

Optimal Binary Search Trees

Tobias Nipkow and Dániel Somogyi
Technical University Munich

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Abstract

This article formalizes recursive algorithms for the construction of optimal binary search trees given fixed access frequencies. We follow Knuth [1], Yao [4] and Mehlhorn [2].

The algorithms are memoized with the help of an AFP entry for memoization [3], thus yielding dynamic programming algorithms.

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1 Introduction

These theories formalize algorithms for the construction of optimal binary search trees from fixed access frequencies for a fixed list of items. The work

is based on the original article by Knuth [1] and the textbook by Mehlhorn [2, Part III, Chapter 4].

Initially the algorithms are expressed as naive recursive functions and have exponential complexity. Nevertheless we already refer to them as the cubic (Section 3) and the quadratic algorithm (Section 5), their running times of their fully memoized dynamic programming versions. In Section 7 the algorithms are memoized with the help of an existing framework [3].

1.1 Data Representation

Instead of labeling our BSTs with (ascending) keys $x_i < \dots < x_j$ we label them with the indices of the actual keys, some interval of integers. Functions taking two integer arguments i and j construct or analyze trees such that $\text{inorder } t = [i..j]$.

The access frequencies are given by two tables (functions) a and b :

$a\ k$ ($i \leq k \leq j + 1$) is the frequency of (failing) searches with a key in the interval (x_{k-1}, x_k) .

$b\ k$ ($i \leq k \leq j$) is the frequency of (successful) searches with key x_k .

2 Weighted Path Length of BST

```
theory Weighted_Path_Length
imports HOL-Library.Tree
begin
```

This theory presents two definitions of the *weighted path length* of a BST, the objective function we want to minimize, and proves them equivalent. Function Wpl is the intuitive global definition that sums a over all leaves and b over all nodes, taking their depth (= number of comparisons to reach that point) into account. Function wpl is a recursive definition and thus suitable for the later dynamic programming approaches to building a BST with the minimal weighted path length.

```
lemma inorder_upto_split:
```

```
  assumes inorder ⟨l,k,r⟩ = [i..j]
```

```
  shows inorder l = [i..k-1] inorder r = [k+1..j] i ≤ k k ≤ j
```

```
proof -
```

```
  have k: k ∈ set [i..j] using assms by (metis set_inorder tree.set_intros(2))
```

```
  have [i..k-1] @ k # [k+1..j] = [i..j]
```

```
    using k upto_rec1 upto_split1 by (metis atLeastAtMost_iff set_upto)
```

```
  also have ... = inorder l @ k # inorder r using assms by auto
```

```
  finally have inorder l = [i..k-1] ∧ inorder r = [k+1..j] (is ?A ∧ ?B)
```

```
    by (auto simp: append_Cons_eq_iff)
```

```
  thus ?A ?B by auto
```

```
  show i ≤ k k ≤ j using k by auto
```

```
qed
```

```

fun incr2 :: int × nat ⇒ int × nat where
incr2 (x,n) = (x, n + 1)

fun leaves :: int ⇒ int tree ⇒ (int * nat) set where
leaves i Leaf = {(i,0)} |
leaves i (Node l k r) = incr2 ‘ (leaves i l ∪ leaves (k+1) r)

fun nodes :: int tree ⇒ (int * nat) set where
nodes Leaf = {} |
nodes (Node l k r) = {(k,1)} ∪ incr2 ‘ (nodes l ∪ nodes r)

lemma finite_nodes: finite (nodes t)
by(induction t) auto

lemma finite_leaves: finite (leaves i t)
by(induction i t rule: leaves.induct) auto

lemma notin_nodes0: (k, 0) ∉ nodes t
by(induction t) auto

lemma sum_incr2: sum f (incr2 ‘ A) = sum (λxy. f(fst xy,snd xy+1)) A
proof –
  have sum f (incr2 ‘ A) = sum (f o incr2) A
    by(subst sum.reindex)(auto simp: inj_on_def)
  also have f o incr2 = (λxy. f(fst xy,snd xy+1))
    by(auto simp: fun_eq_iff)
  finally show ?thesis by simp
qed

lemma fst_nodes: fst ‘ nodes t = set_tree t
apply(induction t)
  apply simp
apply (fastforce simp: image_def set_eq_iff ball_Un)
done

lemma fst_leaves: [ inoder t = [i..j]; i ≤ j+1 ] ⇒ fst ‘ leaves i t = {i..j+1}
proof(induction t arbitrary: i j)
  case Leaf
    then show ?case by auto
  next
    case (Node t1 k t2)
    note inoder = inoder_upto_split[OF Node.prem1]
    show ?case
      using Node.IH(1)[OF inoder(1)] Node.IH(2)[OF inoder(2)] inoder(3,4)
      Node.prem2
      by (fastforce simp: image_def set_eq_iff ball_Un)
qed

```

```

lemma sum_leaves:  $\llbracket \text{inorder } t = [i..j]; i \leq j+1 \rrbracket \implies$ 
   $(\sum_{x \in \text{leaves } i \ t}. (f(\text{fst } x) :: \text{nat})) = \text{sum } f \{i..j+1\}$ 
proof(induction t arbitrary: i j)
  case Leaf
  hence  $i = j+1$  by simp
  thus ?case by simp
next
  case (Node l k r)
  note inorder = inorder_upto_split[OF Node.prems(1)]
  let ?Ll = leaves i l let ?Lr = leaves (k+1) r let ?L = ?Ll  $\cup$  ?Lr
  have fst ' ?Ll  $\cap$  fst ' ?Lr =  $\{\}$  using inorder
  by(simp add: fst_leaves del: set_inorder add: set_inorder[symmetric])
  hence  $\emptyset$ : ?Ll  $\cap$  ?Lr =  $\{\}$  by auto
  have  $\{i..j+1\} = \{i..k\} \cup \{k+1..j+1\}$  using inorder(3,4) by auto
  thus ?case
  using Node.IH(1)[OF inorder(1)] Node.IH(2)[OF inorder(2)] inorder(3,4) Node.prems(2)
  by(simp add: sum_incr2 sum_Un_nat finite_leaves  $\emptyset$ )
qed

```

```

lemma sum_nodes: inorder t = [i..j]  $\implies$ 
   $(\sum_{xy \in \text{nodes } t}. (f(\text{fst } xy) :: \text{nat})) = \text{sum } f \{i..j\}$ 
proof(induction t arbitrary: i j)
  case Leaf thus ?case by simp
next
  case (Node l k r)
  note inorder = inorder_upto_split[OF Node.prems(1)]
  let ?Nl = nodes l let ?Nr = nodes r let ?N = ?Nl  $\cup$  ?Nr
  have (fst ' ?Nl)  $\cap$  (fst ' ?Nr) =  $\{\}$  using inorder(1,2)
  by(simp add: fst_nodes del: set_inorder add: set_inorder[symmetric])
  hence  $n0$ : ?Nl  $\cap$  ?Nr =  $\{\}$  by auto
  have  $(\sum_{xy \in \text{nodes}(\text{Node } l \ k \ r)}. (f(\text{fst } xy) :: \text{nat}))$ 
    =  $(\sum_{xy \in \text{insert } (k, \text{Suc } 0)}. (\text{incr2 ' } (\text{nodes } l \cup \text{nodes } r)). f(\text{fst } xy))$ 
  by(simp)
  also have  $\dots = f \ k + (\sum_{xy \in (\text{incr2 ' } (\text{nodes } l \cup \text{nodes } r))}. f(\text{fst } xy))$ 
  by(subst sum.insert, auto simp: finite_nodes notin_nodes0)
  also have  $\dots = \text{sum } f \{i..j\}$ 
  proof –
  have  $\{i..j\} = \{i..k-1\} \cup \{k\} \cup \{k+1..j\}$  using inorder(3,4) by auto
  thus ?thesis
  using Node.IH(1)[OF inorder(1)] Node.IH(2)[OF inorder(2)] inorder(3,4)
  by(simp add: sum_incr2 sum_Un_nat finite_nodes  $n0$ )
qed
finally show ?case .
qed

```

```

locale wpl =
fixes  $w :: \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$ 
begin

```

```

fun wpl :: int ⇒ int ⇒ int tree ⇒ nat where
wpl i j Leaf = 0 |
wpl i j (Node l k r) = wpl i (k-1) l + wpl (k+1) j r + w i j

end

locale Wpl =
fixes a b :: int ⇒ nat
begin

definition Wpl :: int ⇒ int tree ⇒ nat where
Wpl i t = sum (λ(k,c). c * b k) (nodes t) + sum (λ(k,c). c * a k) (leaves i t)

definition w :: int ⇒ int ⇒ nat where
w i j = sum a {i..j+1} + sum b {i..j}

sublocale wpl where w = w .

lemma inorder t = [i..j] ⇒ wpl i j t = Wpl i t
proof(induction t arbitrary: i j)
  case Leaf thus ?case by(simp add: Wpl_def)
next
  case (Node l k r)
  let ?b = λ(k,c). c * b k let ?a = λ(k,c). c * a k
  note inorder = inorder_upto_split[OF Node.prem]
  let ?Nl = nodes l let ?Nr = nodes r let ?N = ?Nl ∪ ?Nr
  let ?Ll = leaves i l let ?Lr = leaves (k+1) r let ?L = ?Ll ∪ ?Lr
  have (fst ‘ ?Nl) ∩ (fst ‘ ?Nr) = {} using inorder(1,2)
  by(simp add: fst_nodes del: set_inorder add: set_inorder[symmetric])
  hence n0: ?Nl ∩ ?Nr = {} by auto
  have fst ‘ ?Ll ∩ fst ‘ ?Lr = {} using inorder
  by(simp add: fst_leaves del: set_inorder add: set_inorder[symmetric])
  hence 0: ?Ll ∩ ?Lr = {} by auto
  have wpl i j (Node l k r) = Wpl i l + Wpl (k + 1) r + w i j
  using Node.IH inorder by(simp)
  also have ... = sum ?b (nodes l) + sum ?a (leaves i l) +
    sum ?b (nodes r) + sum ?a (leaves (k+1) r) + w i j
  by (simp add: Wpl_def)
  also have ... = (sum ?b (nodes l) + sum ?b (nodes r))
    + (sum ?a (leaves i l) + sum ?a (leaves (k+1) r)) + w i j
  by(simp add: algebra_simps)
  also have ... = sum ?b ?N + sum ?a ?L + w i j
  by(simp add: sum_Un_nat finite_nodes finite_leaves 0 n0)
  also have ... = sum ?b ?N + sum ?a ?L + sum a {i..j+1} + sum b {i..j}
  by (simp add: w_def)
  also have ... = sum ?b ?N + sum b {i..j} + (sum ?a ?L + sum a {i..j+1})
  by(simp add: algebra_simps)
  also have sum ?a ?L + sum a {i..j+1} = sum ?a (incr2 ‘ ?L)
proof -

```

```

    have {i..j+1} = {i..k} ∪ {k+1..j+1} using inorder(3,4) by auto
    thus ?thesis using inorder(3,4)
      by (simp add: sum_incr2 split_def sum.distrib sum_Un_nat finite_leaves l0
        sum_leaves[OF inorder(1)] sum_leaves[OF inorder(2)])
  qed
  also have sum ?b ?N + sum b {i..j}
    = sum ?b ?N + sum b ({i..k-1} ∪ {k+1..j}) + b k
  proof -
    have {i..j} = {k} ∪ {i..k-1} ∪ {k+1..j} using inorder(3,4) by auto
    thus ?thesis by simp
  qed
  also have sum ?b ?N + sum b ({i..k-1} ∪ {k+1..j}) = sum ?b (incr2 ' ?N)
    by (simp add: sum_incr2 split_def sum.distrib sum_Un_nat finite_nodes n0
      sum_nodes[OF inorder(1)] sum_nodes[OF inorder(2)])
  also have sum ?b (incr2 ' ?N) + b k = sum ?b ({(k,1)} ∪ incr2 ' ?N)
    by (simp, subst sum.insert, auto simp add: finite_nodes notin_nodes0)
  also have sum ?b ({(k,1)} ∪ incr2 ' ?N) + sum ?a (incr2 ' ?L) = Wpl i ⟨l,k,r⟩
    by (simp add: Wpl_def)
  finally show ?case .
  qed

end

end

```

3 Optimal BSTs: The ‘Cubic’ Algorithm

```

theory Optimal_BST
imports Weighted_Path_Length Monad_Memo_DP.OptBST
begin

```

3.1 Function *argmin*

Function *argmin* was moved to *Monad_Memo_DP.argmin*. It iterates over a list and returns the rightmost element that minimizes a given function:

```

argmin ?f (?x # ?xs) =
(if ?xs = [] then ?x
 else let m = argmin ?f ?xs in if ?f ?x < ?f m then ?x else m)

```

An optimized version that avoids repeated computation of $f x$:

```

fun argmin2 :: ('a ⇒ ('b::linorder)) ⇒ 'a list ⇒ 'a * 'b where
argmin2 f (x#xs) =
  (let fx = f x
   in if xs = [] then (x, fx)
   else let mfm = argmin2 f xs
        in if fx < snd mfm then (x,fx) else mfm)

```

lemma *argmin2_argmin*: $xs \neq [] \implies \text{argmin2 } f \text{ } xs = (\text{argmin } f \text{ } xs, f(\text{argmin } f \text{ } xs))$
by (*induction xs*) (*auto simp: Let_def*)

lemma *argmin_argmin2*[code]: $\text{argmin } f \text{ } xs = (\text{if } xs = [] \text{ then undefined else } \text{fst}(\text{argmin2 } f \text{ } xs))$
apply (*auto simp: argmin2_argmin*)
apply (*meson argmin.elims list.distinct(1)*)
done

lemma *argmin_in*: $xs \neq [] \implies \text{argmin } f \text{ } xs \in \text{set } xs$
using *argmin_forall*[of $xs \ \lambda x. x \in \text{set } xs$] **by** *blast*

lemma *argmin_pairs*: $xs \neq [] \implies$
 $(\text{argmin } f \text{ } xs, f(\text{argmin } f \text{ } xs)) = \text{argmin } \text{snd} (\text{map } (\lambda x. (x, f \ x)) \text{ } xs)$
by (*induction f xs rule:argmin.induct*) (*auto, smt snd_conv*)

lemma *argmin_map*: $xs \neq [] \implies \text{argmin } c (\text{map } f \text{ } xs) = f(\text{argmin } (c \ o \ f) \text{ } xs)$
by(*induction xs*) (*simp_all add: Let_def*)

3.2 The ‘Cubic’ Algorithm

We hide the details of the access frequencies a and b by working with an abstract version of function w defined above (summing a and b). Later we interpret w accordingly.

locale *Optimal_BST* =
fixes $w :: \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$
begin

3.2.1 Functions wpl and min_wpl

sublocale *wpl* **where** $w = w$.

Function $min_wpl \ i \ j$ computes the minimal weighted path length of any tree t where $\text{inorder } t = [i..j]$. It simply tries all possible indices between i and j as the root. Thus it implicitly constructs all possible trees.

declare *conj_cong* [*fundef_cong*]
function $min_wpl :: \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$ **where**
 $min_wpl \ i \ j =$
 $(\text{if } i > j \text{ then } 0$
 $\text{else } \text{Min} ((\lambda k. min_wpl \ i \ (k-1) + min_wpl \ (k+1) \ j) \ \{i..j\}) + w \ i \ j)$
by *auto*
termination by (*relation measure* $(\lambda(i,j). \text{nat}(j-i+1))$) *auto*
declare $min_wpl.simps$ [*simp del*]

Note that for efficiency reasons we have pulled $+ w \ i \ j$ out of Min . In the lemma below this is reversed because it simplifies the proofs. Similar optimizations are possible in other functions below.

```

lemma min_wpl_simps[simp]:
   $i > j \implies \text{min\_wpl } i \ j = 0$ 
   $i \leq j \implies \text{min\_wpl } i \ j =$ 
     $\text{Min } ((\lambda k. \text{min\_wpl } i \ (k-1)) + \text{min\_wpl } (k+1) \ j + w \ i \ j) \ \{i..j\}$ 
by(auto simp add: min_wpl_simps[of i j] Min_add_commute)

```

```

lemma upto_split1:
   $\llbracket i \leq j; j \leq k \rrbracket \implies [i..k] = [i..j-1] @ [j..k]$ 
proof (induction j rule: int_ge_induct)
  case base thus ?case by (simp add: upto_rec1)
next
  case step thus ?case using upto_rec1 upto_rec2 by simp
qed

```

Function *local.min_wpl* returns a lower bound for all possible BSTs:

```

theorem min_wpl_is_optimal:
   $\text{inorder } t = [i..j] \implies \text{min\_wpl } i \ j \leq \text{wpl } i \ j \ t$ 
proof (induction i j t rule: wpl.induct)
  case 1
  thus ?case by(simp add: upto_simps split: if_splits)
next
  case (2 i j l k r)
  then show ?case
  proof cases
    assume  $i > j$  thus ?thesis by(simp)
  next
    assume [arith]:  $\neg i > j$ 

    note  $\text{inorder} = \text{inorder\_upto\_split}[OF \ 2.\text{prems}]$ 

    let ?M =  $(\lambda k. \text{min\_wpl } i \ (k-1)) + \text{min\_wpl } (k+1) \ j + w \ i \ j$  ‘  $\{i..j\}$ 
    let ?w =  $\text{min\_wpl } i \ (k-1) + \text{min\_wpl } (k+1) \ j + w \ i \ j$ 

    have aux_min:  $\text{Min } ?M \leq ?w$ 
    proof (rule Min_le)
      show finite ?M by simp
      show ?w  $\in$  ?M using inorder(3,4) by simp
    qed

    have  $\text{min\_wpl } i \ j = \text{Min } ?M$  by(simp)
    also have  $\dots \leq ?w$  by (rule aux_min)
    also have  $\dots \leq \text{wpl } i \ (k-1) \ l + \text{wpl } (k+1) \ j \ r + w \ i \ j$ 
      using inorder(1,2) 2.IH by simp
    also have  $\dots = \text{wpl } i \ j \ \langle l, k, r \rangle$  by simp
    finally show ?thesis .
  qed
qed

```

Now we show that the lower bound computed by *local.min_wpl* is the wpl of an optimal tree that can be computed in the same manner.

3.2.2 Function *opt_bst*

This is the functional equivalent of the standard cubic imperative algorithm. Unless it is memoized, the complexity is again exponential. The pattern of recursion is the same as for *local.min_wpl* but instead of the minimal weight it computes a tree with the minimal weight:

```
function opt_bst :: int ⇒ int ⇒ int tree where
opt_bst i j =
  (if i > j then Leaf
   else argmin (wpl i j) [(opt_bst i (k-1)), k, (opt_bst (k+1) j)] . k ← [i..j])
by auto
termination by (relation measure ( $\lambda(i,j) . \text{nat}(j-i+1)$ )) auto
declare opt_bst.simps[simp del]
```

```
corollary opt_bst_simps[simp]:
  i > j ⇒ opt_bst i j = Leaf
  i ≤ j ⇒ opt_bst i j =
    (argmin (wpl i j) [(opt_bst i (k-1)), k, (opt_bst (k+1) j)] . k ← [i..j])
by(auto simp add: opt_bst.simps[of i j])
```

As promised, *local.opt_bst* computes a tree with the minimal wpl:

```
theorem wpl_opt_bst: wpl i j (opt_bst i j) = min_wpl i j
proof(induction i j rule: min_wpl.induct)
  case (1 i j)
  show ?case
  proof cases
    assume i > j
    thus ?thesis by(simp)
  next
    assume [arith]:  $\neg i > j$ 
    let ?ts = [(opt_bst i (k-1)), k, (opt_bst (k+1) j)] . k ← [i..j]
    let ?M = (( $\lambda k. \text{min\_wpl } i (k-1) + \text{min\_wpl } (k+1) j + w \ i \ j$ ) ‘ {i..j})
    have 1: ?ts ≠ [] by (auto simp add: upto.simps)
    have wpl i j (opt_bst i j) = wpl i j (argmin (wpl i j) ?ts) by simp
    also have ... = Min (wpl i j ‘ (set ?ts))
      by(rule argmin_Min[OF 1])
    also have ... = Min ?M
    proof (rule arg_cong[where f=Min])
      show wpl i j ‘ (set ?ts) = ?M using 1.IH
      by (force simp: Bex_def image_iff 1.IH)
    qed
    also have ... = min_wpl i j by simp
    finally show ?thesis .
  qed
qed
```

```
corollary opt_bst_is_optimal:
  inorder t = [i..j] ⇒ wpl i j (opt_bst i j) ≤ wpl i j t
by (simp add: min_wpl_is_optimal wpl_opt_bst)
```

3.2.3 Function `opt_bst_wpl`

Function `local.opt_bst` is simplistic because it computes the wpl of each tree anew rather than returning it with the tree. That is what `opt_bst_wpl` does:

```
function opt_bst_wpl :: int ⇒ int ⇒ int tree × nat where
opt_bst_wpl i j =
  (if i > j then (Leaf, 0)
   else argmin snd [let (t1,c1) = opt_bst_wpl i (k-1);
                      (t2,c2) = opt_bst_wpl (k+1) j
                      in (<t1,k,t2>, c1 + c2 + w i j). k ← [i..j]])
```

by `auto`

termination

by (`relation measure` ($\lambda(i,j). \text{nat}(j-i+1)$))(`auto`)

declare `opt_bst_wpl.simps`[`simp del`]

Function `opt_bst_wpl` returns an optimal tree and its wpl:

lemma `opt_bst_wpl_eq_pair`:

`opt_bst_wpl` `i j` = (`opt_bst` `i j`, `wpl` `i j` (`opt_bst` `i j`))

proof(`induction` `i j` *rule*: `opt_bst_wpl.induct`)

case (`1 i j`)

note [`simp`] = `opt_bst_wpl.simps`[*of* `i j`]

show `?case`

proof `cases`

assume `i > j` **thus** `?thesis` **using** `1.prem`s **by** `auto`

next

assume $\neg i > j$

thus `?thesis` **by** (`simp add`: `argmin_pairs comp_def 1.IH cong: list.map_cong_simp`)

qed

qed

corollary `opt_bst_wpl_eq_pair'`: `opt_bst_wpl` `i j` = (`opt_bst` `i j`, `min_wpl` `i j`)

by (`simp add`: `opt_bst_wpl_eq_pair wpl_opt_bst`)

end

end

4 Quadrangle Inequality

theory `Quadrilateral_Inequality`

imports `Main`

begin

definition `is_arg_min_on` :: (`'a` ⇒ (`'b::linorder`)) ⇒ `'a set` ⇒ `'a` ⇒ `bool` **where**
`is_arg_min_on` `f S x` = (`x` ∈ `S` ∧ (∀ `y` ∈ `S`. `f x` ≤ `f y`))

definition `Args_min_on` :: (`int` ⇒ (`'b::linorder`)) ⇒ `int set` ⇒ `int set` **where**
`Args_min_on` `f I` = {`k`. `is_arg_min_on` `f I k`}

lemmas *Args_min_simps* = *Args_min_on_def is_arg_min_on_def*

lemma *is_arg_min_on_antimono*: **fixes** $f :: _ \Rightarrow _ :: \text{order}$
shows $\llbracket \text{is_arg_min_on } f \ S \ x; f \ y \leq f \ x; y \in S \rrbracket \Longrightarrow \text{is_arg_min_on } f \ S \ y$
by (*metis antisym is_arg_min_on_def*)

lemma *ex_is_arg_min_on_if_finite*: **fixes** $f :: 'a \Rightarrow 'b :: \text{linorder}$
shows $\llbracket \text{finite } S; S \neq \{\} \rrbracket \Longrightarrow \exists x. \text{is_arg_min_on } f \ S \ x$
unfolding *is_arg_min_on_def* **using** *ex_min_if_finite*[*of f ' S*] **by** *fastforce*

locale *QI* =

fixes $c \ k :: \text{int} \Rightarrow \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$

fixes $c :: \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$

and $w :: \text{int} \Rightarrow \text{int} \Rightarrow \text{nat}$

assumes *QI_w*: $\llbracket i \leq i'; i' < j; j \leq j' \rrbracket \Longrightarrow$

$w \ i \ j + w \ i' \ j' \leq w \ i' \ j + w \ i \ j'$

assumes *monotone_w*: $\llbracket i \leq i'; i' < j; j \leq j' \rrbracket \Longrightarrow w \ i' \ j \leq w \ i \ j'$

assumes *c_def*: $i < j \Longrightarrow c \ i \ j = \text{Min} ((c \ k \ i \ j) \text{ ' } \{i+1..j\})$

assumes *c_k_def*: $\llbracket i < j; k \in \{i+1..j\} \rrbracket \Longrightarrow$

$c \ k \ i \ j \ k = w \ i \ j + c \ i \ (k-1) + c \ k \ j$

begin

abbreviation *mins* $i \ j \equiv \text{Args_min_on} \ (c \ k \ i \ j) \ \{i+1..j\}$

definition *K* $i \ j \equiv (\text{if } i = j \text{ then } i \text{ else } \text{Max} \ (\text{mins } i \ j))$

lemma *c_def_rec*:

$i < j \Longrightarrow c \ i \ j = \text{Min} ((\lambda k. c \ i \ (k-1) + c \ k \ j + w \ i \ j) \text{ ' } \{i+1..j\})$

using *c_def c_k_def* **by** (*auto simp: algebra_simps image_def*)

lemma *mins_subset*: $\text{mins } i \ j \subseteq \{i+1..j\}$

by (*auto simp: Args_min_simps*)

lemma *mins_nonempty*: $i < j \Longrightarrow \text{mins } i \ j \neq \{\}$

using *ex_is_arg_min_on_if_finite*[*OF finite_atLeastAtMost_int, of i+1 j c_k i j*]

by(*auto simp: Args_min_simps*)

lemma *finite_mins*: $\text{finite}(\text{mins } i \ j)$

by(*simp add: finite_subset[OF mins_subset]*)

lemma *is_arg_min_on_Min*:

assumes *finite A is_arg_min_on f A a* **shows** $\text{Min} \ (f \text{ ' } A) = f \ a$

proof –

from *assms*(2) **have** $f \text{ ' } A \neq \{\}$

by (*fastforce simp: is_arg_min_on_def*)

thus *?thesis* **using** *assms* **by** (*simp add: antisym is_arg_min_on_def*)

qed

lemma $c_k_with_K: i < j \implies c\ i\ j = c_k\ i\ j\ (K\ i\ j)$
using $Max_in[of\ mins\ i\ j]\ finite_mins[of\ i\ j]\ mins_nonempty[of\ i\ j]$
 $is_arg_min_on_Min[of\ \{i+1..j\}\ c_k\ i\ j]$
by (*auto simp: Args_min_simps c_def K_def*)

lemma $K_subset: assumes\ i \leq j\ shows\ K\ i\ j \in \{i..j\}$ **using** $mins_subset\ K_def$
proof *cases*

assume $i = j$
thus *?thesis*
using K_def **by** *auto*

next

assume $\neg i = j$
hence $K\ i\ j \in \{i+1..j\}$ **using** $mins_subset\ K_def\ \langle i \leq j \rangle$
by (*metis Max_in finite_mins less_le mins_nonempty subsetCE*)

thus *?thesis* **by** *auto*

qed

lemma $lemma_2:$

$\llbracket l = nat\ (j' - i); i \leq i'; i' \leq j; j \leq j' \rrbracket$
 $\implies c\ i\ j + c\ i'\ j' \leq c\ i\ j' + c\ i'\ j$

proof(*induction l arbitrary: i i' j j' rule:less_induct*)

case (*less l*)

show *?case*

proof *cases*

assume $l \leq 1$

hence $i = i' \vee j = j'$ **using** $less.prem\ by\ linarith$

thus *?case* **by** *auto*

next

assume $\neg l \leq 1$

show *?case*

proof *cases*

assume $i \geq i'$ **thus** *?thesis* **using** $less.prem\ by\ auto$

next

assume $\neg i \geq i'$

hence $i < i'$ **by** *simp*

show *?thesis*

proof *cases*

assume $j \geq j'$ **thus** *?thesis* **using** $less.prem\ by\ auto$

next

assume $\neg j \geq j'$

show *?thesis*

proof *cases*

assume $i' = j$

let $?k = K\ i\ j'$

have $?k \in \{i+1..j'\}$

unfolding K_def
using $mins_subset$ $Max_in[OF\ finite_mins\ mins_nonempty]$ $less.prem$ s
 $\langle \neg i' \leq i \rangle$
by ($smt\ subsetCE$)
show $?thesis$

proof cases
assume $?k \leq j$

have $a: c\ i\ j \leq w\ i\ j + c\ i\ (?k-1) + c\ ?k\ j$
proof –
have $c\ i\ j = Min\ ((\lambda k. c\ i\ (k-1) + c\ k\ j + w\ i\ j) \text{ ‘ } \{i+1..j\})$
using c_def_rec $\langle \neg i' \leq i \rangle$ $\langle i' = j \rangle$ **by** $auto$
also have $\dots \leq c\ i\ (?k-1) + c\ ?k\ j + w\ i\ j$
using $\langle ?k \in \{i+1..j'\} \rangle$ $\langle ?k \leq j \rangle$ **by** $simp$
finally show $?thesis$ **by** $simp$
qed

have $nat\ (j' - ?k) < l$ **using** $\langle ?k \in \{i+1..j'\} \rangle$ $less.prem$ s **by** $simp$
hence $b: c\ ?k\ j + c\ j\ j' \leq c\ ?k\ j' + c\ j\ j$
using $\langle ?k \leq j \rangle$ $less.prem$ s
 $less.IH$ [**where** $i = ?k$ **and** $i' = j$ **and** $j = j$ **and** $j' = j'$, OF_refl]
by $auto$

have $c\ i\ j + c\ i'\ j' = c\ i\ j + c\ j\ j'$ **by** ($simp\ add: \langle i' = j \rangle$)
also have $\dots \leq w\ i\ j + c\ i\ (?k-1) + c\ ?k\ j + c\ j\ j'$
using a **by** $auto$
also have $\dots \leq w\ i\ j' + c\ i\ (?k-1) + c\ ?k\ j + c\ j\ j'$
using $less.prem$ s $monotone_w$ $\langle i < i' \rangle$ **by** $simp$
also have $\dots \leq w\ i\ j' + c\ i\ (?k-1) + c\ ?k\ j' + c\ j\ j$
using b **by** $auto$
also have $\dots = c\ i\ j' + c\ j\ j$ **using** $\langle ?k \in \{i+1..j'\} \rangle$
by ($simp\ add: c_k_def\ c_k_with_K$)
finally show $?thesis$ **by** ($simp\ add: \langle i' = j \rangle$)

next

assume $\neg ?k \leq j$
hence $?k \in \{j+1..j'\}$ **using** $\langle ?k \in \{i+1..j'\} \rangle$ **by** $auto$
have $a: c\ j\ j' \leq w\ j\ j' + c\ j\ (?k-1) + c\ ?k\ j'$
proof –
have $c\ j\ j' = Min\ ((\lambda k. c\ j\ (k-1) + c\ k\ j' + w\ j\ j') \text{ ‘ } \{j+1..j'\})$
using c_def_rec $\langle \neg j' \leq j \rangle$ **by** $auto$
also have $\dots \leq c\ j\ (?k-1) + c\ ?k\ j' + w\ j\ j'$
using $\langle ?k \in \{j+1..j'\} \rangle$ **by** $simp$
finally show $c\ j\ j' \leq w\ j\ j' + c\ j\ (?k-1) + c\ ?k\ j'$ **by** $simp$
qed

have $nat\ ((?k-1) - i) < l$ **using** $\langle ?k \in \{i+1..j'\} \rangle$ $less.prem$ s **by** $simp$
hence $b: c\ i\ j + c\ j\ (?k-1) \leq c\ i\ (?k-1) + c\ j\ j$

using *less.prem*s $\langle \neg ?k \leq j \rangle$
less.IH[where $i=i$ and $i'=j$ and $j=j$ and $j'=(?k-1)$, *OF _ refl*]
 by *auto*

have $c\ i\ j + c\ i'\ j' = c\ i\ j + c\ j\ j'$ by (*simp add: $\langle i' = j \rangle$*)
 also have $\dots \leq w\ j\ j' + c\ j\ (?k-1) + c\ ?k\ j' + c\ i\ j$
 using *a* by *simp*
 also have $\dots \leq w\ i\ j' + c\ j\ (?k-1) + c\ ?k\ j' + c\ i\ j$
 using *less.prem*s *monotone_w* $\langle ?k \in \{j+1..j'\} \rangle$ by *simp*
 also have $\dots \leq w\ i\ j' + c\ i\ (?k-1) + c\ ?k\ j' + c\ j\ j$
 using *b* by *simp*
 also have $\dots \leq c\ i\ j' + c\ j\ j$
 using $\langle ?k \in \{i+1..j'\} \rangle$ by (*simp add: c_k_def c_k_with_K*)
 finally show *?thesis* by (*simp add: $\langle i' = j \rangle$*)

qed

next

assume $i' \neq j$
 let $?y = K\ i'\ j$
 let $?z = K\ i\ j'$
 have $?y \in \{i'+1..j\}$
 using *mins_subset less.prem*s $\langle i' \neq j \rangle$ *Max_in*[*OF finite_mins mins_nonempty*]
 unfolding *K_def* by (*metis le_less subsetCE*)
 have $?z \in \{i+1..j'\}$
 using *mins_subset less.prem*s $\langle i' \neq j \rangle$ *Max_in*[*OF finite_mins mins_nonempty*]
 unfolding *K_def* by (*smt subsetCE*)
 have *w_mon*: $w\ i'\ j' + w\ i\ j \leq w\ i'\ j + w\ i\ j'$
 using *less.prem*s *QI_w* $\langle i' \neq j \rangle$ by *force*

have $i' < j' \ i < j$ using $\langle i' \neq j \rangle$ *less.prem*s by *auto*
 show *?thesis*

proof cases

assume $?z \leq ?y$
 have $?y \in \{i'+1..j'\}$ using *less.prem*s $\langle ?y \in \{i'+1..j'\} \rangle$ by *simp*
 have $?z \in \{i+1..j'\}$ using $\langle ?z \in \{i+1..j'\} \rangle \langle ?z \leq ?y \rangle \langle ?y \in \{i'+1..j'\} \rangle$

by *simp*

have *a*: $c\ i'\ j' \leq w\ i'\ j' + c\ i'\ (?y-1) + c\ ?y\ j'$
 proof –
 have $c\ i'\ j' = \text{Min}((\lambda k. c\ i'\ (k-1) + c\ k\ j' + w\ i'\ j'))\ \{i'+1..j'\}$
 by (*simp add: c_def_rec*[*OF $\langle i' < j' \rangle$*])
 also have $\dots \leq w\ i'\ j' + c\ i'\ (?y-1) + c\ ?y\ j'$
 using $\langle ?y \in \{i'+1..j'\} \rangle$ by *simp*
 finally show *?thesis* .

qed

have *b*: $c\ i\ j \leq w\ i\ j + c\ i\ (?z-1) + c\ ?z\ j$
 proof –

have $c\ i\ j = \text{Min}((\lambda k. c\ i\ (k-1) + c\ k\ j + w\ i\ j) \text{ ‘}\{i+1..j\}\text{’})$
using $\langle i < j \rangle$ **by** (*simp add: c_def_rec*)
also have $\dots \leq w\ i\ j + c\ i\ (?z-1) + c\ ?z\ j$
using $\langle ?z \in \{i+1..j\} \rangle$ **by** *simp*
finally show *?thesis* .
qed

have $\text{nat}(j' - ?z) < l$ **using** $\langle ?z \in \{i+1..j\} \rangle$ *less.prem*s **by** *simp*
hence *IH_step*: $c\ ?z\ j + c\ ?y\ j' \leq c\ ?z\ j' + c\ ?y\ j$
using $\langle ?z \leq ?y \rangle \langle j \leq j' \rangle \langle ?y \in \{i'+1..j\} \rangle$
less.IH[**where** $i = ?z$ **and** $i' = ?y$ **and** $j = j$ **and** $j' = j'$, *OF_ refl*]
by *simp*

have $c\ i'\ j' + c\ i\ j$
 $\leq w\ i'\ j + w\ i\ j' + c\ i'\ (?y-1) + c\ i\ (?z-1) + c\ ?y\ j' + c\ ?z\ j$
using *a b w_mon* **by** *simp*
also have $\dots \leq w\ i\ j' + w\ i'\ j + c\ i'\ (?y-1) + c\ i\ (?z-1) + c\ ?y\ j +$
 $c\ ?z\ j'$
using *IH_step* **by** *auto*
also have $\dots = c\ i\ j' + c\ i'\ j$ **using** $\langle ?z \in \{i+1..j'\} \rangle \langle ?y \in \{i'+1..j\} \rangle$
by(*simp add: c_k_def c_k_with_K*)
finally show *?thesis* **by** *linarith*
next

assume $\neg ?z \leq ?y$

have $?y \in \{i+1..j\}$ **using** *less.prem*s $\langle ?y \in \{i'+1..j\} \rangle$ **by** *simp*
have $?z \in \{i'+1..j'\}$ **using** $\langle ?z \in \{i+1..j'\} \rangle \langle \neg ?z \leq ?y \rangle \langle ?y \in \{i'+1..j\} \rangle$
by *simp*

have $a: c\ i'\ j' \leq w\ i'\ j' + c\ i'\ (?z-1) + c\ ?z\ j'$
proof –
have $c\ i'\ j' = \text{Min}((\lambda k. c\ i'\ (k-1) + c\ k\ j' + w\ i'\ j') \text{ ‘}\{i'+1..j'\}\text{’})$
using $\langle i' < j' \rangle$ **by**(*simp add: c_def_rec*)
also have $\dots \leq w\ i'\ j' + c\ i'\ (?z-1) + c\ ?z\ j'$
using $\langle ?z \in \{i'+1..j'\} \rangle$ **by** *simp*
finally show *?thesis* .
qed

have $b: c\ i\ j \leq w\ i\ j + c\ i\ (?y-1) + c\ ?y\ j$
proof –
have $c\ i\ j = \text{Min}((\lambda k. c\ i\ (k-1) + c\ k\ j + w\ i\ j) \text{ ‘}\{i+1..j\}\text{’})$
using $\langle i < j \rangle$ **by**(*simp add: c_def_rec*)
also have $\dots \leq w\ i\ j + c\ i\ (?y-1) + c\ ?y\ j$
using $\langle ?y \in \{i+1..j\} \rangle$ **by** *simp*
finally show *?thesis* .
qed

have $\text{nat}(?z - 1 - i) < l$ **using** $\langle ?z \in \{i'+1..j'\} \rangle$ *less.prem*s **by** *simp*

hence IH_Step : $c\ i\ (?y-1) + c\ i'\ (?z-1) \leq c\ i'\ (?y-1) + c\ i\ (?z-1)$
using $\langle ?y \in \{i'+1..j\} \rangle \langle \neg ?z \leq ?y \rangle \langle i \leq i' \rangle$
less.IH[**where** $i=i$ **and** $i'=i'$ **and** $j=?y-1$ **and** $j'=?z-1$, *OF_ refl*]
by *simp*

have $c\ i'\ j' + c\ i\ j$
 $\leq w\ i'\ j + w\ i\ j' + c\ i'\ (?z-1) + c\ i\ (?y-1) + c\ ?z\ j' + c\ ?y\ j$
using *a b w_mon* **by** *simp*

also have $\dots \leq w\ i'\ j + w\ i\ j' + c\ i\ (?z-1) + c\ i'\ (?y-1) + c\ ?z\ j' +$
 $c\ ?y\ j$
using IH_Step **by** *auto*

also have $\dots = c\ i\ j' + c\ i'\ j$ **using** $\langle ?z \in \{i+1..j'\} \rangle \langle ?y \in \{i'+1..j\} \rangle$
by(*simp add: c_k_def c_k_with_K*)
finally show $?thesis$ **by** *linarith*

qed
qed
qed
qed
qed

corollary QI' : **assumes** $i < k\ k \leq k'\ k' \leq j\ c_k\ i\ j\ k' \leq c_k\ i\ j\ k$
shows $c_k\ i\ (j+1)\ k' \leq c_k\ i\ (j+1)\ k$
proof –
have $c\ k\ j + c\ k'\ (j+1) \leq c\ k'\ j + c\ k\ (j+1)$
using *lemma_2[of_ j+1 k k' j] assms(1-3)* **by** *fastforce*

hence $c_k\ i\ j\ k + c_k\ i\ (j+1)\ k' \leq c_k\ i\ j\ k' + c_k\ i\ (j+1)\ k$
using *assms(1-3) c_k_def* **by** *simp*

thus $c_k\ i\ (j+1)\ k' \leq c_k\ i\ (j+1)\ k$
using *assms(4)* **by** *simp*

qed

corollary QI'' : **assumes** $i+1 < k\ k \leq k'\ k' \leq j+1\ c_k\ i\ (j+1)\ k' \leq c_k\ i\ (j+1)$
 k
shows $c_k\ (i+1)\ (j+1)\ k' \leq c_k\ (i+1)\ (j+1)\ k$
proof –
have $c\ i\ k + c\ (i+1)\ k' \leq c\ i\ k' + c\ (i+1)\ k$
using *lemma_2[of_ k' i i+1 k] assms(1,2)* **by** *fastforce*

hence $c_k\ i\ (j+1)\ k + c_k\ (i+1)\ (j+1)\ k' \leq c_k\ i\ (j+1)\ k' + c_k\ (i+1)\ (j+1)$
 k
using *c_k_def assms(1-3) lemma_2* **by** *simp*

thus $c_k\ (i+1)\ (j+1)\ k' \leq c_k\ (i+1)\ (j+1)\ k$
using *assms(4)* **by** *simp*

qed


```

lemma lemma_3_1: assumes  $i \leq j$  shows  $K\ i\ j \leq K\ i\ (j+1)$ 
proof cases
  assume  $i = j$ 
  thus ?thesis
    by (metis  $K\_def$   $K\_subset$   $atLeastAtMost\_iff$   $less\_add\_one$   $less\_le$ )
next
  assume  $i \neq j$ 
  hence  $i < j$  using  $\langle i \leq j \rangle$  by simp

  let ?k =  $K\ i\ (j+1)$ 
  have  $K\ i\ j \in \{i+1..j\}$  using  $K\_def$ 
    by (metis  $Max\_in$   $\langle i < j \rangle$   $mins\_nonempty[OF\ \langle i < j \rangle]$   $finite\_mins$   $less\_le$ 
     $mins\_subset$   $subsetCE$ )

  have  $i < j+1$  using  $\langle i < j \rangle$  by linarith
  hence  $K\ i\ (j+1) \in \{i+1..j+1\}$ 
    by (metis  $Max\_in$   $K\_def$   $mins\_nonempty[OF\ \langle i < j+1 \rangle]$   $finite\_mins$   $less\_le$ 
     $mins\_subset$   $subsetCE$ )

  have *:  $is\_arg\_min\_on\ (c\_k\ i\ (j+1))\ \{i+1..j+1\}\ ?k$ 
  proof -
    have  $K\ i\ (j+1) \in mins\ i\ (j+1)$  using  $finite\_mins$   $mins\_nonempty\ \langle i < j \rangle$ 
     $K\_def$  by fastforce
    thus  $is\_arg\_min\_on\ (c\_k\ i\ (j+1))\ \{i+1..j+1\}\ (K\ i\ (j+1))$ 
      unfolding  $Args\_min\_simps$  by blast
  qed
  show ?thesis
  proof cases
    assume  $?k = j+1$  thus ?thesis using  $\langle K\ i\ j \in \{i+1..j\} \rangle$  by simp
  next
    assume  $?k \neq j+1$ 
    hence  $?k \in \{i+1..j\}$  using  $\langle K\ i\ (j+1) \in \{i+1..j+1\} \rangle$  by auto
    have  $i \neq j\ i \neq j+1$  using  $\langle i < j \rangle$  by auto
    hence  $K\_simps: K\ i\ j = Max\ (mins\ i\ j)\ K\ i\ (j+1) = Max\ (mins\ i\ (j+1))$ 
      unfolding  $K\_def$  by auto
    show ?thesis unfolding  $K\_simps$ 
      proof (rule  $Max.boundedI[OF\ finite\_mins\ mins\_nonempty[OF\ \langle i < j \rangle]]$ )
        fix  $k'$  assume  $k': k' \in mins\ i\ j$ 
        show  $k' \leq Max\ (mins\ i\ (j+1))$ 
          proof (rule  $ccontr$ )
            assume  $\sim k' \leq Max\ (mins\ i\ (j+1))$ 
            have  $c\_k\ i\ (j+1)\ k' \leq c\_k\ i\ (j+1)\ ?k$  unfolding  $K\_simps$ 
            proof (rule  $QI'$ )
              show  $i < Max\ (mins\ i\ (j+1))$ 
                using  $\langle K\ i\ (j+1) \in \{i+1..j+1\} \rangle$   $K\_simps$  by auto
              show  $Max\ (mins\ i\ (j+1)) \leq k'$  using  $\langle \sim k' \leq Max\ (mins\ i\ (j+1)) \rangle$ 
                by linarith
              show  $k' \leq j$  using  $mins\_subset\ atLeastAtMost\_iff\ k'$  by blast
            qed
          qed
      qed
  qed

```

```

    show  $c\_k\ i\ j\ k' \leq c\_k\ i\ j\ (Max\ (mins\ i\ (j + 1)))$ 
      using  $k' \in \{i+1..j\}$  by (simp add:  $K\_simps\ Args\_min\_simps$ )
  qed

  hence  $is\_arg\_min\_on\ (c\_k\ i\ (j+1))\ \{i+1..j+1\}\ k'$ 
    apply (rule  $is\_arg\_min\_on\_antimono[OF\ *]$ )
    using  $mins\_subset\ k'$  by fastforce
  hence  $k' \in mins\ i\ (j+1)$  using  $k'$  by (auto simp:  $Args\_min\_on\_def$ )
  thus  $False$  using  $finite\_mins\ \neg\ k' \leq Max\ (mins\ i\ (j + 1))$  by auto
  qed
  qed
  qed
  qed

lemma lemma_3_2: assumes  $i \leq j$  shows  $K\ i\ (j+1) \leq K\ (i+1)\ (j+1)$ 
proof cases
  assume  $i = j$ 
  thus ?thesis
    by (metis  $K\_def\ K\_subset\ atLeastAtMost\_iff\ less\_add\_one\ less\_le$ )
next
  assume  $i \neq j$ 
  hence  $i < j$  using  $i \leq j$  by simp
  let ?k =  $K\ (i+1)\ (j+1)$ 
  have  $K\ i\ (j+1) \in \{i+1..j+1\}$  unfolding  $K\_def$ 
    by (metis  $Max\_in\ i < j\ finite\_mins\ less\_irrefl\ mins\_nonempty\ mins\_subset\ subsetCE\ zless\_add1\_eq$ )

  have  $i+1 < j+1$  using  $i < j$  by linarith
  hence  $K\ (i+1)\ (j+1) \in \{i+1+1..j+1\}$ 
    using  $mins\_nonempty[OF\ i+1 < j+1]\ mins\_subset\ Max\_in\ K\_def\ finite\_mins$ 
    by (metis  $atLeastatMost\_empty\ atLeastatMost\_empty\_iff2\ contra\_subsetD\ empty\_subsetI\ less\_add\_one\ psubsetI$ )

  have *:  $is\_arg\_min\_on\ (c\_k\ (i+1)(j+1))\ \{i+1+1..j+1\}\ ?k$ 
  proof -
    have  $K\ (i+1)\ (j+1) \in mins\ (i+1)\ (j+1)$ 
      using  $finite\_mins\ mins\_nonempty\ i + 1 < j + 1$  unfolding  $K\_def$ 
      by (metis  $Max\_in\ not\_less\_iff\_gr\_or\_eq$ )
    thus  $is\_arg\_min\_on\ (c\_k\ (i+1)\ (j+1))\ \{i+1+1..j+1\}\ (K\ (i+1)\ (j+1))$ 
      unfolding  $Args\_min\_on\_def$  by blast
  qed
  qed
  show ?thesis
  proof cases
    assume  $?k = j+1$  thus ?thesis using  $K\ i\ (j+1) \in \{i+1..j+1\}$  by simp
  next
    assume  $?k \neq j+1$ 
    hence  $?k \in \{i+1+1..j\}$  using  $K\ (i+1)\ (j+1) \in \{i+1+1..j+1\}$  by auto

    have  $i \neq j+1\ i+1 \neq j+1$  using  $i < j$  by auto

```

```

hence  $K\_simps$ :  $K\ i\ (j+1) = Max\ (mins\ i\ (j+1))$ 
            $K\ (i+1)\ (j+1) = Max\ (mins\ (i+1)\ (j+1))$ 
  unfolding  $K\_def$  by auto
have  $i < j+1$  using  $\langle i+1 < j+1 \rangle$  by simp

show ?thesis unfolding  $K\_simps$ 
proof (rule  $Max.boundedI[OF\ finite\_mins\ mins\_nonempty[OF\ \langle i < j+1 \rangle]]$ )
  fix  $k'$  assume  $k': k' \in mins\ i\ (j+1)$ 
  show  $k' \leq Max\ (mins\ (i+1)\ (j+1))$ 
  proof (rule ccontr)
    assume  $\sim k' \leq Max\ (mins\ (i+1)(j+1))$ 
    have  $c\_k\ (i+1)\ (j+1)\ k' \leq c\_k\ (i+1)\ (j+1)\ ?k$  unfolding  $K\_simps$ 
      thm  $QI'$ [of  $i+1\ Max(mins\ (i+1)(j+1))\ k'\ j$ ]
    proof (rule  $QI''$ )
      show  $i+1 < Max\ (mins\ (i+1)(j+1))$ 
        using  $\langle K\ (i+1)\ (j+1) \in \{i+1+1..j+1\} \rangle\ K\_simps$ 
        by auto
      show  $Max\ (mins\ (i+1)\ (j+1)) \leq k'$ 
        using  $\langle \sim k' \leq Max\ (mins\ (i+1)(j+1)) \rangle\ K\_simps$  by linarith
      show  $k' \leq j+1$ 
        using  $mins\_subset\ k'$  by fastforce
      show  $c\_k\ i\ (j+1)\ k' \leq c\_k\ i\ (j+1)\ (Max\ (mins\ (i+1)\ (j+1)))$ 
        using  $k' \langle ?k \in \{(i+1)+1..j+1\} \rangle\ K\_simps$ 
        by (simp add:  $Args\_min\_simps$ )
    qed
  qed

hence  $is\_arg\_min\_on\ (c\_k\ (i+1)\ (j+1))\ \{i+1+1..j+1\}\ k'$ 
  apply (rule  $is\_arg\_min\_on\_antimono[OF\ *]$ )
  using  $mins\_subset\ k'\ K\_simps\ \langle ?k \in \{i+1+1..j\} \rangle$ 
     $\langle \neg k' \leq Max\ (mins\ (i+1)\ (j+1)) \rangle\ atLeastAtMost\_iff$ 
  by force
hence  $k' \in mins\ (i+1)\ (j+1)$  by (simp add:  $k'\ Args\_min\_on\_def$ )
thus False using  $finite\_mins\ \langle \neg k' \leq Max\ (mins\ (i+1)(j+1)) \rangle\ Max\_ge$ 
  by blast
qed
qed
qed
qed

lemma lemma_3: assumes  $i \leq j$ 
  shows  $K\ i\ j \leq K\ i\ (j+1)\ K\ i\ (j+1) \leq K\ (i+1)\ (j+1)$ 
  using  $assms\ lemma\_3\_1\ lemma\_3\_2$  by blast+

end

end

```

5 Optimal BSTs: The ‘Quadratic’ Algorithm

```

theory Optimal_BST2
imports
  Optimal_BST
  Quadrilateral_Inequality
begin

```

Knuth presented an optimization of the previously known cubic dynamic programming algorithm to a quadratic one. A simplified proof of this optimization was found by Yao [4]. Mehlhorn follows Yao closely. The core of the optimization argument is given abstractly in theory *Optimal_BST.Quadrilateral_Inequality*. In addition we first need to establish some more properties of *argmin*.

An index-based specification of *argmin* expressing that the last minimal list-element is picked:

```

lemma argmin_takes_last:  $xs \neq [] \implies$ 
   $argmin\ f\ xs = xs\ !\ Max\ \{i.\ i < length\ xs \wedge (\forall x \in set\ xs.\ f(xs!i) \leq f\ x)\}$ 
  (is  $\_ \implies \_ = \_ !\ Max\ (?M\ xs)$ )
proof(induction xs)
  case (Cons x xs)
  show ?case
  proof cases
    assume  $xs = []$  thus ?thesis by(simp cong: conj_cong)
  next
    assume  $0: xs \neq []$ 
    show ?thesis
    proof cases
      assume  $1: \forall u \in set\ xs.\ f\ x < f\ u$ 
      hence  $2: ?M\ (x\#\ xs) = \{0\}$ 
      by (fastforce simp: not_less[symmetric] less_Suc_eq_0_disj)
      have  $f\ x < f\ (argmin\ f\ xs)$  using  $0\ 1$  argmin_Min[of xs f] by auto
      with  $1$  Cons.prem show ?case by(subst 2) (auto simp: Let_def)
    next
      assume  $1: \neg(\forall u \in set\ xs.\ f\ x < f\ u)$ 
      have  $2: \neg f\ x < f\ (argmin\ f\ xs)$  using  $1$  argmin_Min[of xs f]  $0$  by auto
      have  $argmin\ f\ xs : \{u \in set\ xs.\ \forall x \in set\ xs.\ f\ u \leq f\ x\}$ 
      using  $0$  argmin_Min[of xs f] by (simp add: argmin_in)
      hence  $\{u \in set\ xs.\ \forall x \in set\ xs.\ f\ u \leq f\ x\} \neq \{\}$  by blast
      hence  $ne: ?M\ xs \neq \{\}$  by(auto simp: in_set_conv_nth)
      have  $Max\ (?M\ (x\#\ xs)) = Max\ (?M\ xs) + 1$ 
      proof (cases  $\exists u \in set\ xs.\ f\ u < f\ x$ )
        case True
          hence  $?M\ (x\#\ xs) = (+)\ 1\ \text{'}\ ?M\ xs$ 
          by (auto simp: nth_Cons' image_def less_Suc_eq_0_disj)
        thus ?thesis
        using mono_Max_commute[of  $(+)\ 1\ ?M\ xs$ ]  $ne$  by (auto simp: mono_def)
      next

```

```

    case False
    hence *:  $?M (x\#xs) = \text{insert } 0 ((+) 1 \text{ ' } ?M xs)$ 
      using 1 by (auto simp: nth_Cons' image_def less_Suc_eq_0_disj)
    hence  $\text{Max } (?M (x\#xs)) = \text{Max } ((+) 1 \text{ ' } ?M xs)$  using Max_insert ne by
simp
    thus ?thesis using mono_Max_commute[of (+) 1 ?M xs] ne by (auto simp:
mono_def)
    qed
    with Cons 2 0 show ?case by auto
    qed
    qed
  qed simp

```

lemma *Min_ex*: $\llbracket \text{finite } F; F \neq \{\} \rrbracket \implies \exists m \in F. \forall n \in F. m \leq (n::\text{::linorder})$
using *eq_Min_iff*[of *F Min F*] **by** (*fastforce*)

A consequence of *argmin_takes_last*:

lemma *argmin_Max_Args_min_on*: **assumes** [*arith*]: $i \leq j$
shows $\text{argmin } f [i..j] = \text{Max } (\text{Args_min_on } f \{i..j\})$

proof –

```

let ?min =  $\lambda k. \forall n \in \{i..j\}. f([i..j]!k) \leq f n$ 
let ?M =  $\{k. k < \text{nat}(j-i+1) \wedge ?min k\}$ 
let ?Max =  $\text{Max } ?M$ 
have  $?M \neq \{\}$  using Min_ex[of f ' {i..j}]
  apply (auto simp add: nth_upto)
  apply (rule_tac  $x = \text{nat } (m-i)$  in exI)
  by simp
hence  $?Max < \text{nat}(j-i+1)$  by (simp add: nth_upto)
hence 1:  $i + \text{int } ?Max \leq j$  by linarith
have  $\text{argmin } f [i..j] = [i..j] ! ?Max$ 
  using argmin_takes_last[of  $[i..j] f$ ] by simp
also have  $\dots = i + \text{int } ?Max$  using 1 by (simp add: nth_upto)
also have  $\dots = i + \text{Max } (\text{int ' } \{k. k < \text{nat}(j-i+1) \wedge ?min k\})$ 
  using  $\langle ?M \neq \{\} \rangle$  by (simp add: monoI mono_Max_commute)
also have  $\dots = \text{Max } ((\lambda x. i + x) \text{ ' } (\text{int ' } \{k. k < \text{nat}(j-i+1) \wedge ?min k\}))$ 
  using  $\langle ?M \neq \{\} \rangle$  by (simp add: monoI mono_Max_commute)
also have  $(\lambda x. i + x) \text{ ' } (\text{int ' } \{k. k < \text{nat}(j-i+1) \wedge ?min k\}) =$ 
 $\{k. \text{is\_arg\_min\_on } f \{i..j\} k\}$ 
  apply (auto simp: is_arg_min_on_def Ball_def nth_upto image_def cong:
conj_cong)
  apply (rule_tac  $x = x-i$  in exI)
  apply auto
  apply (rule_tac  $x = \text{nat}(x-i)$  in exI)
  by auto
finally show ?thesis by (simp add: Args_min_simps)
qed

```

As a consequence of *argmin_Max_Args_min_on* the following lemma allows us to justify the restriction of the index range of *argmin* used below in the optimized (quadratic) algorithm.

```

lemma argmin_red_ivl:
assumes  $i \leq i'$   $\text{argmin } f [i..j] \in \{i'..j\}$   $j' \leq j$ 
shows  $\text{argmin } f [i'..j'] = \text{argmin } f [i..j]$ 
proof -
  have  $ij[\text{arith}]$ :  $i \leq j$  using assms by simp
  have  $ij'[\text{arith}]$ :  $i' \leq j'$  using assms by simp
  from Min_ex[of f ' {i..j}] have  $m$ :  $\exists m \in \{i..j\}. \forall n \in \{i..j\}. f m \leq f n$  by auto
  note  $*$  = argmin_Max_Args_min_on[OF ij, of f]
  note  $**$  = argmin_Max_Args_min_on[OF ij', of f]
  let  $?M = \text{Args\_min\_on } f \{i..j\}$ 
  let  $?M' = \text{Args\_min\_on } f \{i'..j'\}$ 
  have  $M$ : finite  $?M$   $?M \neq \{\}$ 
    using  $m$  by (fastforce simp: Args_min_simps simp del: atLeastAtMost_iff)+
  have  $\text{Max } ?M \in ?M$  by (simp add: M)
  have  $\text{Max } ?M \in ?M'$  using Max_in[OF M] assms  $*$  by (auto simp: Args_min_simps)
  have  $?M' \subseteq ?M$  using  $\langle \text{Max } ?M \in ?M \rangle \langle \text{Max } ?M \in ?M' \rangle$  assms(1,3)
    by(force simp add: Args_min_simps Ball_def)
  have finite  $?M'$  using  $M(1) \langle ?M' \subseteq ?M \rangle$  infinite_super by blast
  hence  $\text{Max } ?M \leq \text{Max } ?M'$  by (simp add: \langle Max ?M \in ?M' \rangle)
  have  $\text{Max } ?M' \leq \text{Max } ?M$  using Max_subset_imp[OF \langle ?M' \subseteq ?M \rangle _ M(1)]
   $\langle \text{Max } ?M \in ?M' \rangle$  by auto
  thus  $?thesis$  using  $**$   $\langle \text{Max } ?M \leq \text{Max } ?M' \rangle$  by force
qed

```

```

fun root:: 'a tree  $\Rightarrow$  'a where
root  $\langle \_, r, \_ \rangle = r$ 

```

Now we can formulate and verify the improved algorithm. This requires two assumptions on the weight function w .

```

locale Optimal_BST2 = Optimal_BST +
assumes monotone_w:  $\llbracket i \leq i'; i' \leq j; j \leq j' \rrbracket \Longrightarrow w i' j \leq w i j'$ 
assumes QL_w:  $\llbracket i \leq i'; i' \leq j; j \leq j' \rrbracket \Longrightarrow w i j + w i' j' \leq w i' j + w i j'$ 
begin

```

When finding an optimal tree for $[i..j]$ the optimization consists in reducing the search for the root from $[i..j]$ to $[\text{root } (\text{opt_bst2 } i (j - (1::'b))).. \text{root } (\text{opt_bst2 } (i + (1::'a)) j)]$:

```

function opt_bst2 :: int  $\Rightarrow$  int  $\Rightarrow$  int tree where
opt_bst2  $i j =$ 
  (if  $i > j$  then Leaf else
   if  $i = j$  then Node Leaf i Leaf else
   let  $\text{left} = \text{root } (\text{opt\_bst2 } i (j-1))$  in
   let  $\text{right} = \text{root } (\text{opt\_bst2 } (i+1) j)$  in
    $\text{argmin } (\text{wpl } i j) [\langle \text{opt\_bst2 } i (k-1), k, \text{opt\_bst2 } (k+1) j \rangle. k \leftarrow [\text{left}.. \text{right}]]$ )
by auto

```

The termination of *opt_bst2* is not completely obvious. We first need to establish some functional properties of the terminating computations. We start by showing that the root of the returned tree is always between *left*

and *right*. This is essentially equivalent to proving that $left \leq right$ because otherwise *argmin* is applied to [], which is undefined.

lemma *left_le_right*:

opt_bst2_dom(i,j) \implies
(i=j \implies root(opt_bst2 i j) = i) \wedge
(i<j \implies root(opt_bst2 i j) \in {root(opt_bst2 i (j-1)) .. root(opt_bst2 (i+1) j)})

proof (*induction rule: opt_bst2.pinduct*)

case (1 i j)

let ?left = root (opt_bst2 i (j-1))

let ?right = root (opt_bst2 (i+1) j)

let ?f = ($\lambda k. \langle opt_bst2\ i\ (k - 1),\ k,\ opt_bst2\ (k + 1)\ j \rangle$)

show ?case

proof *cases*

assume $i > j$ **thus** ?thesis **by** *auto*

next

assume [*arith*]: $\neg i > j$

show ?thesis

proof *cases*

assume $i = j$ **thus** ?thesis **using** *opt_bst2.psimps[OF 1.hyps]* **by** *simp*

next

assume [*arith*]: $i \neq j$

have *left_le_right*: ?left \leq ?right

proof *cases*

assume [*arith*]: $i = j - 1$

have *l*: root (opt_bst2 i (j - 1)) = i **using** 1.IH(1) **by** *auto*

have *r*: root (opt_bst2 (i+1) j) = j **using** 1.IH(2) **by** *auto*

show ?thesis **using** *l r* **by** *auto*

next

assume $\neg i = j - 1$

hence[*arith*]: $i < j - 1$ **by** *arith*

have ?left \leq root (opt_bst2 (i + 1) (j - 1)) **using** 1.IH(1) **by** *auto*

also have ... \leq root (opt_bst2 (i+1) j) **using** 1.IH(2) **by** *auto*

finally have ?left \leq ?right .

thus ?thesis **by** *auto*

qed

let ?lambda = $\lambda t. \text{root } t \in \{ ?left .. ?right \}$

show ?thesis

using *argmin_forall[of $\langle \text{map } ?f [?left .. ?right] \rangle \langle ?lambda \rangle \langle \text{wpl } i\ j \rangle$]* *left_le_right*
by (*fastforce simp add: opt_bst2.psimps[OF 1.hyps]*)

qed

qed

qed

Now we can bound the result of *opt_bst2* easily:

lemma *root_opt_bst2_bound*:

opt_bst2_dom (i,j) $\implies i \leq j \implies$ root (opt_bst2 i j) $\in \{i..j\}$

proof(*induction i j rule:opt_bst2.pinduct*)

case (1 i j)

show *?case* **using** *1.prem*s 1.IH(1,2) *left_le_right*[OF 1.hyps] **by** *force*
qed

Now termination follows easily:

lemma *opt_bst2_dom*: \forall *args*. *opt_bst2_dom args*
by (*relation measure* ($\lambda(i,j). \text{nat } (j-i+1)$)) (*auto dest*: *root_opt_bst2_bound*)

termination **by**(*rule opt_bst2_dom*)

declare *opt_bst2.simps*[*simp del*]

abbreviation *min_wpl3* *i j k* \equiv *min_wpl* *i (k-1) + min_wpl (k+1) j + w i j*

The correctness proof [?] is based on a general theory of ‘quadrilateral inequalities’ developed in locale QI that we now instantiate:

interpretation *QI*

where

c = $\lambda i j. \text{min_wpl } (i+1) j$
and *c_k* = $\lambda i j. \text{min_wpl3 } (i+1) j$
and *w* = $\lambda i j. w (i+1) j$

proof (*standard, goal_cases*)

case (1 *i i' j j'*)

thus *?case* **using** *QI_w* **by** *simp*

next

case (2 *i i' j j'*)

thus *?case* **using** *monotone_w* **by** *simp*

next

case (3 *i j*)

thus *?case* **by** *simp*

next

case (4 *i j k*)

show *?case* **by** *simp*

qed

lemma *K_argmin*: $i < j \implies K i j = \text{argmin } (\text{min_wpl3 } (i+1) j) [i+1..j]$
by(*simp add*: *K_def argmin_Max_Args_min_on Args_min_on_def*)

theorem *opt_bst2_opt_bst*: *opt_bst2 i j = opt_bst i j*

proof (*induction i j rule*: *opt_bst2.induct*)

case (1 *i j*)

show *?case*

proof *cases*

assume $i \geq j$ **thus** *?thesis* **by**(*cases i=j*) (*auto simp*: *opt_bst2.simps*)

next

assume [*arith*]: $\neg i \geq j$

let *?c* = $\lambda k. \text{min_wpl } i (k-1) + \text{min_wpl } (k+1) j + w i j$

let *?opt* = $\lambda k. \langle \text{opt_bst } i (k-1), k, \text{opt_bst } (k+1) j \rangle$

have 1: $i \leq K (i-1) (j-1)$

using *argmin_in*[of [*i..j-1*]] **by**(*auto simp add*: *K_argmin*)


```

have 2: argmin ?c [i..j] ∈ {K (i-1) (j-1)..K i j}
  using lemma_3[of i-1 j-1] by(simp add: K_argmin)
have 3: K i j ≤ j using argmin_in[of [i+1..j]] by(auto simp: K_argmin)
have *: argmin ?c [K (i-1) (j-1)..K i j] = argmin ?c [i..j]
  by(rule argmin_red_ivl[OF 1 2 3])
have opt_bst2 i j =
  argmin (wpl i j) (map ?opt [root(opt_bst2 i (j-1))..root(opt_bst2 (i+1) j)])
  using [[simp_depth_limit=3]]
by(simp add: 1.IH(3,4)[OF _ _ refl refl] opt_bst2.simps[of i j] cong: list.map_cong_simp)
also have ... = argmin (wpl i j) (map ?opt [root(opt_bst i (j-1))..root(opt_bst
(i+1) j)])
  by (simp add: 1.IH(1,2))
also have root(opt_bst i (j-1)) = K (i-1) (j-1)
  by(simp add: argmin_map wpl_opt_bst_comp_def K_argmin)
also have root(opt_bst (i+1) j) = K i j
  by(simp add: argmin_map wpl_opt_bst_comp_def K_argmin)
also have argmin (wpl i j) (map ?opt [K (i-1) (j-1)..K i j])
  = ?opt (argmin (wpl i j o ?opt) [K (i-1) (j-1)..K i j])
  using lemma_3[of i-1 j-1] by(simp add: argmin_map)
also have ... = ?opt (argmin ?c [K (i-1) (j-1)..K i j])
  by(simp add: comp_def wpl_opt_bst)
also have ... = ?opt(argmin ?c [i..j])
  by (simp add: *)
also have ... = ?opt(argmin (wpl i j o ?opt) [i..j])
  by(simp add: comp_def wpl_opt_bst)
also have ... = argmin (wpl i j) (map ?opt [i..j])
  by(simp add: argmin_map)
also have ... = opt_bst i j
  by simp
finally show ?thesis .
qed
qed

```

corollary *opt_bst2_is_optimal*: $wpl\ i\ j\ (opt_bst2\ i\ j) = min_wpl\ i\ j$
by (simp add: *opt_bst2_opt_bst wpl_opt_bst*)

function *opt_bst_wpl2* :: $int \Rightarrow int \Rightarrow int\ tree \times nat$ **where**
opt_bst_wpl2 i j =
 (if i > j then (Leaf,0) else
 if i = j then (Node Leaf i Leaf, w i i) else
 let l = root(fst(*opt_bst_wpl2* i (j-1)));
 r = root(fst(*opt_bst_wpl2* (i+1) j)) in
 argmin snd
 [let (tl,wl) = *opt_bst_wpl2* i (k-1); (tr,wr) = *opt_bst_wpl2* (k+1) j
 in ((tl, k, tr), wl + wr + w i j) . k ← [l..r]])
by *auto*

lemma *left_le_right2*:

```

opt_bst_wpl2_dom(i,j) ==>
(i=j -> root(fst(opt_bst_wpl2 i j)) = i) ^
(i<j -> root(fst(opt_bst_wpl2 i j)) ∈
  {root(fst(opt_bst_wpl2 i (j-1))) .. root(fst(opt_bst_wpl2 (i+1) j))})
proof (induction rule: opt_bst_wpl2.pinduct)
case (1 i j)
let ?l = root (fst(opt_bst_wpl2 i (j-1)))
let ?r = root (fst(opt_bst_wpl2 (i+1) j))
let ?f = λk. let (tl,wl) = opt_bst_wpl2 i (k-1); (tr,wr) = opt_bst_wpl2 (k+1) j
  in ((tl, k, tr), wl + wr + w i j)
show ?case
proof cases
  assume i > j thus ?thesis by auto
next
  assume [arith]: ¬ i > j
  show ?thesis
  proof cases
    assume i = j thus ?thesis using opt_bst_wpl2.psimps[OF 1.hyps] by simp
  next
    assume [arith]: i ≠ j
    have left_le_right: ?l ≤ ?r
    proof cases
      assume [arith]: i = j-1
      have l: root (fst(opt_bst_wpl2 i (j-1))) = i using 1.IH(1) by auto
      have r: root (fst(opt_bst_wpl2 (i+1) j)) = j using ⟨i = j-1⟩ 1.IH(2)
        by auto
      show ?thesis using l r by auto
    next
      assume ¬ i = j-1
      hence[arith]: i < j-1 by arith
      have ?l ≤ root (fst(opt_bst_wpl2 (i+1) (j-1))) using 1.IH(1) by auto
      also have ... ≤ root (fst(opt_bst_wpl2 (i+1) j)) using 1.IH(2) by auto
      finally have ?l ≤ ?r .
      thus ?thesis by auto
    qed

let ?P = λt. root (fst t) ∈ {?l .. ?r}
show ?thesis
  using argmin_forall[of ⟨map ?f [?l..?r]⟩ ?P snd] left_le_right
  by (fastforce simp add: opt_bst_wpl2.psimps[OF 1.hyps] split: prod.splits)
qed
qed
qed

```

Now we can bound the result of `opt_bst_wpl2`:

```

lemma root_opt_bst_wpl2_bound:
  opt_bst_wpl2_dom (i,j) ==> i ≤ j ==> root (fst(opt_bst_wpl2 i j)) ∈ {i..j}
proof(induction i j rule:opt_bst_wpl2.pinduct)
  case (1 i j)

```

```

show ?case using 1.prem1 1.IH(1) 1.IH(2)[OF ___ refl] left_le_right2[OF
1.hyps]
by fastforce
qed

```

Now termination follows easily:

```

lemma opt_bst_wpl2_dom:  $\forall$  args. opt_bst_wpl2_dom args
by (relation measure ( $\lambda(i,j). \text{nat } (j-i+1)$ )) (auto dest: root_opt_bst_wpl2_bound)

```

```

termination by(rule opt_bst_wpl2_dom)

```

```

declare opt_bst_wpl2.simps[simp del]

```

```

lemma opt_bst_wpl2_eq_pair:
  opt_bst_wpl2 i j = (opt_bst2 i j, wpl i j (opt_bst2 i j))
proof(induction i j rule: opt_bst_wpl2.induct)
  case (1 i j)
  note [simp] = opt_bst2.simps[of i j] opt_bst_wpl2.simps[of i j]
  show ?case
  proof cases
    assume  $i > j$  thus ?thesis using 1.prem1 by (simp)
  next
    assume [arith]:  $\neg i > j$ 
    show ?case
    proof cases
      assume [arith]:  $i = j$ 
      show ?thesis by(simp) (simp add:  $\langle i = j \rangle$ )
    next
      assume [arith]:  $i \neq j$ 
      let ?l = root (opt_bst2 i (j-1)) let ?r = root (opt_bst2 (i+1) j)
      have *: ?l  $\leq$  ?r
      using left_le_right[of i j] by (fastforce simp: opt_bst2_opt_bst opt_bst2_dom)
      let ?f =  $\lambda k. \text{case } \text{opt\_bst\_wpl2 } i (k-1) \text{ of}$ 
        ( $l, wl$ )  $\Rightarrow$   $\text{case } \text{opt\_bst\_wpl2 } (k+1) j \text{ of}$ 
          ( $r, wr$ )  $\Rightarrow$  ( $\langle l, k, r \rangle, wl + wr + w i j$ )
      let ?g =  $\lambda k. (\langle \text{opt\_bst2 } i (k-1), k, \text{opt\_bst2 } (k+1) j \rangle,$ 
         $wpl i (k-1) (\text{opt\_bst2 } i (k-1)) + wpl (k+1) j (\text{opt\_bst2 } (k+1) j)$ 
         $+ w i j)$ 
      have fg: ?f k = ?g k if  $k \in \{?l..?r\}$  for k
      proof -
        have 1: opt_bst_wpl2 i (k-1) = (opt_bst2 i (k-1), wpl i (k-1) (opt_bst2
i (k-1)))
          using k 1.IH(3) by(simp add: 1.IH(1,2))
        have 2: opt_bst_wpl2 (k+1) j = (opt_bst2 (k+1) j, wpl (k+1) j (opt_bst2
(k+1) j))
          using 1 k 1.IH(4) by(simp add: 1.IH(1,2))
        show ?thesis using 1 2 by(simp)
      qed
      have opt_bst_wpl2 i j =

```

```

    argmin snd (map ?f [root(fst(opt_bst_wpl2 i (j-1)))..root(fst(opt_bst_wpl2
(i+1) j))])
    by(simp)
    also have ... = argmin snd (map ?f [?l..?r])
    by(simp add: 1.IH(1,2))
    also have ... = argmin snd (map ?g [?l..?r])
    using fg by (simp cong: list.map_cong_simp)
    also have ... = (opt_bst2 i j, wpl i j (opt_bst2 i j)) using *
    by(simp add: argmin_pairs_comp_def)
    finally show ?thesis .
  qed
end
end

```

```

corollary opt_bst_wpl2_eq_pair': opt_bst_wpl2 i j = (opt_bst i j, min_wpl i j)
by (simp add: opt_bst_wpl2_eq_pair opt_bst2_opt_bst wpl_opt_bst)

```

end

end

```

theory Optimal_BST_Examples
imports HOL-Library.Tree
begin

```

Example by Mehlhorn:

```

definition a_ex1 :: int ⇒ nat where
a_ex1 i = [4,0,0,3,10] ! nat i

```

```

definition b_ex1 :: int ⇒ nat where
b_ex1 i = [1,3,3,0] ! nat i

```

```

definition t_opt_ex1 :: int tree where
t_opt_ex1 = ⟨⟨⟨⟩, 0, ⟨⟨⟩, 1, ⟨⟩⟩⟩, 2, ⟨⟨⟩, 3, ⟨⟩⟩⟩

```

Example by Knuth:

```

definition a_ex2 :: int ⇒ nat where
a_ex2 i = 0

```

```

definition b_ex2 :: int ⇒ nat where
b_ex2 i = [32,7,69,13,6,15,10,8,64,142,22,79,18,9] ! nat i

```

```

definition t_opt_ex2 :: int tree where
t_opt_ex2 =

```

```

⟨
  ⟨
    ⟨⟨⟩, 0, ⟨⟨⟩, 1, ⟨⟩⟩⟩,
    2,

```

```

  <
  <
  <<>, 3, <<>, 4, <>>>,
  5,
  <<>, 6, <<>, 7, <>>>
  >,
  8,
  <>
  >
  >,
  9,
  <<<>, 10, <>>,
  11,
  <<>, 12, <<>, 13, <>>
  >
  >
  >
  >

```

end

6 Code Generation (unmemoized)

theory *Optimal_BST_Code*

imports

Optimal_BST2

Optimal_BST_Examples

begin

locale *Wpl_Optimal_BST* = *Wpl a b* + *Optimal_BST* **where** $w = Wpl.w a b$
for $a b$

locale *Wpl_Optimal_BST2* = *Wpl a b* + *Optimal_BST2* **where** $w = Wpl.w a b$
for $a b$

global_interpretation *Wpl_Optimal_BST* + *Wpl_Optimal_BST2*

defines $wpl_ab = wpl$ **and** $opt_bst_ab = opt_bst$ **and** $opt_bst2_ab = opt_bst2$

proof (*standard, unfold Wpl.w_def, goal_cases*)

case (1 $i i' j j'$)

thus $?case$ **by** (*simp add: add_mono_thms_linordered_semiring(1) sum_mono2*)

next

note $un1 = ivl_disj_un_two(7)[symmetric]$

note $un2 = ivl_disj_un_two(8)[symmetric]$

case (2 $i i' j j'$)

have $\{i..<i'\} \cap \{j<..ub\} = \{\}$ **for** ub **using** $\langle i' \leq j \rangle$ **by** *auto*

with 2 **show** $?case$

using $un2[of i' j j']$ $un1[of i i' j]$ $un1[of i i' j']$

$un2[of i' j j'+1]$ $un1[of i i' j+1]$ $un1[of i i' j'+1]$

by (*simp add: sum_Un_nat algebra_simps ivl_disj_int Int_Un_distrib*)

qed

Examples:

lemma *opt_bst_ab a_ex1 b_ex1 0 3 = t_opt_ex1*
by *eval*

lemma *opt_bst2_ab a_ex2 b_ex2 0 13 = t_opt_ex2*
by *eval*

end

7 Memoization

theory *Optimal_BST_Memo*

imports

Optimal_BST
Monad_Memo_DP.State_Main
HOL-Library.Product_Lexorder
HOL-Library.RBT_Mapping
Optimal_BST_Examples

begin

This theory memoizes the recursive algorithms with the help of our generic memoization framework. Note that currently only the tree building (function *Optimal_BST.opt_bst*) is memoized but not the computation of w .

global_interpretation *Wpl*
where $a = a$ **and** $b = b$ **for** $a\ b$
defines $w_{ab} = w$ **and** $wpl_{ab} = wpl.wpl\ w_{ab}$.

First we express *argmin* via *fold*. Primarily because we have a monadic version of *fold* already. At the same time we improve efficiency.

lemma *fold_argmin*: *fold* $(\lambda x\ (m, fm).\ \text{let } fx = f\ x\ \text{in if } fx \leq fm\ \text{then } (x, fx)\ \text{else } (m, fm))\ xs\ (x, f\ x)$
 $= (\text{argmin } f\ (x\#\!xs), f(\text{argmin } f\ (x\#\!xs)))$
by $(\text{induction } xs\ \text{arbitrary: } x)\ (\text{auto simp: Let_def split: prod.split})$

lemma *argmin_fold*: $\text{argmin } f\ xs = (\text{case } xs\ \text{of } [] \Rightarrow \text{undefined} \mid x\#\!xs \Rightarrow \text{fst}(\text{fold } (\lambda x\ (m, fm).\ \text{let } fx = f\ x\ \text{in if } fx \leq fm\ \text{then } (x, fx)\ \text{else } (m, fm))\ xs\ (x, f\ x)))$
apply $(\text{auto simp: fold_argmin split: list.split})$
apply $(\text{meson argmin.elims list.distinct}(1))$
done

The actual memoization of the cubic algorithm:

context *Optimal_BST*
begin

```
memoize_fun opt_bst_m: opt_bst with_memory dp_consistency_mapping
monadifies (state) opt_bst.simps[unfolded argmin_fold]
```

```
thm opt_bst_m'.simps
```

```
memoize_correct
by memoize_prover
```

```
lemmas [code] = opt_bst_m.memoized_correct
```

```
end
```

Code generation:

```
global_interpretation Optimal_BST
where w = w_ab a b
rewrites wpl.wpl (w_ab a b) = wpl_ab a b for a b
defines opt_bst_ab = opt_bst and opt_bst_ab' = opt_bst_m'
by(simp add: wpl_ab_def)
```

Examples:

```
lemma opt_bst_ab a_ex1 b_ex1 0 3 = t_opt_ex1
by eval
```

```
lemma opt_bst_ab a_ex2 b_ex2 0 13 = t_opt_ex2
by eval
```

```
end
```

References

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- [2] K. Mehlhorn. *Data Structures and Algorithms 1: Sorting and Searching*, volume 1 of *EATCS Monographs on Theoretical Computer Science*. Springer, 1984.
- [3] S. Wimmer, S. Hu, and T. Nipkow. Monadification, memoization and dynamic programming. *Archive of Formal Proofs*, 2018. http://isa-afp.org/entries/Monad_Memo_DP.html, Formal proof development.
- [4] F. F. Yao. Efficient dynamic programming using quadrangle inequalities. In *STOC*, pages 429–435. ACM, 1980.