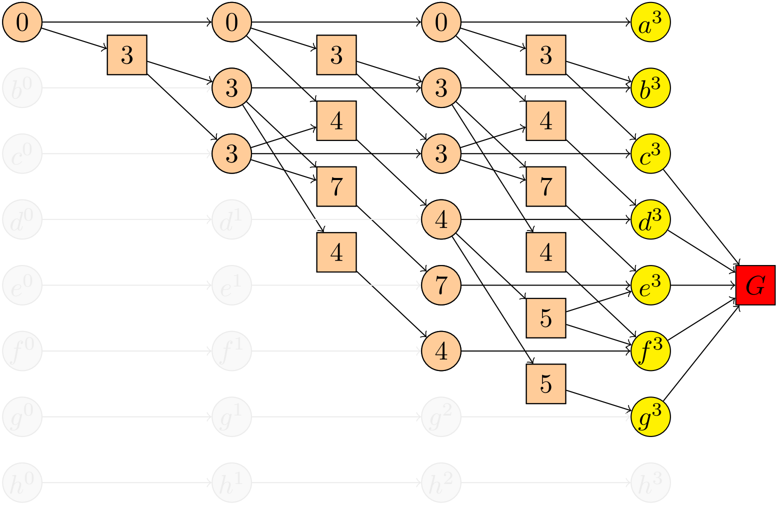
Illustrative Example: Additive Heuristic h^{add}



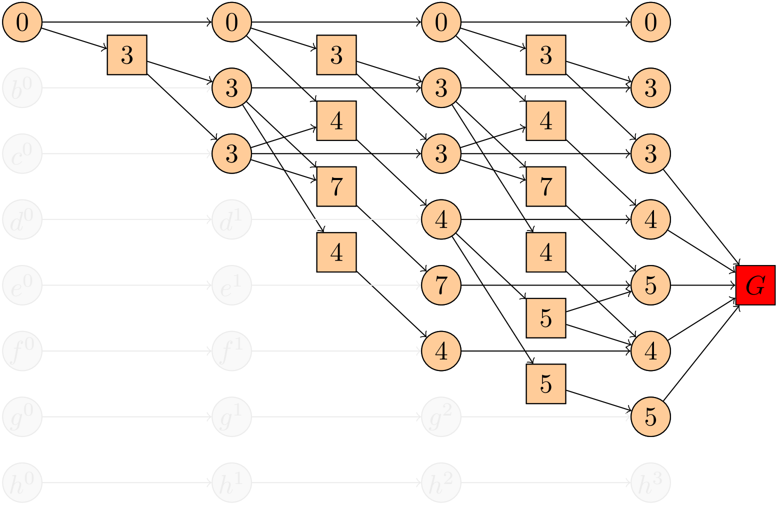
Illustrative Example: Additive Heuristic h^{add}



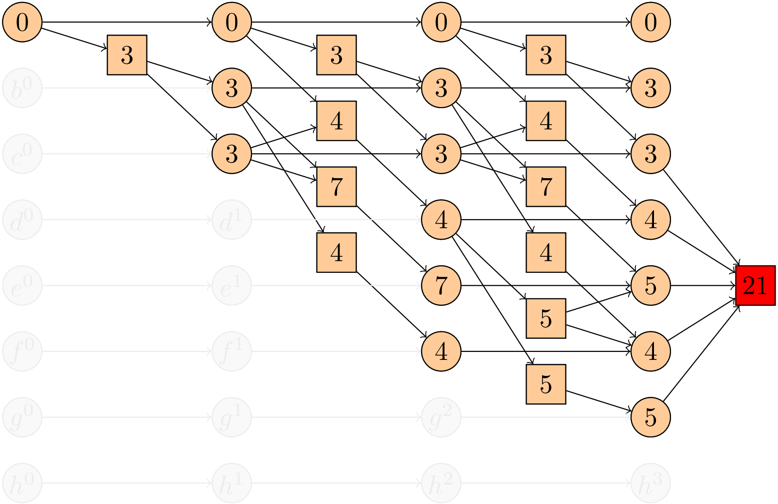
Illustrative Example: Additive Heuristic h^{add}



Illustrative Example: Additive Heuristic h^{add}



Illustrative Example: Additive Heuristic h^{add}



$$h^{\mathsf{add}}(\{a\}) = 21$$

FF Heuristic h^{FF}

FF Heuristic

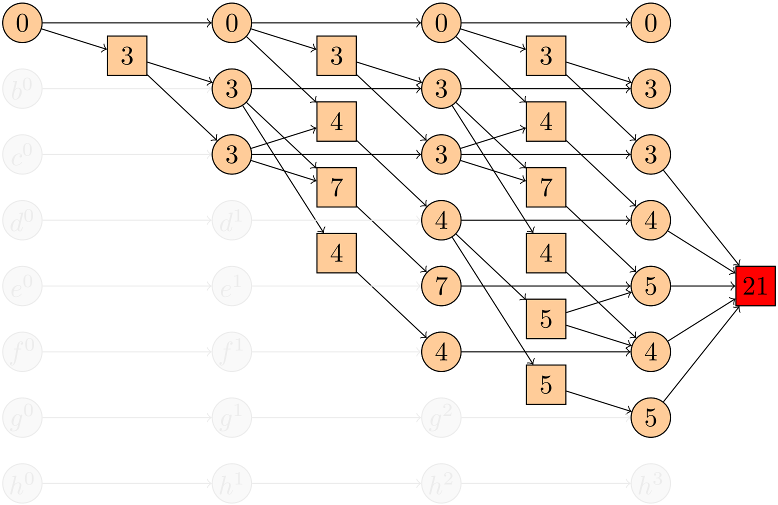
like h^{add} but with additional post-processing steps

- mark goal node in last graph layer.
- apply following rules until fixpoint reached:
  - marked action or goal node?
    $\rightsquigarrow$ mark all predecessors
  - variable node v^i in layer $i \geq 1$ marked?
    $\rightsquigarrow$ mark one predecessor with minimal h^{add} value
    (Tie-breaking: prefer variable nodes; otherwise arbitrarily)

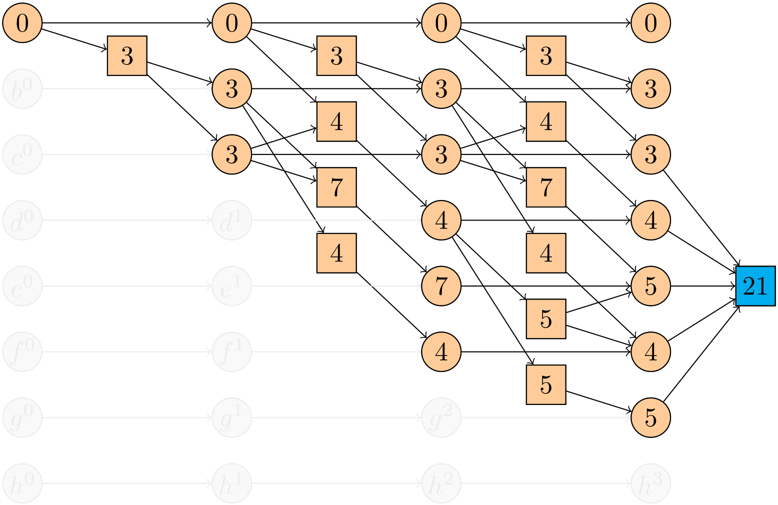
heuristic estimate:

- marked action nodes form a relaxed plan
- heuristic estimate is cost of this plan

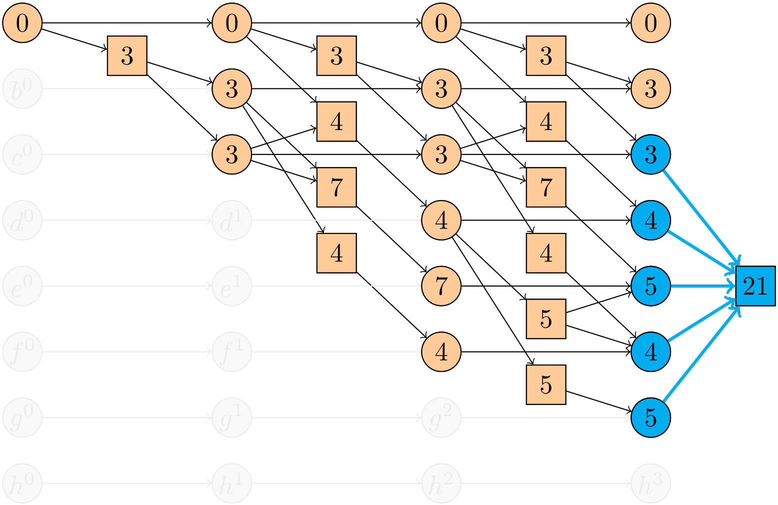
Illustrative Example: h^{FF}



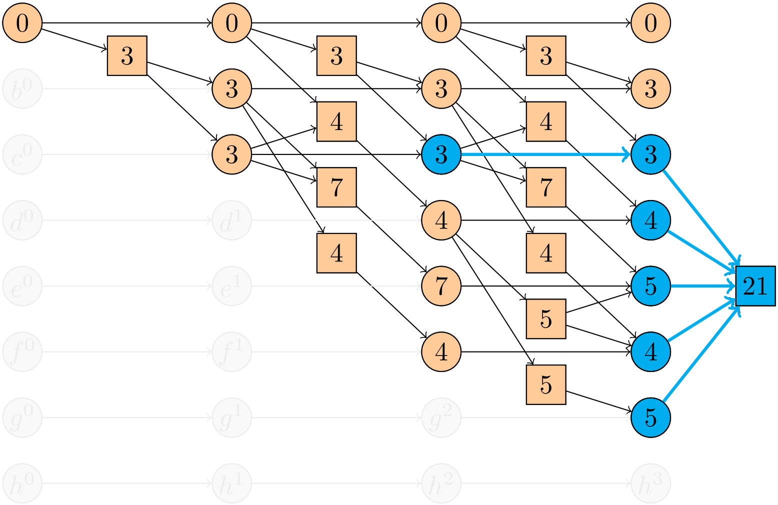
Illustrative Example: h^{FF}



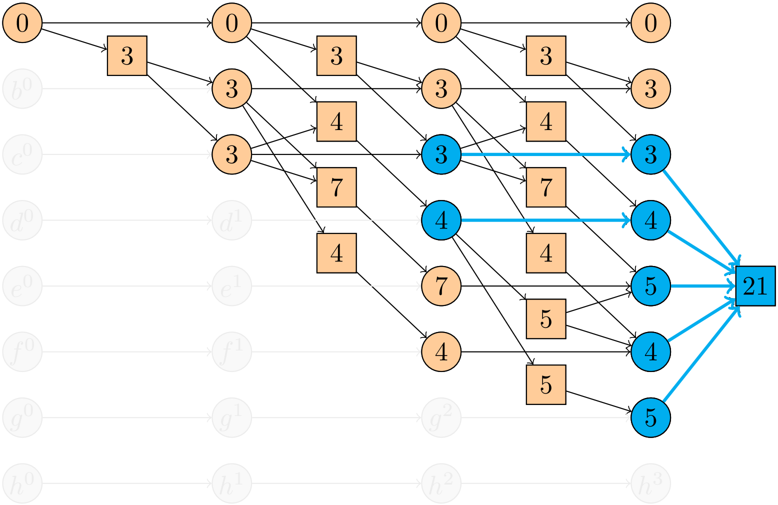
Illustrative Example: h^{FF}



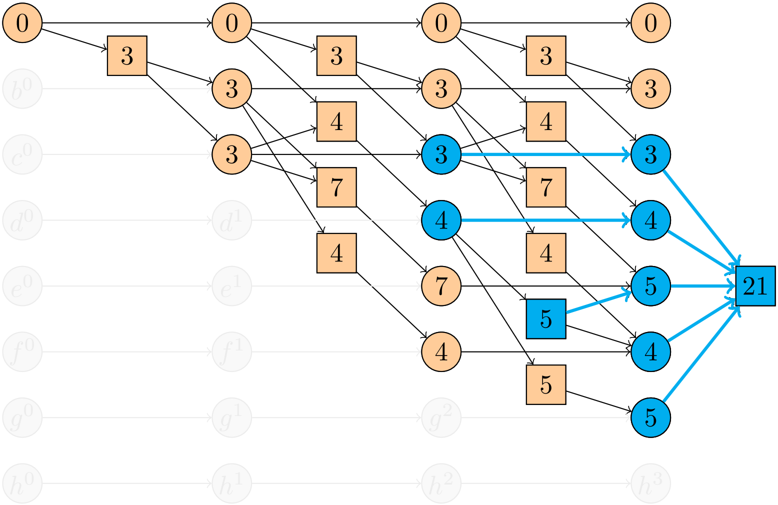
Illustrative Example: h^{FF}



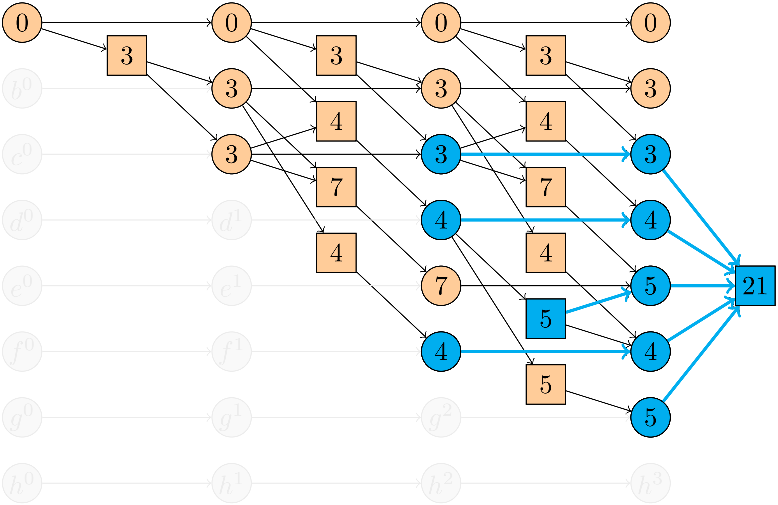
Illustrative Example: h^{FF}



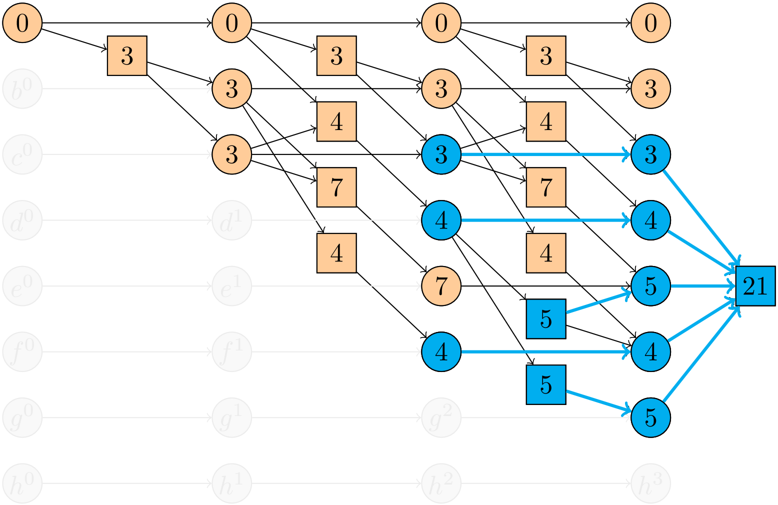
Illustrative Example: h^{FF}



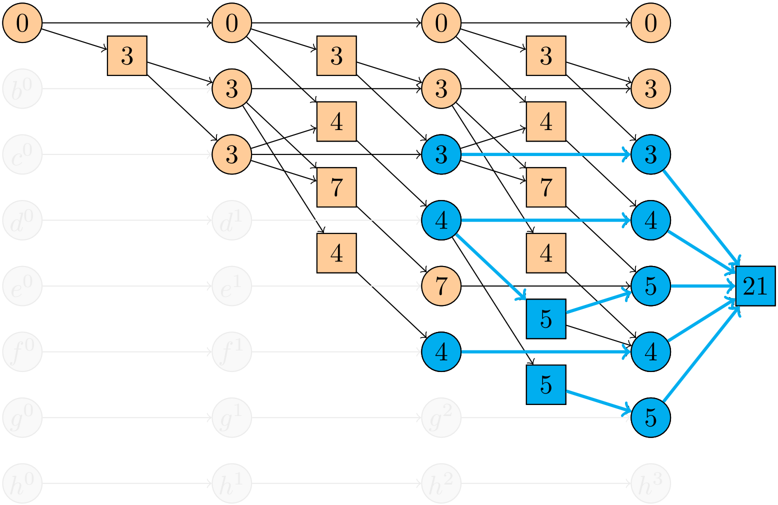
Illustrative Example: h^{FF}



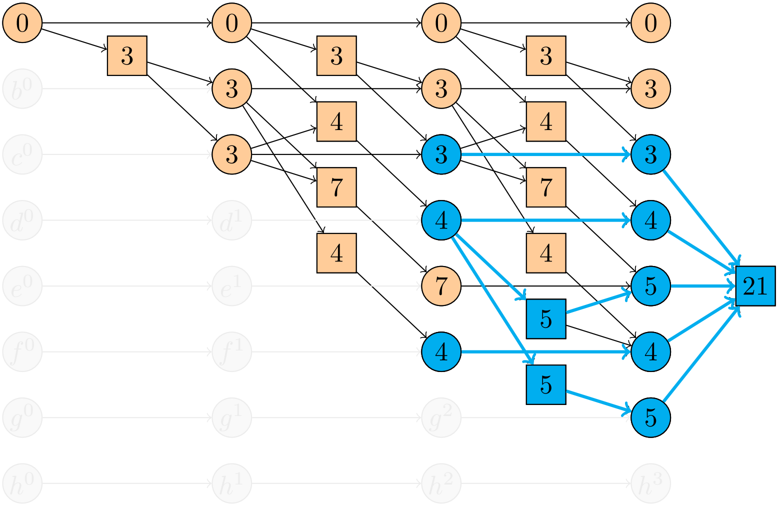
Illustrative Example: h^{FF}



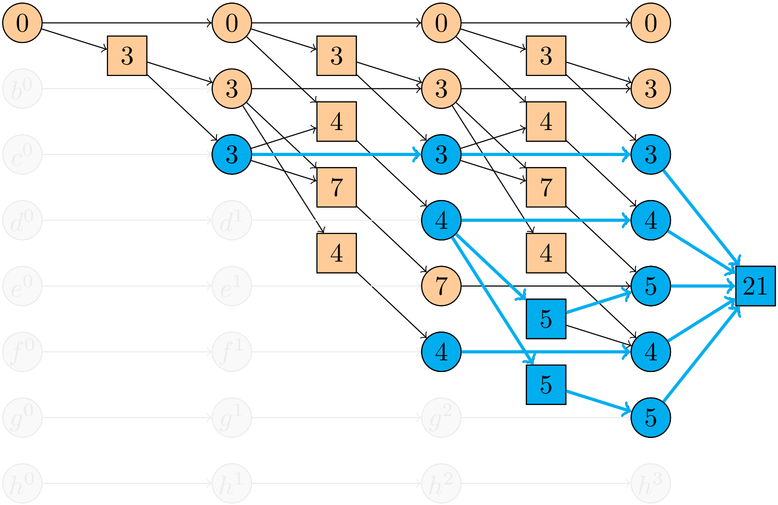
Illustrative Example: h^{FF}



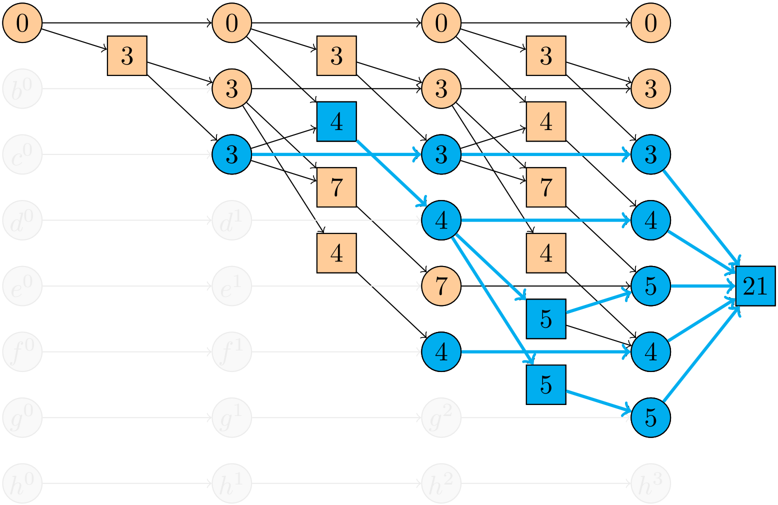
Illustrative Example: h^{FF}



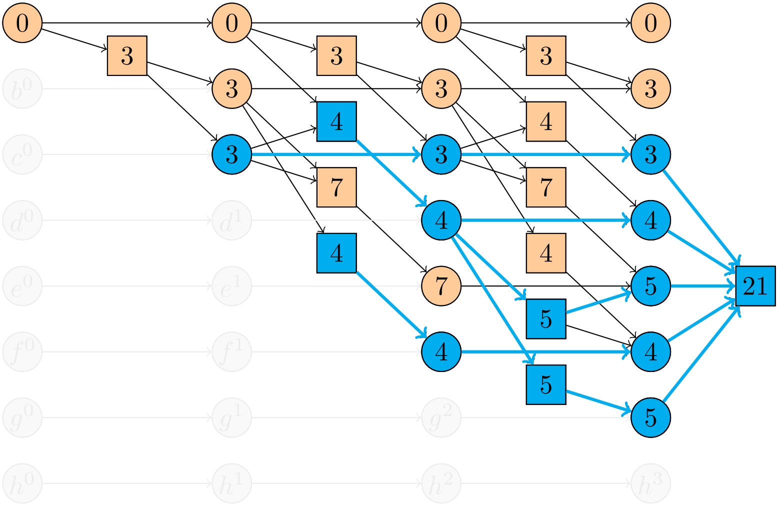
Illustrative Example: h^{FF}



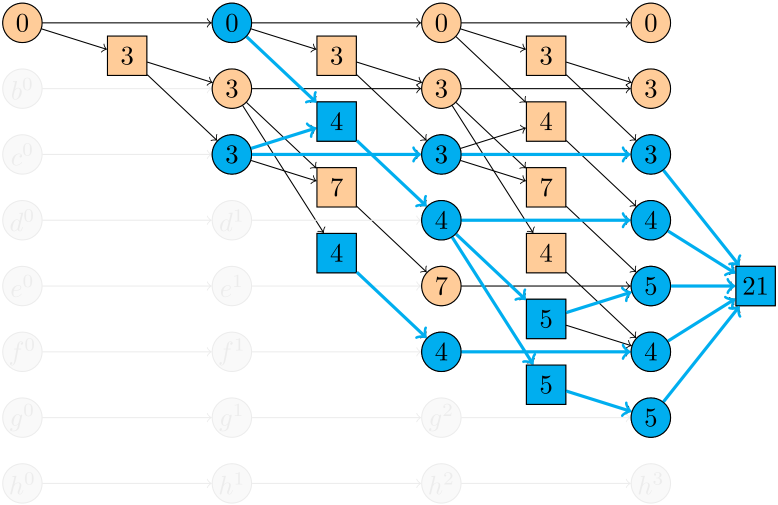
Illustrative Example: h^{FF}



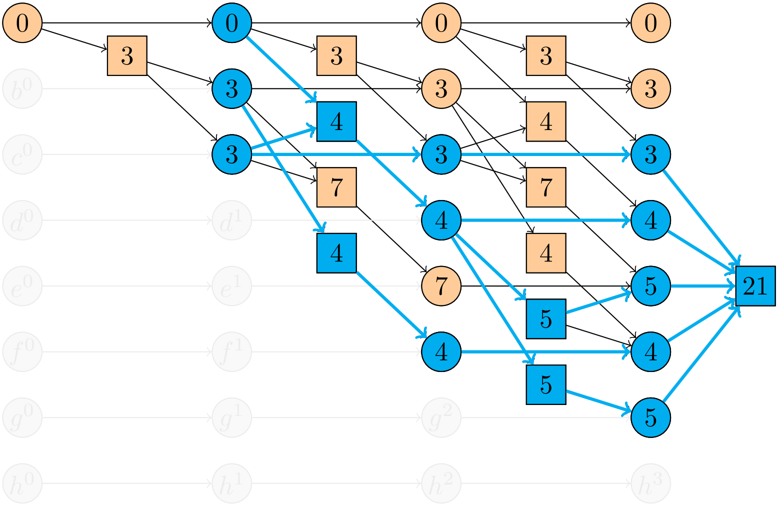
Illustrative Example: h^{FF}



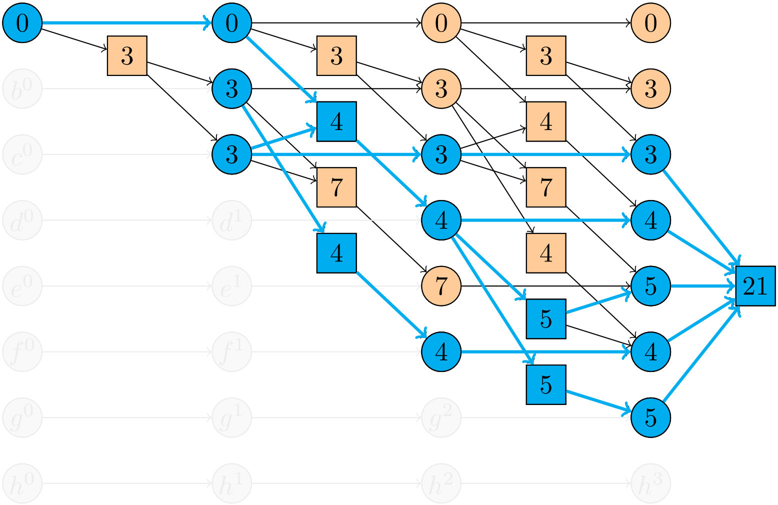
Illustrative Example: h^{FF}



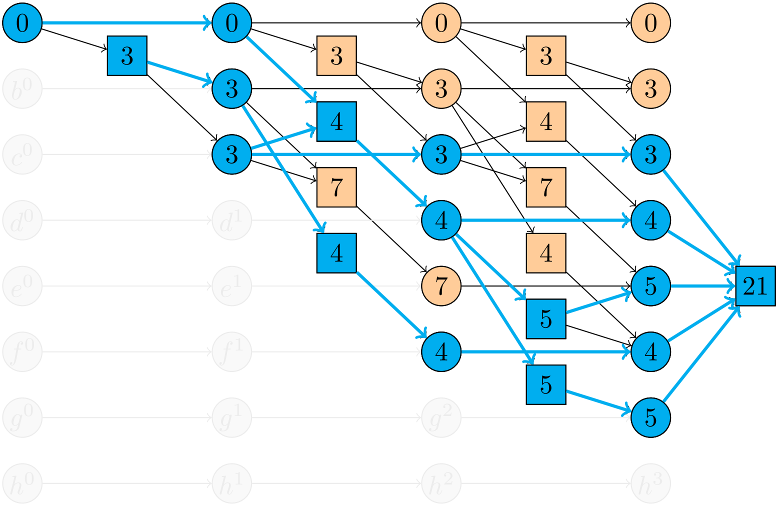
Illustrative Example: h^{FF}



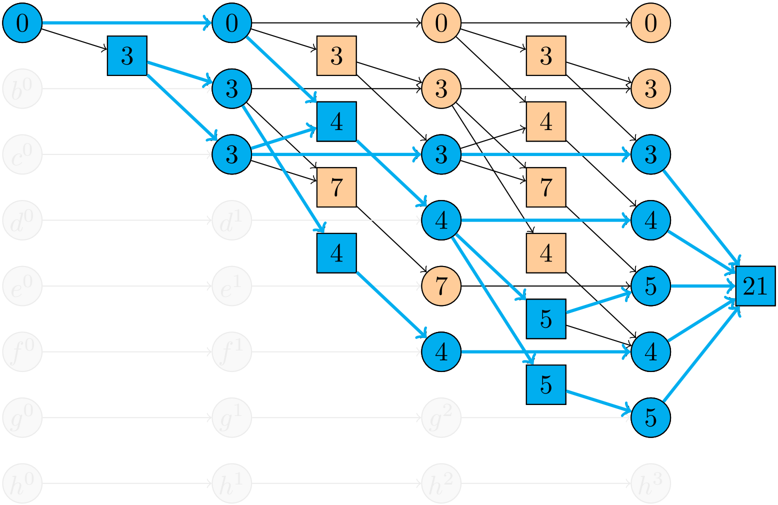
Illustrative Example: h^{FF}



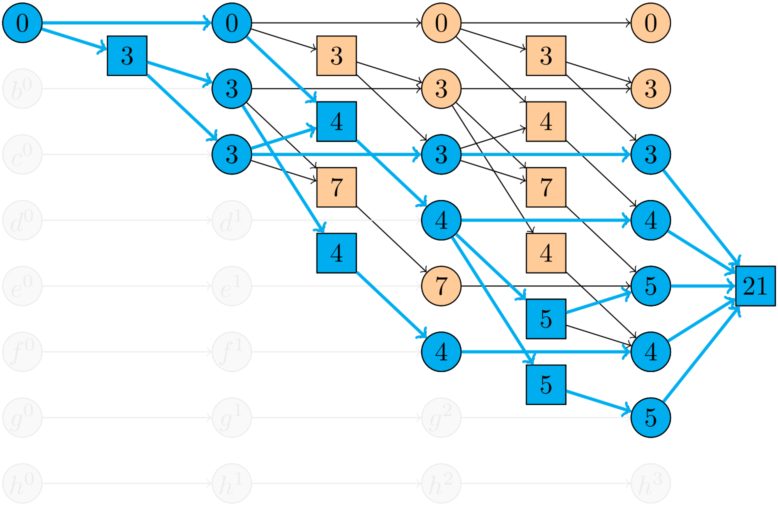
Illustrative Example: h^{FF}



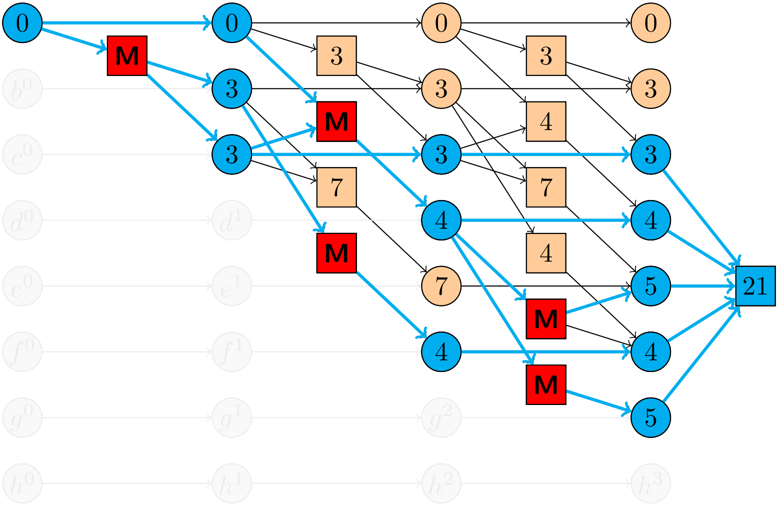
Illustrative Example: h^{FF}



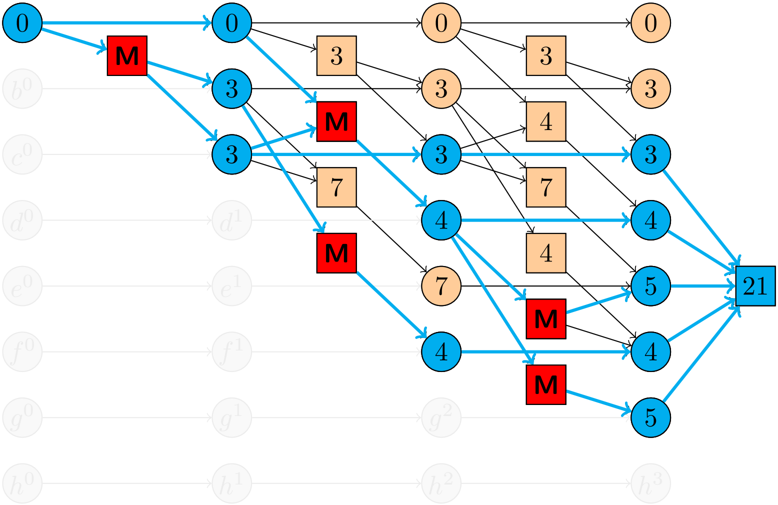
Illustrative Example: h^{FF}



Illustrative Example: h^{FF}



Illustrative Example: h^{FF}



$$h^{\mathsf{FF}}(\{a\}) = 3 + 1 + 1 + 1 + 1 = 7$$

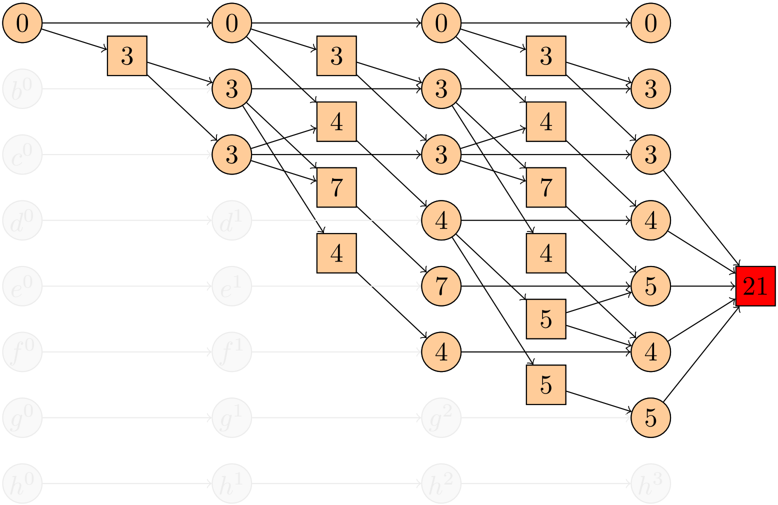
Implementation of h^{add} and h^{FF}

Naive implementation:
build up relaxed planning graph and follow the algorithms just seen

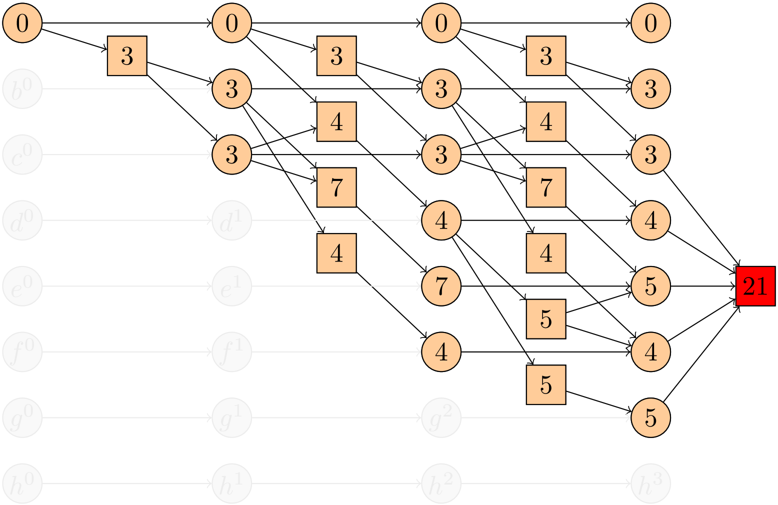
Questions for more efficient implementation:

- What is actually computed?
- Which aspects of the task can contribute to the heuristic estimate?
- When do these aspects become relevant?
- Which operations should our data structures cheaply support?

Again: Additive Heuristic h^{add}

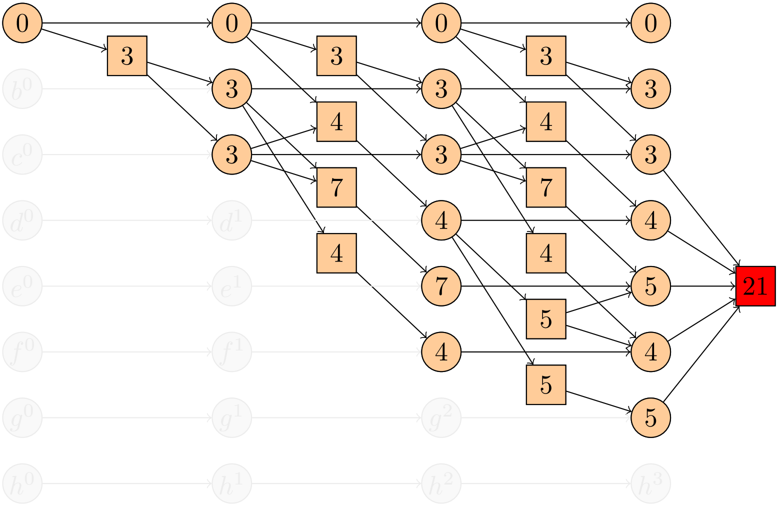


Again: Additive Heuristic h^{add}



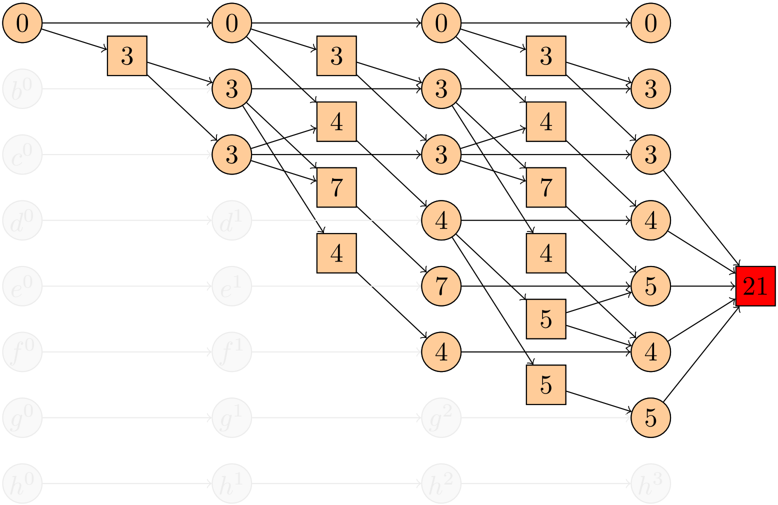
heuristic estimate is sum of cheapest values of goal propositions

Again: Additive Heuristic h^{add}



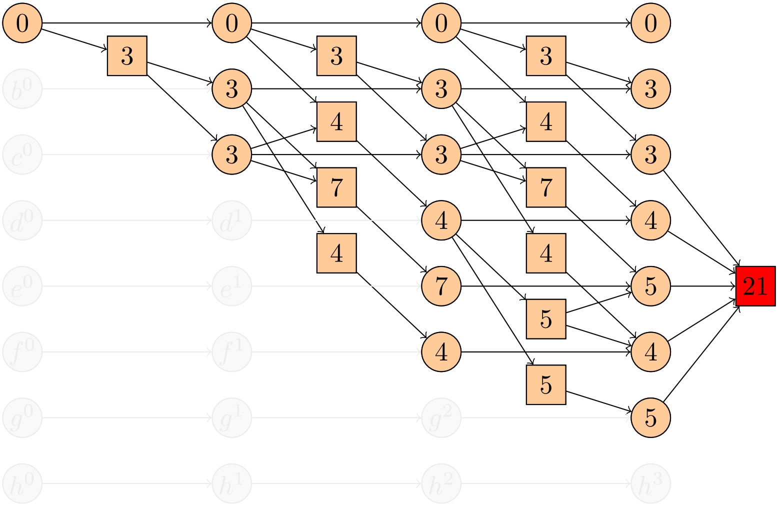
cheapest value of initially true proposition is 0

Again: Additive Heuristic h^{add}



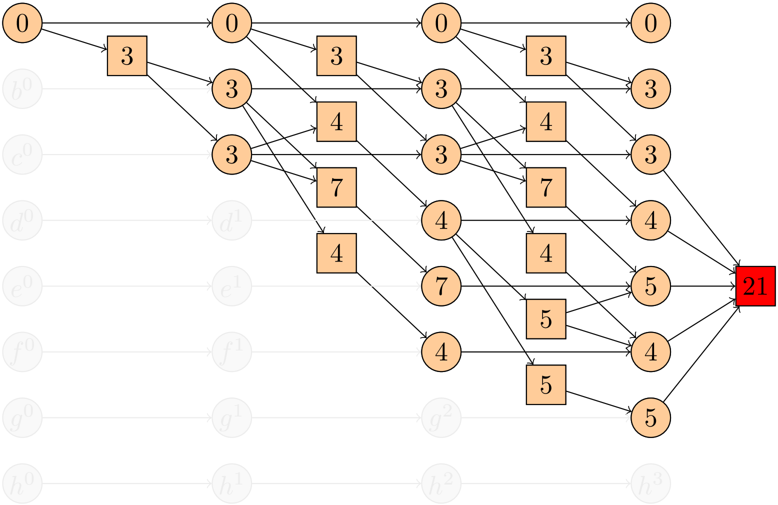
cheapest value of other proposition is cheapest value of an action achieving it

Again: Additive Heuristic h^{add}



cheapest value of action nodes is sum of cheapest values of precondition values plus costs of action

Again: Additive Heuristic h^{add}



"concurrency" of action effects irrelevant

Change Task Representation For Heuristic Computation

"concurrency" of operator effects irrelevant
$\rightsquigarrow$ change task representation

Use one unary operator for each single effect of an action, e.g., replace

$$a_1 = \langle a \rightarrow b, c \rangle_3$$

with

$$a_{1,b} = \langle a \rightarrow b \rangle_3^{a_1}$$
$$a_{1,c} = \langle a \rightarrow c \rangle_3^{a_1}$$

Advantage: easy support of axioms and conditional effects

Change Task Representation For Heuristic Computation

"concurrency" of operator effects irrelevant
$\rightsquigarrow$ change task representation

Use one unary operator for each single effect of an action, e.g., replace

$$a_1 = \langle a \rightarrow b, c \rangle_3$$

with

$$a_{1,b} = \langle a \rightarrow b \rangle_3^{a_1}$$
$$a_{1,c} = \langle a \rightarrow c \rangle_3^{a_1}$$

Prop

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
```

Advantage: easy support of axioms and conditional effects

Exploration Queue Algorithm for h^{add}

```
queue = priority_queue over (value, proposition) pairs
        ordered by value
enqueue all initially true propositions with value 0
set value of all operators to operator cost
while queue is not empty:
  (p_value, prop) = queue.pop()
  if we already encountered prop with a cheaper value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of best seen values of goal propositions
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < best seen value of its effect:
        update best seen value of effect proposition
        queue.push((h_add of op, effect))
  return deadend
```

Exploration Queue Algorithm for h^{add}

```
queue = priority_queue over (value, proposition) pairs
        ordered by value
enqueue all initially true propositions with value 0
set value of all operators to operator cost
while queue is not empty:
  (p_value, prop) = queue.pop()
  if we already encountered prop with a cheaper value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of best seen values of goal propositions
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < best seen value of its effect:
        update best seen value of effect proposition
        queue.push((h_add of op, effect))
  return deadend
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
set value of all operators to operator cost
while queue is not empty:
  (p_value, prop) = queue.pop()
  if we already encountered prop with a cheaper value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of best seen values of goal propositions
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < best seen value of its effect:
        update best seen value of effect proposition
        queue.push((h_add of op, effect))
  return deadend
```

Exploration Queue Algorithm for h^{add}

Prop

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
```

```
queue = in                                    )
set value                                     to
while queue is not empty:
  (p_value, prop) = queue.pop()
  if we already encountered prop with a cheaper value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of best seen values of goal propositions
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < best seen value of its effect:
        update best seen value of effect proposition
        queue.push((h_add of op, effect))
  return deadend
```

Exploration Queue Algorithm for h^{add}

Prop

hadd_value : int = infty

UnaryOperator

precond : vector<Prop>
effect : Prop
op_cost: int

```
queue = in                                )
set value                                 to
while queue is not empty:
  (p_value, prop) = queue.pop()
  if we already encountered prop with a cheaper value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of best seen values of goal propositions
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < best seen value of its effect:
        update best seen value of effect proposition
        queue.push((h_add of op, effect))
  return deadend
```

Exploration Queue Algorithm for h^{add}

```
queue = in                                                    )
set value                                                     to
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of g.hadd_value for all goal propositions g
  for operator op with precondition prop:
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < op.effect.hadd_value:
        op.effect.hadd_value = h_add of op
        queue.push((h_add of op, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
```

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
set value of all operators to operator cost
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal pr
    return sum of g.hadd_value for al
  for operator op with precondition p
    increase value of op by p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if value of op < op.effect.hadd_value:
        op.effect.hadd_value = h_add of op
        queue.push((h_add of op, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
```

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.hadd_value = op.op_cost for all operators op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal pr
    return sum of g.hadd_value for al
  for operator op with precondition p
    op.hadd_value += p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
```

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
hadd_value : int
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.hadd_value = op.op_cost for all operators op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal pr
    return sum of g.hadd_value for al
  for operator op with precondition p
    op.hadd_value += p_value
    mark precondition prop of op as satisfied
    if all preconditions of op satisfied:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

hadd_value : int = infty

UnaryOperator

precond : vector<Prop>
effect : Prop
op_cost: int
hadd_value : int

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
op.hadd_value = op.op_cost for all op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal pr
    return sum of g.hadd_value for al
  for operator op with precondition p
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
```

UnaryOperator

```
precond : vector<Prop>
effect : Prop
op_cost: int
hadd_value : int
unsat_preconditions : int
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
op.hadd_value = op.op_cost for all op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop is last unsatisfied goal proposition
    return sum of g.hadd_value for all goal propositions g
  for operator op with precondition prop:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

hadd_value : int = infty

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
goal_counter = |G|
op.hadd_value = op.op_cost for all op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop.is_goal and --goal_counter == 0:
    return sum of g.hadd_value for all goal propositions g
  for operator op with precondition prop:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
is_goal : bool
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
goal_counter = |G|
op.hadd_value = op.op_cost for all op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop.is_goal and --goal_counter == 0:
    return sum of g.hadd_value for all goal propositions g
  for operator op with precondition prop:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
is_goal : bool
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
goal_counter = |G|
op.hadd_value = op.op_cost for all op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop.is_goal and --goal_counter == 0:
    return sum of g.hadd_value for all goal propositions g
  for op in prop.precond_of:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Prop

```
hadd_value : int = infty
is_goal : bool
precond_of :
vector<UnaryOperator>
```

Exploration Queue Algorithm for h^{add}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
goal_counter = |G|
op.hadd_value = op.op_cost for all operators op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop.is_goal and --goal_counter == 0:
    return sum of g.hadd_value for all goal propositions g
  for op in prop.precond_of:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        queue.push((op.hadd_value, effect))
  return deadend
```

Illustrative Example: h^{add} with Exploration Queue

$$
\begin{aligned}
V &= \{a, b, c, d, e, f, g, h\} \\
I &= \{a\} \\
G &= \{c, d, e, f, g\} \\
A &= \{a_1, a_2, a_3, a_4, a_5, a_6\} \\
a_1 &= \langle a \rightarrow b, c \rangle_3 \\
a_2 &= \langle a, c \rightarrow d \rangle_1 \\
a_3 &= \langle b, c \rightarrow e \rangle_1 \\
a_4 &= \langle b \rightarrow f \rangle_1 \\
a_5 &= \langle d \rightarrow e, f \rangle_1 \\
a_6 &= \langle d \rightarrow g \rangle_1
\end{aligned}
$$

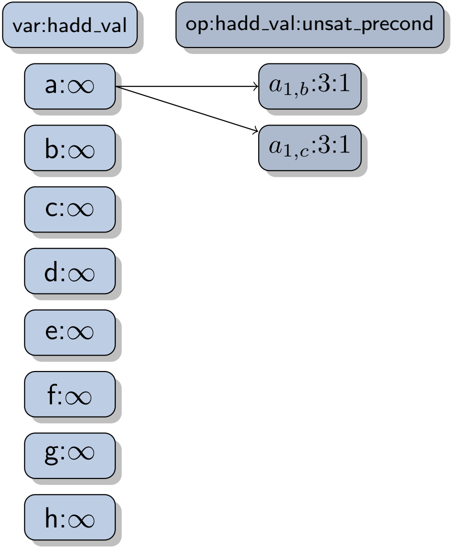
Illustrative Example: h^{add} with Exploration Queue

$$V = \{a, b, c, d, e, f, g, h\}$$
$$I = \{a\}$$
$$G = \{c, d, e, f, g\}$$
$$A = \{a_1, a_2, a_3, a_4, a_5, a_6\}$$
$$a_1 = \langle a \rightarrow b, c \rangle_3$$
$$a_2 = \langle a, c \rightarrow d \rangle_1$$
$$a_3 = \langle b, c \rightarrow e \rangle_1$$
$$a_4 = \langle b \rightarrow f \rangle_1$$
$$a_5 = \langle d \rightarrow e, f \rangle_1$$
$$a_6 = \langle d \rightarrow g \rangle_1$$

var:hadd_val
a:∞
b:∞
c:∞
d:∞
e:∞
f:∞
g:∞
h:∞

Illustrative Example: h^{add} with Exploration Queue

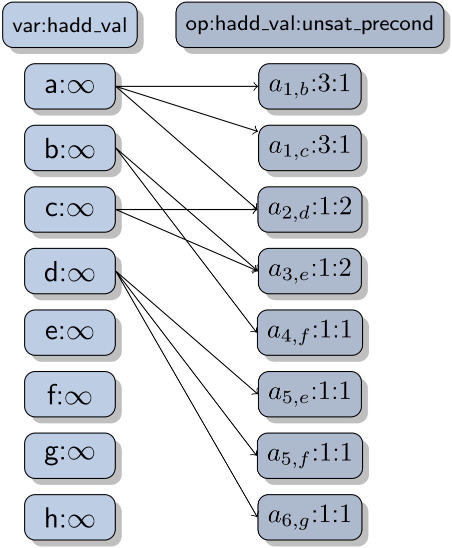
$$I = \{a\}$$
$$G = \{c, d, e, f, g\}$$
$$A = \{a_1, a_2, a_3, a_4, a_5, a_6\}$$
$$a_1 = \langle a \rightarrow b, c\rangle_3$$
$$a_2 = \langle a, c \rightarrow d\rangle_1$$
$$a_3 = \langle b, c \rightarrow e\rangle_1$$
$$a_4 = \langle b \rightarrow f\rangle_1$$
$$a_5 = \langle d \rightarrow e, f\rangle_1$$
$$a_6 = \langle d \rightarrow g\rangle_1$$



Illustrative Example: h^{add} with Exploration Queue

$$I = \{a\}$$
$$G = \{c, d, e, f, g\}$$
$$A = \{a_1, a_2, a_3, a_4, a_5, a_6\}$$

$$a_2 = \langle a, c \rightarrow d \rangle_1$$
$$a_3 = \langle b, c \rightarrow e \rangle_1$$
$$a_4 = \langle b \rightarrow f \rangle_1$$
$$a_5 = \langle d \rightarrow e, f \rangle_1$$
$$a_6 = \langle d \rightarrow g \rangle_1$$

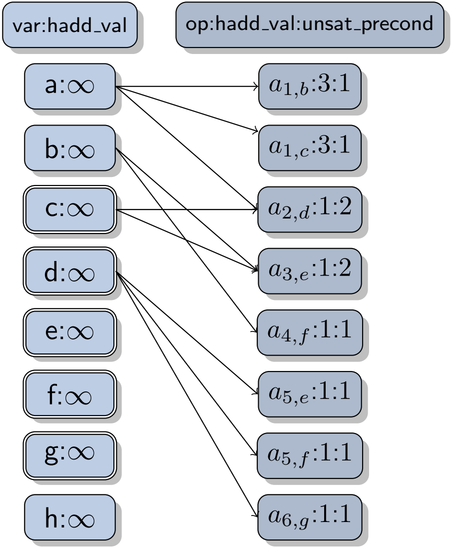


Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

$I = \{a\}$

$G = \{c, d, e, f, g\}$

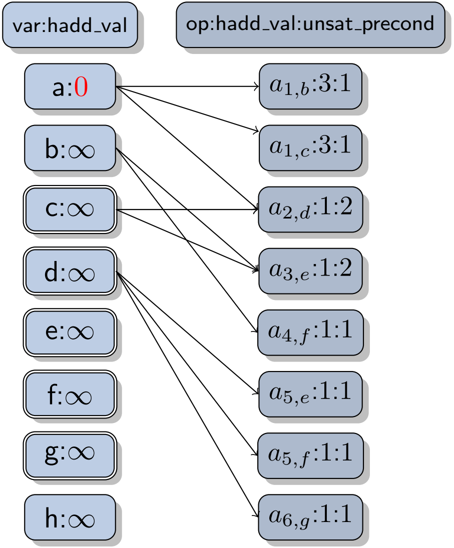


Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

(0,a)

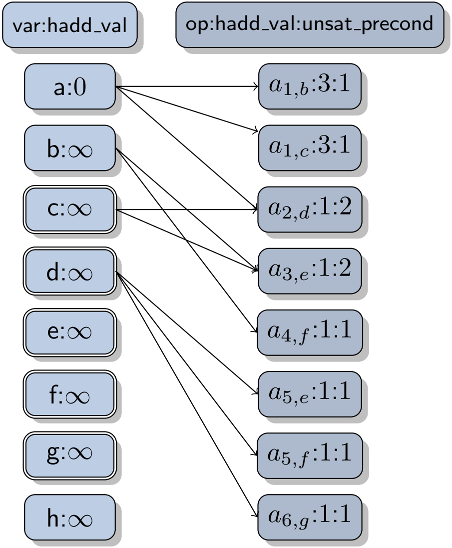
$I = \{a\}$



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

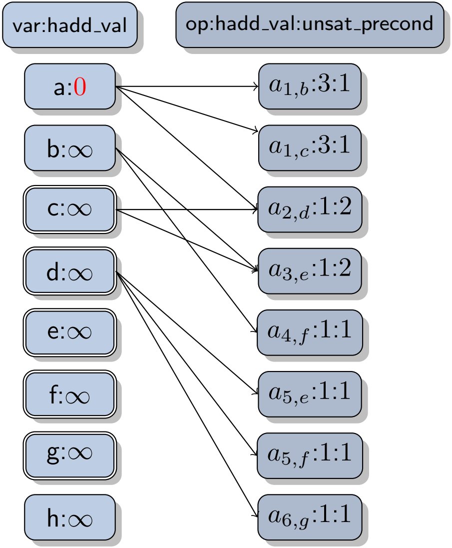
(0,a)



Illustrative Example: h^{add} with Exploration Queue

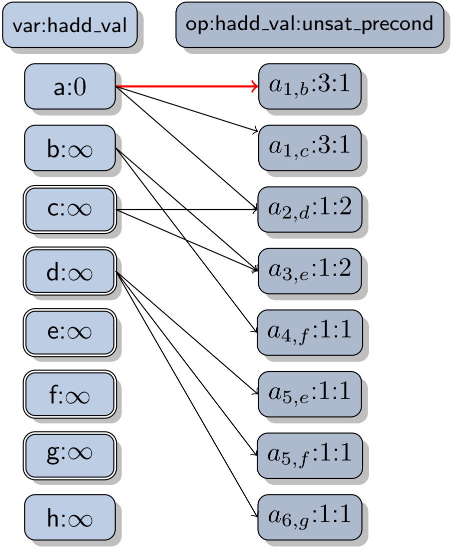
unsatisfied_goalprops $= 5$

(0,a)



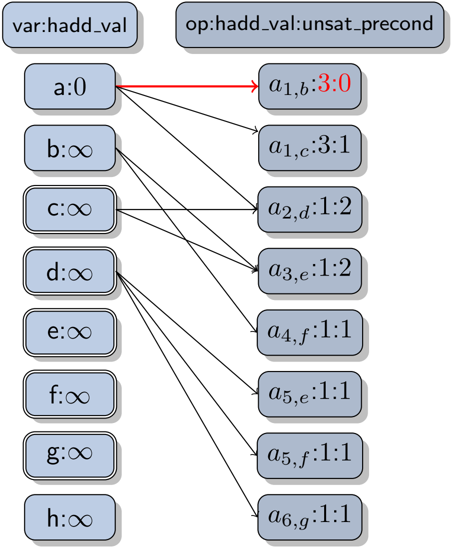
Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5



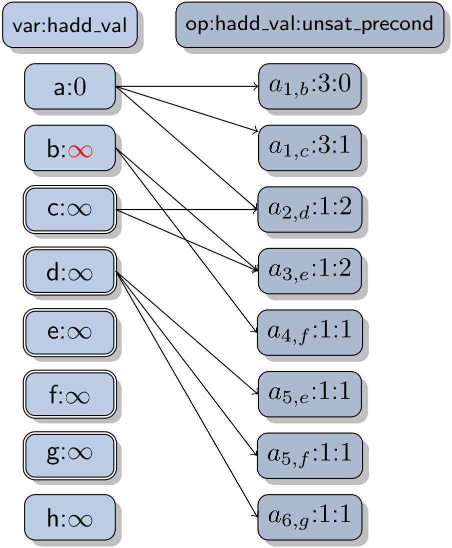
Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$



Illustrative Example: h^{add} with Exploration Queue

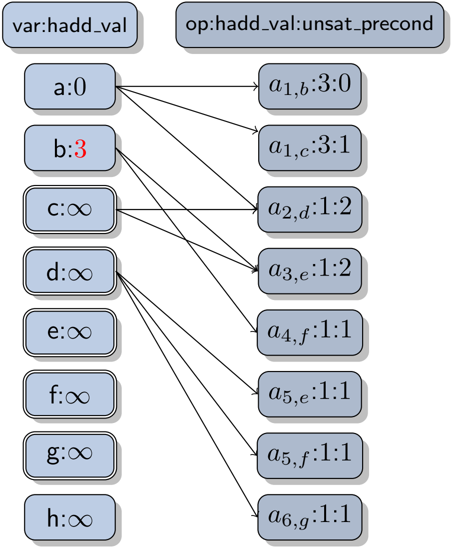
unsatisfied_goalprops $= 5$



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

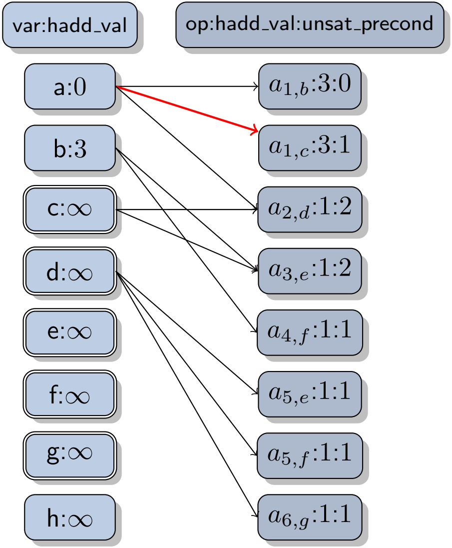
(3,b)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

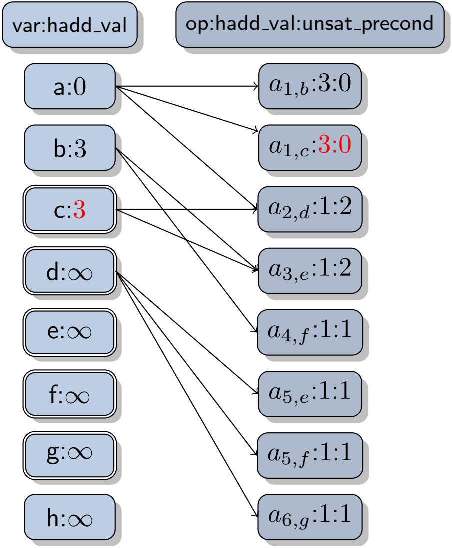
(3,b)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

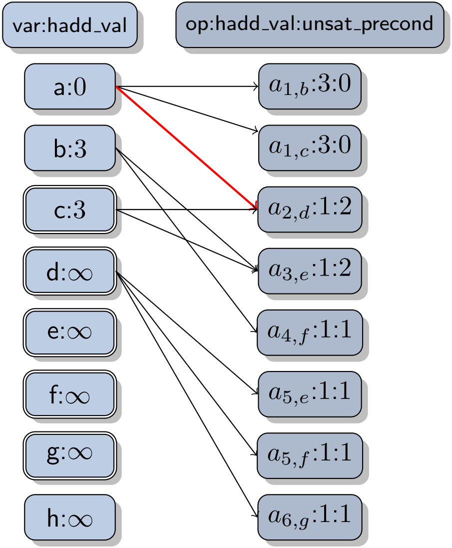
(3,b)	(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

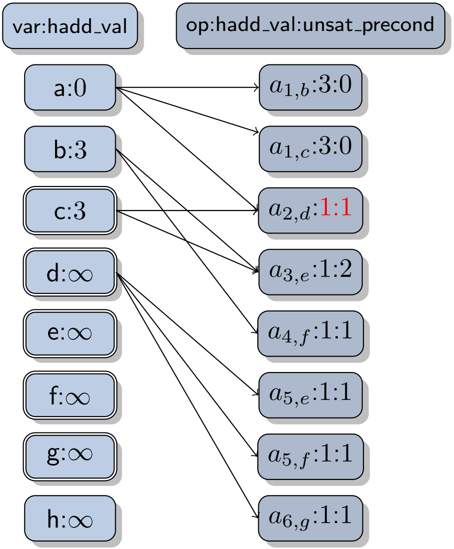
(3,b)	(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 5$

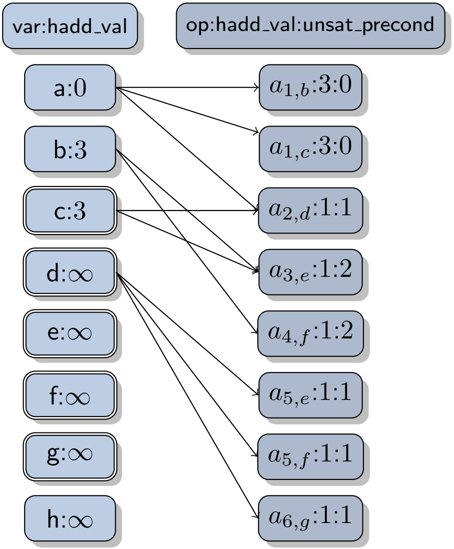
(3,b)	(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

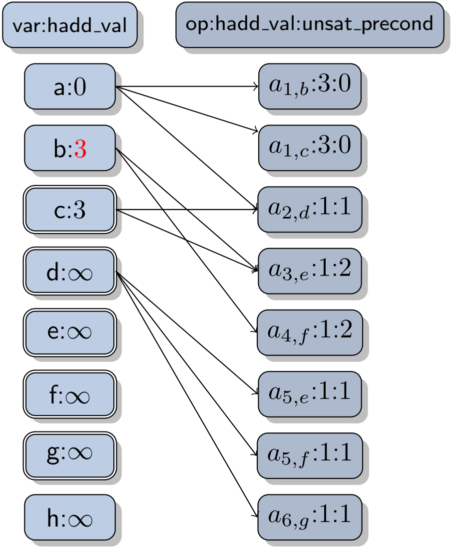
(3,b)	(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

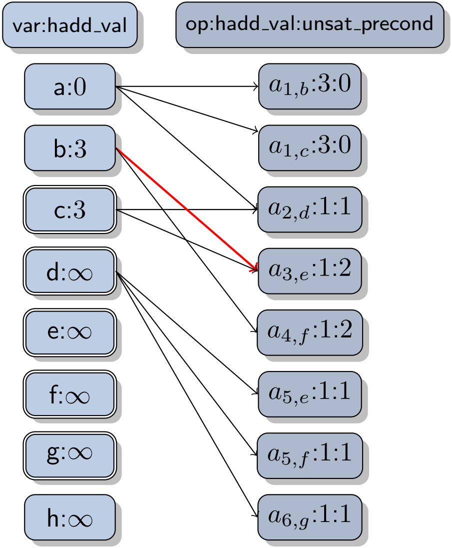
(3,b) (3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

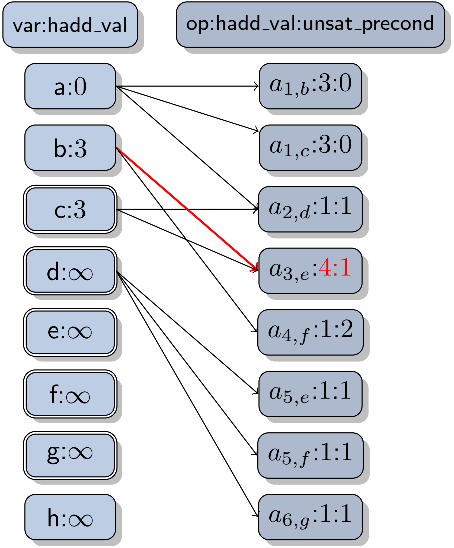
(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

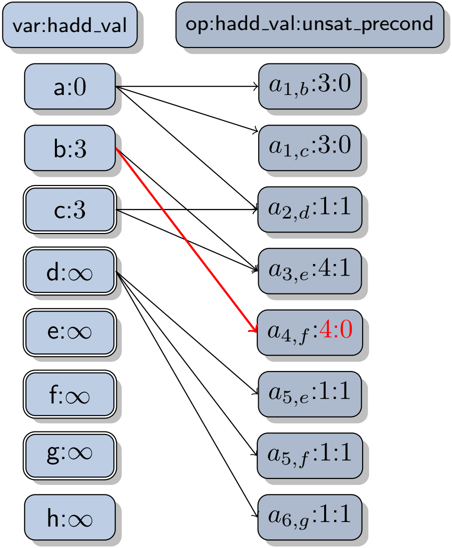
(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

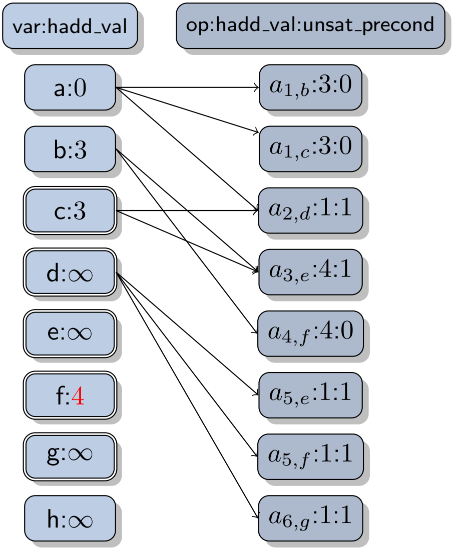
(3,c)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

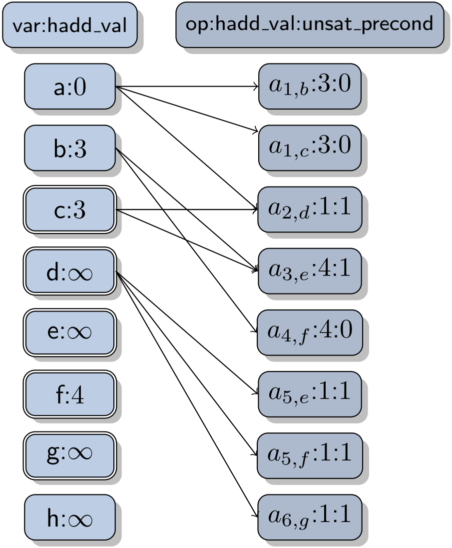
(3,c)	(4,f)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 5

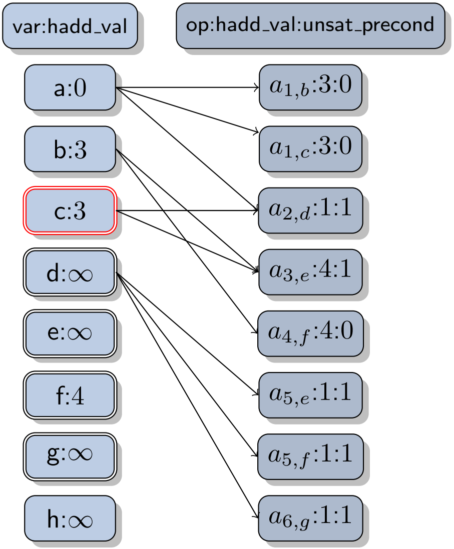
(3,c) (4,f)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 4$

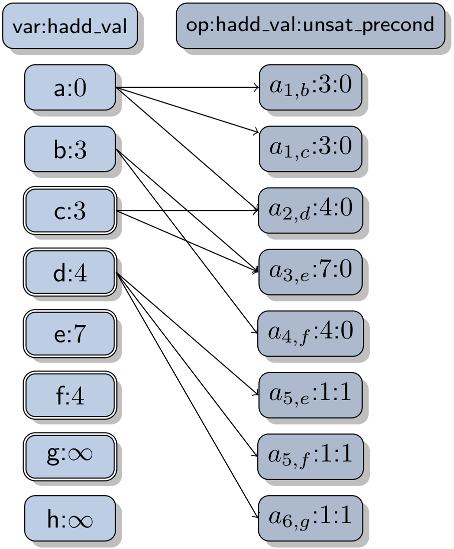
(4,f)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 4

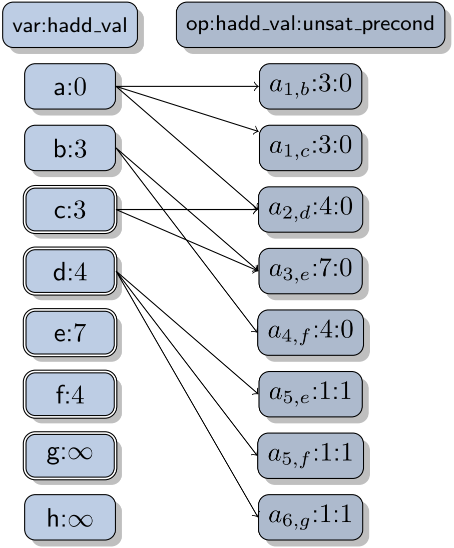
(4,f)	(4,d)	(7,e)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 3

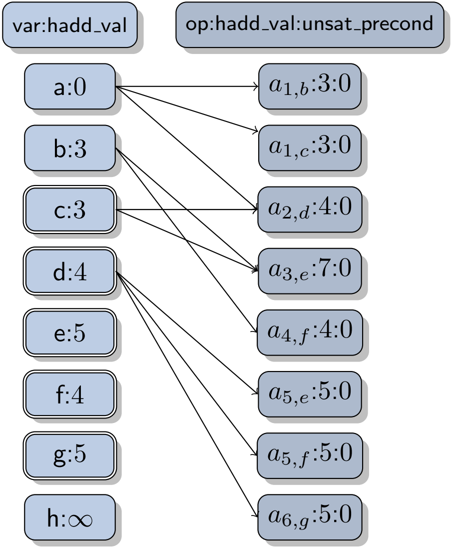
(4,d)	(7,e)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops = 2

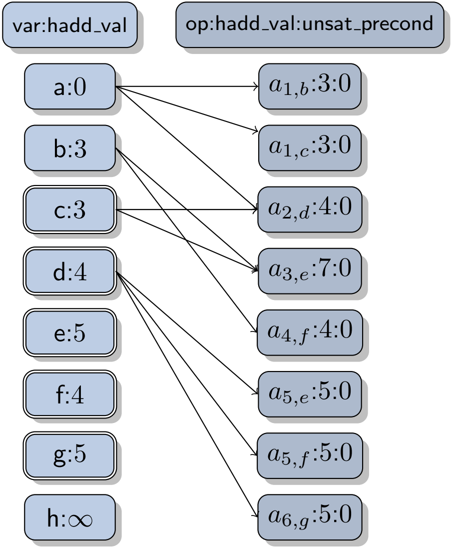
(5,e) (5,g) (7,e)



Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 1$

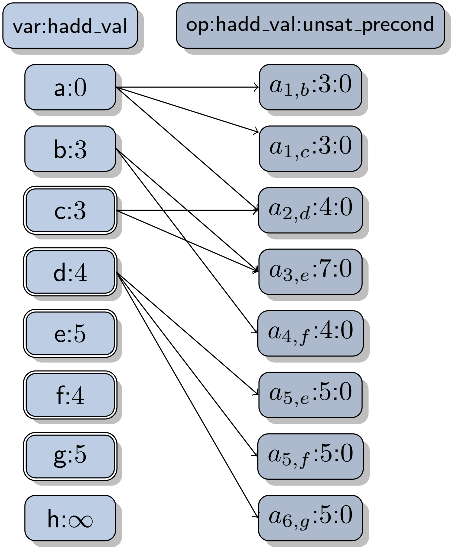
(5,g)	(7,e)



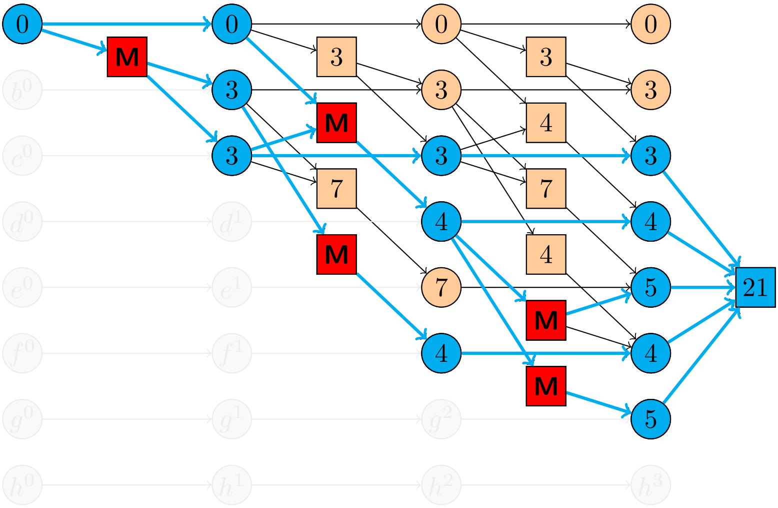
Illustrative Example: h^{add} with Exploration Queue

unsatisfied_goalprops $= 0$

(7,e)



Illustrative Example: h^{FF}



Prop

```
hadd_value : int = infty
is_goal : bool
precond_of : vector<UnaryOperator>
reached_by : UnaryOperator = 0
marked : bool = false
```

UnaryOperator

```
precond : vector<Prop*>
effect : Prop*
op_cost: int
hadd_value : int
unsat_preconditions : int
orig_op: Operator
```

Exploration Queue Algorithm for h^{FF}

```
queue = initialize_priority_queue(I)
op.unsat_preconditions = op.precond.size() for all operators op
goal_counter = |G|
op.hadd_value = op.op_cost for all operators op
while queue is not empty:
  (p_value, prop) = queue.pop()
  if prop.hadd_value < p_value:
    continue
  if prop.is_goal and --goal_counter == 0:
    return sum of g.hadd_value for all goal propositions g
  for op in prop.precond_of:
    op.hadd_value += p_value
    if --op.unsat_preconditions == 0:
      if op.hadd_value < op.effect.hadd_value:
        op.effect.hadd_value = op.hadd_value
        op.effect.reached_by = op
        queue.push(op.hadd_value, effect)
  return deadend
```

Mark Relaxed Plan

```
for goal_prop in G:
    mark_relaxed_plan(goal_prop)

void mark_relaxed_plan(goal_prop):
    // Only consider each subgoal once.
    if !goal_prop->marked
        goal_prop->marked = true;
        unary_op = goal.reached_by;
        // If we have not yet chained back to a start node.
        if unary_op:
            for prop in op.precond;
                mark_relaxed_plan(prop);
            mark unary_op.orig_op
```

Experimental Results

coverage	expqueue	textbook
airport (50)	**34**	31
barman-opt11-strips (20)	**20**	9
elevators-sat08-strips (30)	**11**	9
floortile (40)	**15**	10
freecell (80)	**79**	76
logistics98 (35)	**30**	25
mprime (35)	**31**	19
mystery (30)	**17**	13
nomystery (40)	**26**	21
parcprinter (70)	43	**70**
parking (40)	**40**	16
pipesworld-notankage (50)	**33**	29
pipesworld-tankage (50)	21	**25**
satellite (36)	**27**	25
scanalyzer-opt11-strips (20)	**20**	18
tidybot (40)	**31**	23
tpp (30)	**23**	16
trucks-strips (30)	**17**	14
woodworking-sat08-strips (30)	**27**	25
Sum	554	492