Formalization of an Algorithm for Greedily Computing Associative Aggregations on Sliding Windows

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Abstract

Basin et al.'s sliding window algorithm (SWA) [1] is an algorithm for combining the elements of subsequences of a sequence with an associative operator. It is greedy and minimizes the number of operator applications. We formalize the algorithm and verify its functional correctness. We extend the algorithm with additional operations and provide an alternative interface to the slide operation that does not require the entire input sequence.

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1 Sliding Window Algorithm

datatype *'a tree* =
  Leaf
| *Node* (*l*: *nat*) (*r*: *nat*) (*val*: *'a option*) (*lchild*: *'a tree*) (*rchild*: *'a tree*)
where
  l Leaf = *0*
| *r Leaf* = *0*
| *val Leaf* = *None*
| *lchild Leaf* = *Leaf*
| *rchild Leaf* = *Leaf*

lemma *neq_Leaf_if_l_gt0*: *0* < *l t* ⟹ *t* ≠ *Leaf*
  by *auto*

primrec *discharge* :: *'a tree* ⇒ *'a tree* **where**
  discharge Leaf = *Leaf*
| *discharge* (*Node i j _ t u*) = *Node i j None t u*

instantiation *option* :: (*semigroup_add*) *semigroup_add* **begin**

fun *plus_option* :: *'a option* ⇒ *'a option* ⇒ *'a option* **where**
  plus_option None _ = None
| *plus_option _ None = None*
| *plus_option* (*Some a*) (*Some b*) = *Some* (*a* + *b*)

instance proof
  fix *a b c* :: *'a option*
  show *a* + *b* + *c* = *a* + (*b* + *c*)
    by (*induct a b rule*: *plus_option.induct*; *cases c*)
      (*auto simp*: *algebra_simps*)
qed

end

fun *combine* :: *'a* :: *semigroup_add tree* ⇒ *'a tree* ⇒ *'a tree* **where**
  combine t Leaf = t
| *combine Leaf t = t*
| *combine t u = Node* (*l t*) (*r u*) (*val t* + *val u*) (*discharge t*) *u*

lemma *combine_non_Leaves*: ⟦*t* ≠ *Leaf*; *u* ≠ *Leaf*⟧ ⟹ *combine t u = Node* (*l t*) (*r u*) (*val t* + *val u*) (*discharge t*) *u*
proof −
  assume *assms*: *t* ≠ *Leaf u* ≠ *Leaf*
  from *assms* **have** *combine t u = Node* (*l* (*Node* (*l t*) (*r t*) (*val t*) (*lchild t*) (*rchild t*))) (*r* (*Node* (*l u*) (*r u*) (*val u*) (*lchild u*) (*rchild u*))) (*val* (*Node* (*l t*) (*r t*) (*val t*) (*lchild t*) (*rchild t*)) + *val* (*Node* (*l u*) (*r u*) (*val u*) (*lchild u*) (*rchild u*))) (*discharge* (*Node* (*l t*) (*r t*) (*val t*) (*lchild t*) (*rchild t*))) (*Node* (*l u*) (*r u*) (*val u*) (*lchild u*) (*rchild u*))
    by (*metis* (*no_types*) *combine.simps*(*3*) *tree.exhaust_sel*)
  with *assms* **show** *?thesis*
    by *simp*
qed

lemma *r_combine_non_Leaves*: ⟦*t* ≠ *Leaf*; *u* ≠ *Leaf*⟧ ⟹ *r* (*combine t u*) = *r u*
  by (*simp add*: *combine_non_Leaves*)

type_synonym *window* = *nat* × *nat*

definition *window* :: *'a list* ⇒ *window* ⇒ *bool* **where**
  window as = (λ(*l*, *r*). *0* < *l* ∧ *l* ≤ *r* ∧ *r* ≤ *length as*)

definition *windows* :: *'a list* ⇒ *window list* ⇒ *bool* **where**
  windows as ws = ((∀ *w* ∈ *set ws*. *window as w*) ∧
    sorted (*map fst ws*) ∧ *sorted* (*map snd ws*))

function *reusables* :: *'a tree* ⇒ *window* ⇒ *'a tree list* **where**
  reusables t w = (*if fst w* > *r t then* [] *else if fst w* = *l t then* [*t*]
    else let v = *lchild t*; *u* = *rchild t in if fst w* ≥ *l u then*
      reusables u w else u # *reusables v w*)
  by *auto*
termination
  by (*relation measure* (λ*p*. *size* (*fst p*)))
    (*auto simp*: *lchild_def rchild_def split*: *tree.splits*)

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

lemma *reusables_Leaf*[*simp*]: *0* < *fst w* ⟹ *reusables Leaf w* = []

```
  by (simp add: reusables.simps)

primrec well_shaped :: 'a tree ⇒ bool where
  well_shaped Leaf = True
| well_shaped (Node i j _ t u) = (i ≤ j ∧ (i = j ⟶ t = Leaf ∧ u = Leaf) ∧
    (i < j ⟶ t ≠ Leaf ∧ u ≠ Leaf ∧ well_shaped t ∧ well_shaped u ∧
      i = l t ∧ j = r u ∧ Suc (r t) = l u))

lemma l_lchild_eq_l_if_well_shaped[simp]:
  ⟦well_shaped t; l t < r t⟧ ⟹ l (lchild t) = l t
  by (induct t) auto

lemma r_rchild_eq_r_if_well_shaped[simp]:
  ⟦well_shaped t; l t < r t⟧ ⟹ r (rchild t) = r t
  by (induct t) auto

lemma r_lchild_eq_l_rchild_if_well_shaped:
  ⟦well_shaped t; l t < r t⟧ ⟹ r (lchild t) = l (rchild t) - 1
  by (induct t) auto

lemma r_lchild_le_r: well_shaped t ⟹ r (lchild t) ≤ r t
proof (induct t)
  case (Node i j a t1 t2)
  then show ?case
    by auto
      (metis Suc_eq_plus1_left order.trans le_add2 tree.exhaust_sel well_shaped.simps(2))
qed simp

lemma well_shaped_lchild[simp]: well_shaped t ⟹ well_shaped (lchild t)
  by (induct t) auto

lemma well_shaped_rchild[simp]: well_shaped t ⟹ well_shaped (rchild t)
  by (induct t) auto

definition adjacent where
  adjacent w ts = (Leaf ∉ set ts ∧
    list_all2 (λt u. l t = Suc (r u)) (butlast ts) (tl ts) ∧
    (ts = [] ∨ (l (last ts) = fst w ∧ r (hd ts) = snd w)))

lemma adjacent_Nil[simp]: adjacent w []
  unfolding adjacent_def by simp

lemma adjacent_Cons: adjacent w (t # ts) =
  (t ≠ Leaf ∧ r t = snd w ∧ (case ts of [] ⇒ l t = fst w
    | u # us ⇒ adjacent (fst w, r u) ts ∧ l t = Suc (r u)))
  unfolding adjacent_def by (auto split: list.splits)

lemma adjacent_ConsI: ⟦t ≠ Leaf; r t = snd w;
  (case ts of [] ⇒ l t = fst w
    | u # us ⇒ adjacent (fst w, r u) ts ∧ l t = Suc (r u))⟧ ⟹
  adjacent w (t # ts)
  by (simp add: adjacent_Cons)

lemma adjacent_singleton: t ≠ Leaf ⟹ adjacent (l t, r t) [t]
  unfolding adjacent_def by simp

lemma append_Cons_eq_append_append: xs @ y # ys = xs @ [y] @ ys
  by simp
```

lemma *list_all2_append_singletonI*: ⟦*list_all2 P xs ys*; *P x y*⟧ ⟹ *list_all2 P* (*xs* @ [*x*]) (*ys* @ [*y*])
by (*simp add*: *list_all2_appendI*)

lemma *list_all2_Cons_append_singletonI*: ⟦*xs* ≠ []; *list_all2 P* (*x* # *butlast xs*) *ys*; *P* (*last xs*) *y*⟧ ⟹ *list_all2 P* (*x* # *xs*) (*ys* @ [*y*])
using *list_all2_append_singletonI* **by** *fastforce*

lemma *adjacent_appendI*: ⟦*0* < *fst w*; *fst w* ≤ *snd w*;
(*case us of* [] ⇒ *adjacent w ts*
| *u* # *us'* ⇒ *adjacent* (*Suc* (*r u*), *snd w*) *ts* ∧ *adjacent* (*fst w*, (*case ts of* [] ⇒ *snd w* | *ts* ⇒ *r u*)) (*u* # *us'*))⟧ ⟹
adjacent w (*ts* @ *us*)
unfolding *adjacent_def butlast_append*
by (*auto simp*: *intro*: *list_all2_Cons_append_singletonI*
list_all2_appendI[*OF list_all2_Cons_append_singletonI*, *simplified*] *split*: *list.splits if_splits*)

lemma *adjacent_Cons_implies_adjacent*: *adjacent* (*a*, *b*) (*t* # *ts*) ⟹ *adjacent* (*a*, *l t* − *Suc 0*) *ts*
by (*cases ts*) (*simp_all add*: *adjacent_def*)

lemma (**in** *semigroup_add*) *fold_add_add*: *fold* (+) *xs* (*x* + *y*) = *fold* (+) *xs x* + *y*
by (*induct xs arbitrary*: *x*) (*auto simp*: *add_assoc*[*symmetric*])

context
fixes *as* :: *'a* :: *semigroup_add list*
and *ws* :: *window list*
begin

abbreviation *atomic* **where**
atomic i ≡ *Node i i* (*Some* (*nth as* (*i* − *1*))) *Leaf Leaf*

definition *atomics* :: *nat* ⇒ *nat* ⇒ *'a tree list* **where**
atomics i j ≡ *map atomic* (*rev* [*i* ..< *Suc j*])

definition *slide* :: *'a tree* ⇒ *window* ⇒ *'a tree* **where**
slide t w =
(*let*
ts = *atomics* (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*);
ts' = *reusables t w*
in fold combine (*ts* @ *ts'*) *Leaf*)

primrec *iterate* :: *'a tree* ⇒ *window list* ⇒ *'a list* **where**
iterate t [] = []
| *iterate t* (*w* # *xs*) = (*let t'* = *slide t w in the* (*val t'*) # *iterate t' xs*)

definition *sliding_window* :: *'a list* **where**
sliding_window = *iterate Leaf ws*

2 Correctness

abbreviation *sum* **where**
sum i j ≡ *fold* (+) (*rev* (*map* (*nth as*) [*i* − *1* ..< *j* − *1*])) (*nth as* (*j* − *1*))

primrec *well_valued0* :: *'a tree* ⇒ *bool* **where**
well_valued0 Leaf = *True*
| *well_valued0* (*Node i j a t u*) = (*0* < *i* ∧ *j* ≤ *length as* ∧ (*a* ≠ *None* ⟶ *a* = *Some* (*sum i j*)) ∧
well_valued0 t ∧ *well_valued0 u* ∧ (*u* = *Leaf* ∨ *val u* ≠ *None*))

abbreviation *well_valued* :: *'a tree* ⇒ *bool* **where**
well_valued t ≡ (*well_valued0 t* ∧ (*t* ≠ *Leaf* ⟶ *val t* ≠ *None*))

definition *valid* :: *'a tree* ⇒ *bool* **where**
valid t = (*well_shaped t* ∧ *well_valued t*)

lemma *valid_Leaf*: *valid Leaf*
unfolding *valid_def* **by** *auto*

lemma *add_sum*:
assumes *i* > *0 j* ≥ *i k* > *j*
shows *sum i j* + *sum* (*Suc j*) *k* = *sum i k*
proof −
have ∗: [*i* − *1* ..< *k* − *1*] = [*i* − *1*..< *j*] @ [*j*..< *k* − *1*]
using *assms upt_add_eq_append*[*of i* − *1 j* − *1 k* − *j*]
by (*cases j*) (*auto simp*: *upt_conv_Cons*)
then show *?thesis* **using** *assms*
by (*cases j*) (*auto simp*: *fold_add_add*)
qed

lemma *well_valued0_rchild_if_well_valued0*[*simp*]: *well_valued0 t* ⟹ *well_valued0* (*rchild t*)
by (*induct t*) *auto*

lemma *well_valued0_lchild_if_well_valued0*[*simp*]: *well_valued0 t* ⟹ *well_valued0* (*lchild t*)
by (*induct t*) *auto*

lemma *valid_rchild_if_valid*: *valid t* ⟹ *valid* (*rchild t*)
by (*metis tree.exhaust_sel tree.sel*(*9*) *valid_def well_shaped_rchild well_valued0.simps*(*2*))

lemma *val_eq_Some_sum_if_valid_neq_Leaf*: ⟦*valid t*; *t* ≠ *Leaf*⟧ ⟹ *val t* = *Some* (*sum* (*l t*) (*r t*))
by (*auto simp*: *valid_def foldr_conv_fold*)
(*metis One_nat_def option.distinct*(*1*) *option.inject tree.exhaust_sel well_valued0.simps*(*2*))

2.1 Correctness of the Slide Function

lemma *adjacent_atomics*: *adjacent* (*i*, *j*) (*atomics i j*)
unfolding *adjacent_def atomics_def*
by (*auto 0 1 simp*: *last_map last_rev nth_tl*
map_butlast[*symmetric*] *list_all2_conv_all_nth nth_Cons' rev_nth nth_append*)

lemma *valid_atomics*: ⟦*t* ∈ *set* (*atomics i j*); *0* < *i*; *j* ≤ *length as*⟧ ⟹ *valid t*
unfolding *atomics_def*
by (*auto simp*: *valid_def*)

lemma *reusables_neq_Nil_if_well_shaped_and_overlapping*:
⟦*well_shaped t*; *l t* ≤ *fst w*; *r t* ≤ *snd w*; *fst w* ≤ *r t*⟧ ⟹ *reusables t w* ≠ []
by (*induction t w rule*: *reusables.induct*) (*simp add*: *reusables.simps Let_def*)

lemma *reusables_lchild_neq_Nil_under_some_conditions*:
⟦*well_shaped t*; *l t* ≤ *fst w*; *r t* ≤ *snd w*; *fst w* ≠ *l t*; *r t* ≥ *fst w*; *l* (*rchild t*) > *fst w*⟧ ⟹
reusables (*lchild t*) *w* ≠ []
using *r_lchild_eq_l_rchild_if_well_shaped*[*of t*] *r_lchild_le_r*[*of t*]
by (*intro reusables_neq_Nil_if_well_shaped_and_overlapping*) *auto*

lemma *adjacent_reusables*: ⟦*0* < *fst w*; *well_shaped t*; *l t* ≤ *fst w*; *r t* ≤ *snd w*⟧ ⟹
adjacent (*fst w*, *r t*) (*reusables t w*)

```
proof (induction t w rule: reusables.induct)
  case (1 t w)
  show ?case
  proof (cases fst w > r t)
    case False
    with 1 show ?thesis
    proof (cases fst w = l t)
      case False
      then show ?thesis
      proof (cases fst w ≥ l (rchild t))
        case True
        with 1 ‹fst w ≠ l t› show ?thesis by (subst reusables.simps) auto
      next
        case False
        with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› obtain x xs where ∗: reusables (lchild t) w = x # xs
          by (cases reusables (lchild t) w) (auto simp: reusables_lchild_neq_Nil_under_some_conditions)
        with 1(2−6) ‹fst w ≠ l t› ‹¬ fst w > r t› ‹¬ l (rchild t) ≤ fst w›
        have adjacent (fst w, r (lchild t)) (x # xs)
          by (simp add: adjacent_Cons r_lchild_le_r dual_order.trans)
        with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› ∗ show ?thesis
          by (subst reusables.simps)
            (auto simp add: Let_def adjacent_Cons r_lchild_eq_l_rchild_if_well_shaped)
      qed
    qed (auto simp: reusables.simps intro!: adjacent_singleton)
  qed (auto simp: reusables.simps)
qed

lemma valid_rchild_if_well_valued0: ⟦well_shaped t; well_valued0 t⟧ ⟹ valid (rchild t)
  by (metis tree.exhaust_sel tree.sel(9) valid_def well_shaped_rchild well_valued0.simps(2))

lemma valid_reusables_under_some_conditions:
  ⟦0 < fst w; well_valued0 t; well_shaped t; l t < fst w; r t ≤ snd w⟧ ⟹
    ∀ t′ ∈ set (reusables t w). valid t′
proof (induction t w rule: reusables.induct)
  case (1 t w)
  show ?case
  proof (cases fst w > r t)
    case False
    with 1 show ?thesis
    proof (cases fst w = l t)
    next
      case False
      then show ?thesis
      proof (cases fst w ≥ l (rchild t))
        case True
        with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› have ∗: Ball (set (reusables (rchild t) w)) valid
            by (metis (no_types, lifting) ball_empty dual_order.strict_trans2 leI le_neq_implies_less
list.set(1) r_rchild_eq_r_if_well_shaped reusables.simps set_ConsD valid_rchild_if_well_valued0 well_shaped_rchild
well_valued0_rchild_if_well_valued0)
        from 1 ‹fst w ≠ l t› ‹¬ fst w > r t› True have reusables t w = reusables (rchild t) w
          by (subst reusables.simps)
            simp
        with 1 ∗ show ?thesis
          by simp
      next
        case False
        with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› have ∗: Ball (set (reusables (lchild t) w)) valid
          by (metis dual_order.strict_trans2 l_lchild_eq_l_if_well_shaped leI order_trans r_lchild_le_r
```

```
well_shaped_lchild well_valued0_lchild_if_well_valued0)
      with 1 have valid_rchild: valid (rchild t)
        by (simp add: valid_rchild_if_well_valued0)
      with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› False have reusables t w = rchild t # reusables (lchild t) w
        by (subst reusables.simps) presburger
      with 1 ‹fst w ≠ l t› ‹¬ fst w > r t› False ∗ valid_rchild show ?thesis
        by (metis set_ConsD)
    qed
  qed (auto simp: reusables.simps)
 qed (auto simp: reusables.simps)
qed


lemma valid_reusables:
 assumes 0 < fst w valid t l t ≤ fst w r t ≤ snd w
 shows ∀ t' ∈ set (reusables t w). valid t'
proof (cases l t < fst w)
 case True
 with assms show ?thesis
  using valid_def valid_reusables_under_some_conditions by blast
next
 case False
 with assms show ?thesis
  by (simp add: reusables.simps)
qed

lemma combine_valid_Nodes_aux:
 assumes prems: 0 < l a a ≠ Leaf z ≠ Leaf l z = Suc (r a) well_shaped a well_shaped z
  well_valued0 a val a = Some va well_valued0 z val z = Some vz
 shows va + vz = fold (+) (rev (map ((!) as) [l a − Suc 0..<r z − Suc 0])) (as ! (r z − Suc 0))
proof −
 from prems have l a > 0 by simp
 moreover from prems have r a ≥ l a
  by (metis tree.collapse well_shaped.simps(2))
 moreover have r z > r a
  by (metis Suc_le_lessD prems(3) prems(4) prems(6) tree.collapse well_shaped.simps(2))
 ultimately have ∗: sum (l a) (r a) + sum (Suc (r a)) (r z) = sum (l a) (r z)
  by (frule add_sum)
 from prems have va = sum (l a) (r a)
  by (metis option.discI option.inject tree.collapse well_valued0.simps(2))
 moreover from prems have vz = sum (Suc (r a)) (r z)
  by (metis option.discI option.inject prems(2) prems(3) prems(8) prems(9) tree.collapse well_valued0.simps(2))
 moreover have fold (+) (rev (map ((!) as) [l a − Suc 0..<r z − Suc 0])) (as ! (r z − Suc 0)) = sum
(l a) (r z)
  by simp
 ultimately show ?thesis
  using ∗ by (auto simp: add_sum)
qed

lemma discharge_is_Leaf[simp]: discharge a = Leaf ⟷ a = Leaf
 by (cases a) auto

lemma well_shaped_discharge[simp]: well_shaped a ⟹ well_shaped (discharge a)
 by (cases a) auto

lemma well_valued0_discharge[simp]: well_valued0 a ⟹ well_valued0 (discharge a)
 by (cases a) auto
```

lemma *l_discharge*[*simp*]: *l* (*discharge a*) = *l a*
by (*cases a*) *auto*

lemma *r_discharge*[*simp*]: *r* (*discharge a*) = *r a*
by (*cases a*) *auto*

lemma *well_shaped_lr*: *well_shaped a* ⟹ *l a* ≤ *r a*
by (*cases a*) *auto*

lemma *well_valued0_r*: *well_valued0 a* ⟹ *a* ≠ *Leaf* ⟹ *r a* ≤ *length as*
by (*cases a*) *auto*

lemma *valid_combine_if_valid*: ⟦*0* < *l a*; *valid a*; *valid z*; *a* ≠ *Leaf*; *z* ≠ *Leaf*; *l z* = *Suc* (*r a*)⟧ ⟹
valid (*combine a z*)
by (*force simp add*: *valid_def combine_non_Leaves combine_valid_Nodes_aux*
dest: *well_shaped_lr well_valued0_r*)

lemma *combine_neq_Leaf_if_both_non_Leaf*: ⟦*a* ≠ *Leaf*; *z* ≠ *Leaf*⟧ ⟹
combine a z ≠ *Leaf*
by (*simp add*: *combine_non_Leaves*)

lemma *valid_fold_combine*: ⟦*0* < *fst w*; *ts* = *h* # *ts'*; ∀ *t* ∈ *set ts*. *valid t*; *adjacent* (*fst w*, *l h* − *1*) *ts'*;
valid z; *z* ≠ *Leaf*; *l z* = (*case ts' of* [] ⇒ *fst w* | *t*₁ # *ts''* ⇒ *Suc* (*r t*₁)); *r z* = *snd w*⟧ ⟹
valid (*fold combine ts' z*) ∧
l (*fold combine ts' z*) = *fst w* ∧ *r* (*fold combine ts' z*) = *snd w*
proof (*induction ts' arbitrary*: *z ts h*)
case *Nil*
then show *?case* **by** *simp*
next
case (*Cons a ts'*)
moreover from *Cons*(*3*−*4*) **have** *valid a* **by** *simp*
moreover from *Cons*(*5*) **have** *adjacent* (*fst w*, *l a* − *Suc 0*) *ts'*
unfolding *adjacent_Cons* **by** (*auto split*: *list.splits*)
moreover from *Cons*(*2*−*6*,*8*) **have** *valid* (*combine a z*)
unfolding *adjacent_Cons*
by (*intro valid_combine_if_valid*) (*auto split*: *list.splits*)
moreover from *Cons*(*5*,*7*) **have** *combine a z* ≠ *Leaf*
by (*intro combine_neq_Leaf_if_both_non_Leaf*) (*simp_all add*: *adjacent_Cons*)
moreover from *Cons*(*5*,*7*) **have** *l* (*combine a z*) = (*case ts' of* [] ⇒ *fst w* | *t*₁ # *ts''* ⇒ *Suc* (*r t*₁))
by (*auto simp add*: *adjacent_def combine_non_Leaves split*: *list.splits*)
moreover from *Cons*(*5*,*7*,*9*) **have** *r* (*combine a z*) = *snd w*
by (*subst r_combine_non_Leaves*) (*auto simp add*: *adjacent_def*)
ultimately show *?case*
by *simp*
qed

lemma *valid_fold_combine_Leaf*:
assumes *0* < *fst w ts* = *h* # *ts'* ∀ *t* ∈ *set ts*. *valid t adjacent w ts*
shows *valid* (*fold combine ts Leaf*) ∧
l (*fold combine ts Leaf*) = *fst w* ∧ *r* (*fold combine ts Leaf*) = *snd w*
proof −
from *assms*(*2*) **have** *fold combine ts Leaf* = *fold combine ts' h*
by *simp*
moreover have *valid* (*fold combine ts' h*) ∧
l (*fold combine ts' h*) = *fst w* ∧ *r* (*fold combine ts' h*) = *snd w*
proof (*rule valid_fold_combine*)

from *assms* **show** *0 < fst w ts = h # ts' ∀ t ∈ set ts. valid t valid h h ≠ Leaf r h = snd w*
l h = (case ts' of [] ⇒ fst w | t₁ # ts'' ⇒ Suc (r t₁))
by (*simp_all add*: *adjacent_Cons list.case_eq_if*)
from *assms* **show** *adjacent (fst w, l h − 1) ts'*
by (*metis One_nat_def adjacent_Cons_implies_adjacent prod.collapse*)
qed
ultimately show *?thesis* **by** *simp*
qed

lemma *adjacent_atomics_nonempty_reusables*:
fixes *x* :: *'a tree* **and** *xs* :: *'a tree list*
assumes *a1*: *0 < fst w*
and *a2*: *l t ≤ fst w*
and *a3*: *r t ≤ snd w*
and *a4*: *valid t*
and *a5*: *reusables t w = x # xs*
shows *adjacent (Suc (r x), snd w) (atomics (max (fst w) (Suc (r t))) (snd w))*
proof −
have *f6*: *∀ p ts. adjacent p ts = ((Leaf::'a tree) ∉ set ts ∧ list_all2 (λt ta. l t = Suc (r ta)) (butlast ts) (tl ts) ∧ (ts = [] ∨ l (last ts) = fst p ∧ r (hd ts) = snd p))*
using *adjacent_def* **by** *blast*
then have *f7*: *Leaf ∉ set (atomics (max (fst w) (Suc (r t))) (snd w)) ∧ list_all2 (λt ta. l t = Suc (r ta)) (butlast (atomics (max (fst w) (Suc (r t))) (snd w))) (tl (atomics (max (fst w) (Suc (r t))) (snd w))) ∧ (atomics (max (fst w) (Suc (r t))) (snd w) = [] ∨ l (last (atomics (max (fst w) (Suc (r t))) (snd w))) = fst (max (fst w) (Suc (r t)), snd w) ∧ r (hd (atomics (max (fst w) (Suc (r t))) (snd w))) = snd (max (fst w) (Suc (r t)), snd w))*
using *adjacent_atomics* **by** *presburger*
have *adjacent (fst w, r t) (reusables t w)*
using *a4 a3 a2 a1* **by** (*simp add*: *adjacent_reusables valid_def*)
then have *f8*: *r x = r t*
using *a5* **by** (*simp add*: *adjacent_Cons*)
have *max (fst w) (Suc (r t)) = Suc (r t)*
using *a5* **by** (*metis* (*no_types*) *Suc_n_not_le_n list.simps*(*3*) *max.bounded_iff max_def_raw not_le_imp_less reusables.simps*)
then show *?thesis*
using *f8 f7 f6* **by** *presburger*
qed

lemma *adjacent_Cons_r*: *adjacent (a, r t) (x # xs) ⟹ adjacent (a, r x) (x # xs)*
by (*simp add*: *adjacent_Cons*)

lemma *adjacent_Cons_r2*:
adjacent (fst w, r t) (x # xs) ⟹ 0 < fst w ⟹ fst w ≤ snd w ⟹ r t ≤ snd w ⟹
atomics (max (fst w) (Suc (r t))) (snd w) = [] ⟹
adjacent w (x # xs)
by (*metis* (*no_types*, *lifting*) *atomics_def adjacent_def append_is_Nil_conv diff_Suc_Suc diff_zero le_Suc_eq list.simps*(*3*) *map_is_Nil_conv max_Suc_Suc max_def_raw prod.sel*(*1*) *prod.sel*(*2*) *rev_is_Nil_conv upt.simps*(*2*))

lemma *adjacent_append_atomics_reusables*:
⟦*0 < fst w*; *fst w ≤ snd w*; *valid t*; *l t ≤ fst w*; *r t ≤ snd w*⟧ ⟹
adjacent w (atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w)
using *adjacent_atomics_nonempty_reusables*[*of w t*] *reusables_neq_Nil_if_well_shaped_and_overlapping*[*of t w*]
adjacent_atomics[*of fst w snd w*] *adjacent_reusables*[*of w t*]
by (*intro adjacent_appendI*) (*auto simp*: *valid_def max.absorb1 atomize_not elim*: *adjacent_Cons_r adjacent_Cons_r2 split*: *list.splits nat.splits*)

lemma *valid_append_atomics_reusables*: ⟦*0 < fst w*; *valid t*; *l t ≤ fst w*; *r t ≤ snd w*; *snd w ≤ length as*⟧ ⟹
∀ t ∈ set (atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w). valid t
by (*auto simp only*: *set_append valid_reusables dest*: *valid_atomics split*: *if_splits*)

lemma *append_atomics_reusables_neq_Nil*: ⟦*0 < fst w*; *fst w ≤ snd w*; *valid t*; *l t ≤ fst w*; *r t ≤ snd w*⟧ ⟹
atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w ≠ []
by (*simp add*: *reusables_neq_Nil_if_well_shaped_and_overlapping valid_def atomics_def*)

lemma *valid_slide*:
assumes *0 < fst w fst w ≤ snd w valid t l t ≤ fst w r t ≤ snd w snd w ≤ length as*
shows *valid (slide t w) ∧ l (slide t w) = fst w ∧ r (slide t w) = snd w*
proof −
from *assms* **have** *non_empty*: *atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w ≠ []*
using *append_atomics_reusables_neq_Nil* **by** *blast*
from *assms* **have** *adjacent*: *adjacent w (atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w)*
using *adjacent_append_atomics_reusables* **by** *blast*
from *assms* **have** *valid*: *∀ t ∈ set (atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w). valid t*
using *valid_append_atomics_reusables* **by** *blast*
have ∗: *slide t w = fold combine (atomics (max (fst w) (Suc (r t))) (snd w) @ reusables t w) Leaf*
by (*simp add*: *slide_def*)
from *assms*(*1*) *non_empty adjacent valid* **show** *valid (slide t w) ∧ l (slide t w) = fst w ∧ r (slide t w) = snd w*
unfolding ∗ *neq_Nil_conv* **using** *valid_fold_combine_Leaf* **by** *blast*
qed

2.2 Correctness of the Sliding Window Algorithm

lemma *iterate_eq_map_sum*: ⟦*valid t*; *windows as xs*; (*case xs of* [] ⇒ *True* | *x # xs′* ⇒ *l t ≤ fst x ∧ r t ≤ snd x*)⟧ ⟹
iterate t xs = map (λw. sum (fst w) (snd w)) xs
by (*induction xs arbitrary*: *t*)
(*auto simp*: *valid_slide windows_def window_def val_eq_Some_sum_if_valid_neq_Leaf neq_Leaf_if_l_gt0 split*: *list.split*)

theorem *correctness*: *windows as ws* ⟹ *sliding_window = map (λw. sum (fst w) (snd w)) ws*
by (*auto simp only*: *sliding_window_def intro*!: *iterate_eq_map_sum*)
(*auto simp*: *valid_def split*: *list.split*)

end

2.3 Summary of the Correctness Proof

We closely follow Basin et al.'s proof outline [1].

1. Lemma 1, the correctness result about the function *slide*, is formalized by *SWA.valid_slide*. It follows from the following auxiliary facts:
   - Fact (a) is formalized by *SWA.adjacent_reusables* and *SWA.valid_reusables*.
   - Fact (b) is formalized by *SWA.adjacent_atomics* and *SWA.valid_atomics*.
   - Fact (c) is formalized by *SWA.valid_fold_combine_Leaf*.
2. Theorem 2, the correctness result about the function *sliding_window*, is formalized by *SWA.correctness*.

3 Alternative Slide Interface and Additional Operations

3.1 Alternative Slide Interface

The slide operation above takes the *entire* input sequence as a parameter. This is often impractical. We provide an alternative interface to the slide operation that takes only the *new* elements as a parameter.

abbreviation *atomic′* **where**
atomic′ as b idx ≡ *Node b b* (*Some* (*nth as idx*)) *Leaf Leaf*

abbreviation *atomics′* :: *′a list* ⇒ *nat* ⇒ *nat* ⇒ *nat* ⇒ *′a tree list* **where**
atomics′ as i j sidx ≡ *map* (λ*b*. *atomic′ as b* (*b* − *sidx*)) (*rev* [*i* ..< *Suc j*])

definition *slide′* :: *′a* :: *semigroup_add list* ⇒ *′a tree* ⇒ *window* ⇒ *′a tree* **where**
slide′ as t w =
(*let*
ts = *atomics′ as* (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*) (*Suc* (*r t*));
ts′ = *reusables t w*
in fold combine (*ts* @ *ts′*) *Leaf*)

lemma *slide_eq_slide′*:
assumes *0* < *fst w fst w* ≤ *snd w valid as t r t* = *length as l t* ≤ *fst w r t* ≤ *snd w snd w* ≤ *length* (*as* @ *as′*)
shows *slide* (*as* @ *as′*) *t w* = *slide′ as′ t w*
proof (*cases r t* = *snd w*)
case *True*
with *assms* **have** ∗: *atomics′* (*as* @ *as′*) (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*) *1* = []
by *simp*
from *True assms* **have** *atomics′ as′* (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*) (*Suc* (*r t*)) = []
by *simp*
with ∗ **show** *?thesis*
unfolding *slide_def slide′_def atomics_def* **by** *simp*
next
case *False*
with *assms* **have** *r t* < *snd w*
by *simp*
with *assms* **have** *atomic′* (*as* @ *as′*) (*snd w*) (*snd w* − *Suc 0*) = *atomic′ as′* (*snd w*) (*snd w* − *Suc* (*length as*))
by (*simp add*: *leD nth_append*)
with *assms* **have** ∗: ∀ *i*. *i* ∈ *set* ([*max* (*fst w*) (*Suc* (*length as*))..<*snd w*]) ⟶ *atomic′* (*as* @ *as′*) *i* (*i* − *Suc 0*) = *atomic′ as′ i* (*i* − *Suc* (*length as*))
by (*auto simp*: *nth_append*)
then have *map* (λ*i*. *atomic′* (*as* @ *as′*) *i* (*i* − *Suc 0*)) (*rev* [*max* (*fst w*) (*Suc* (*length as*))..<*snd w*]) = *map* (λ*b*. *atomic′ as′ b* (*b* − *Suc* (*r t*))) (*rev* [*max* (*fst w*) (*Suc* (*r t*))..<*snd w*])
by (*simp add*: *assms*(*4*))
with *assms* **have** *atomics′* (*as* @ *as′*) (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*) *1* = *atomics′ as′* (*max* (*fst w*) (*Suc* (*r t*))) (*snd w*) (*Suc* (*r t*))
by (*auto simp*: *nth_append*)
then show *?thesis*
unfolding *slide_def slide′_def atomics_def*
by *presburger*
qed

lemma *sum_eq_sum_append*: ⟦*0* < *i*; *i* ≤ *j*; *j* ≤ *length as*⟧ ⟹ *sum as i j* = *sum* (*as* @ *as′*) *i j*
proof −
assume *assms*: *0* < *i i* ≤ *j j* ≤ *length as*
then have ∗: *rev* (*map* ((!) *as*) [*i* − *Suc 0*..<*j* − *Suc 0*]) = *rev* (*map* ((!) (*as*@*as′*)) [*i* − *Suc 0*..<*j* −

Suc 0])
  by (*auto simp*: *nth_append*)
 from *assms* **have** *as* ! (*j* − *Suc 0*) = (*as* @ *as'*) ! (*j* − *Suc 0*)
  by (*auto simp*: *nth_append*)
 then show *?thesis*
  by (*simp add*: ∗)
qed

lemma *well_valued0_append*: ⟦*well_shaped t*; *well_valued0 as t*⟧ ⟹ *well_valued0* (*as* @ *as'*) *t*
proof (*induction t*)
 case (*Node i j a t1 t2*)
 then show *?case*
  using *sum_eq_sum_append*
  by (*auto 4 0*)
qed *simp*

lemma *valid_append*: *valid as t* ⟹ *valid* (*as* @ *as'*) *t*
 unfolding *valid_def*
 by (*auto intro*: *well_valued0_append*)

lemma *valid_slide_append*: ⟦*0* < *fst w*; *fst w* ≤ *snd w*; *valid as t*; *l t* ≤ *fst w*; *r t* ≤ *snd w*; *snd w* ≤ *length as* + *length as'*⟧ ⟹
 valid (*as* @ *as'*) (*slide* (*as* @ *as'*) *t w*) ∧ *l* (*slide* (*as* @ *as'*) *t w*) = *fst w* ∧ *r* (*slide* (*as* @ *as'*) *t w*) = *snd w*
 by (*auto simp*: *valid_append valid_slide*)

theorem *valid_slide'*:
 assumes *0* < *fst w fst w* ≤ *snd w valid as t length as* = *r t length as'* ≥ *snd w* − *r t l t* ≤ *fst w r t* ≤ *snd w*
 shows *valid* (*as* @ *as'*) (*slide' as' t w*) ∧ *l* (*slide' as' t w*) = *fst w* ∧ *r* (*slide' as' t w*) = *snd w*
proof −
 from *assms* **have** *valid* (*as* @ *as'*) (*slide* (*as* @ *as'*) *t w*) ∧ *l* (*slide* (*as* @ *as'*) *t w*) = *fst w* ∧ *r* (*slide* (*as* @ *as'*) *t w*) = *snd w*
  using *valid_slide_append* **by** (*metis add_le_cancel_left le_add_diff_inverse*)
 with *assms* **show** *?thesis*
  using *slide_eq_slide'* **by** (*metis add_le_cancel_left le_add_diff_inverse length_append*)
qed

3.2 Updating all Values in the Tree

So far, we have assumed that the sequence is fixed. However, under certain conditions, SWA can be applied even if the sequence changes. In particular, if a function that distributes over the associative operation is mapped onto the sequence, validity of the tree can be preserved by mapping the same function onto the tree using *map_tree*.

lemma *map_tree_eq_Leaf_iff*: *map_tree f t* = *Leaf* ⟷ *t* = *Leaf*
 by *simp*

lemma *l_map_tree_eq_l*[*simp*]: *l* (*map_tree f t*) = *l t*
 by (*cases t*)
  (*auto split*: *option.splits*)

lemma *r_map_tree_eq_r*[*simp*]: *r* (*map_tree f t*) = *r t*
 by (*cases t*)
  (*auto split*: *option.splits*)

lemma *val_map_tree_neq_None*: *val t* ≠ *None* ⟹ *val* (*map_tree f t*) ≠ *None*
 by (*cases t*) *auto*

lemma *well_shaped_map_tree*: *well_shaped t* $\Longrightarrow$ *well_shaped* (*map_tree f t*)
by (*induction t*)
(*auto split*: *option.split*)

lemma *fold_distr*: ($\forall$ *x y*. *f* (*x* + *y*) = *f x* + *f y*) $\Longrightarrow$ *f* (*fold* (+) *list e*) = *fold* (+) (*map f list*) (*f e*)
by (*induction list arbitrary*: *e*) *auto*

lemma *map_rev_map_nth_eq*: $\forall$ *x* $\in$ *set xs*. *x* < *length as* $\Longrightarrow$ *map f* (*rev* (*map* ((!) *as*) *xs*)) = *rev* (*map* ((!) (*map f as*)) *xs*)
by (*simp add*: *rev_map*)

lemma *f_nth_eq_map_f_nth*: $[\![$*as* $\neq$ []; *length as* $\geq$ *n*$]\!]$ $\Longrightarrow$ *f* (*as* ! (*n* − *Suc 0*)) = *map f as* ! (*n* − *Suc 0*)
by (*cases n* = *length as*) *auto*

lemma *well_valued0_map_map_tree*:
$[\![\forall$ *x y*. *f* (*x* + *y*) = *f x* + *f y*; *well_shaped t*; *well_valued0 as t*; *r t* $\leq$ *length as*; *as* $\neq$ []$]\!]$ $\Longrightarrow$
well_shaped (*map_tree f t*) $\wedge$ *well_valued0* (*map f as*) (*map_tree f t*)
proof (*rule conjI*[*OF well_shaped_map_tree*], *assumption*, *induction t*)
case (*Node i j a t1 t2*)
then have *map f* (*rev* (*map* ((!) *as*) [*l t1* − *Suc 0*..<*r t2* − *Suc 0*])) =
rev (*map* ((!) (*map f as*)) [*l t1* − *Suc 0*..<*r t2* − *Suc 0*])
by (*subst map_rev_map_nth_eq*) *auto*
moreover from *Node* **have** *r t1* $\leq$ *length as*
by (*cases t1*) *auto*
ultimately show *?case* **using** *Node*(*3*−*7*)
by (*auto simp*: *fold_distr*[*of f*] *val_map_tree_neq_None*
well_shaped_map_tree intro!: *Node*(*1*,*2*))
qed *simp*

lemma *valid_map_map_tree*:
assumes $\forall$ *x y*. *f* (*x* + *y*) = *f x* + *f y valid as t r t* $\leq$ *length as*
shows *valid* (*map f as*) (*map_tree f t*)
proof (*cases as* $\neq$ [])
case *True*
with *assms* **show** *?thesis*
by (*metis map_tree_eq_Leaf_iff val_map_tree_neq_None valid_def well_valued0_map_map_tree*)
next
case *False*
with *assms* **show** *?thesis*
by (*metis le_zero_eq list.size*(*3*) *tree.exhaust_sel map_tree_eq_Leaf_iff valid_Leaf valid_def well_shaped.simps*(*2*) *well_valued0.simps*(*2*))
qed

lemma *valid_Nil_iff*: *valid* [] *t* $\longleftrightarrow$ *t* = *Leaf*
unfolding *valid_def*
proof
assume *well_shaped t* $\wedge$ *well_valued* [] *t*
then show *t* = *Leaf*
by (*metis le_neq_implies_less list.size*(*3*) *not_less_zero tree.collapse well_shaped.simps*(*2*) *well_valued0.simps*(*2*))
qed *simp*

3.3 Updating the Rightmost Leaf of the Tree

We provide a function to update the rightmost leaf of the tree. This may be used in an online setting where the input sequence is not known in advance to update the latest observed element using the same associative operation used in SWA. We show that validity of the tree is preserved

in this case.

```
fun update_rightmost :: ('a ⇒ 'a) ⇒ 'a tree ⇒ 'a tree where
  update_rightmost _ Leaf = Leaf
| update_rightmost f (Node i j a t u) = Node i j (map_option f a) t (update_rightmost f u)

lemma update_rightmost_eq_Leaf_iff: update_rightmost f t = Leaf ⟷ t = Leaf
  by (cases t)
    (auto split: option.splits)

lemma l_update_rightmost_eq_l[simp]: l (update_rightmost f t) = l t
  by (cases t)
    (auto split: option.splits)

lemma r_update_rightmost_eq_r[simp]: r (update_rightmost f t) = r t
  by (cases t)
    (auto split: option.splits)

lemma val_update_rightmost_neq_None: val t ≠ None ⟹ val (update_rightmost f t) ≠ None
  by (cases t) auto

lemma well_shaped_update_rightmost: well_shaped t ⟹ well_shaped (update_rightmost f t)
  by (induction t)
    (auto simp: update_rightmost_eq_Leaf_iff split: option.split)

lemma sum_eq_sum_prepend: ⟦0 < i; i ≤ j; length xs < i; length ys = length xs⟧ ⟹ sum (xs @ as) i
j = sum (ys @ as) i j
proof −
  assume assms: 0 < i i ≤ j length xs < i length ys = length xs
  then have ∗: rev (map ((!) (xs @ as)) [i − Suc 0..<j − Suc 0]) = rev (map ((!) (ys @ as)) [i − Suc
0..<j − Suc 0])
    by (auto simp: nth_append)
  from assms have (xs @ as) ! (j − Suc 0) = (ys @ as) ! (j − Suc 0)
    by (auto simp: nth_append)
  then show ?thesis
    by (simp add: ∗)
qed

lemma well_valued0_prepend: ⟦length xs ≤ l t − 1; length ys = length xs; well_shaped t; well_valued0
(xs @ as) t⟧ ⟹ well_valued0 (ys @ as) t
proof (induction t)
  case (Node i j a t1 t2)
  then have well_valued0_t1: well_valued0 (ys @ as) t1
    by auto
  from Node have well_valued0 (ys @ as) t2
  proof (cases a)
    case None
    with Node show ?thesis
      by auto
        (metis One_nat_def Suc_pred diff_Suc_1 le_Suc_eq le_Suc_ex trans_le_add1 tree.exhaust_sel
well_shaped.simps(2))
  next
    case (Some a')
    with Node show ?thesis
      by auto
        (metis One_nat_def diff_Suc_1 diff_le_self le_trans tree.exhaust_sel well_shaped.simps(2))
  qed
  with Node well_valued0_t1 show ?case
  proof −
```

have *f1*: *0 < i ∧ j ≤ length (xs @ as) ∧ (a = None ∨ a = Some (SWA.sum (xs @ as) i j)) ∧ well_valued0 (xs @ as) t1 ∧ well_valued0 (xs @ as) t2 ∧ (t2 = Leaf ∨ val t2 ≠ None)*
by (*meson ‹well_valued0 (xs @ as) (Node i j a t1 t2)› well_valued0.simps(2)*)
then have *f2*: *j ≤ length (ys @ as)*
by (*simp add*: *‹length ys = length xs›*)
have *a = None ∨ a = Some (SWA.sum (ys @ as) i j)*
using *f1* **by** (*metis Node.prems(1) Node.prems(2) Node.prems(3) One_nat_def Suc_pred le_imp_less_Suc sum_eq_sum_prepend tree.sel(2) well_shaped.simps(2)*)
then show *?thesis*
using *f2 f1 ‹well_valued0 (ys @ as) t2› well_valued0.simps(2) well_valued0_t1* **by** *blast*
qed
qed *simp*

lemma *valid_prepend*: *⟦length xs ≤ l t − 1; length ys = length xs; valid (xs @ as) t⟧ ⟹ valid (ys @ as) t*
unfolding *valid_def*
by (*auto intro*: *well_valued0_prepend*)

lemma *take_eq_append_take_take_drop*: *m ≤ n ⟹ take n xs = take m xs @ take (n−m) (drop m xs)*
proof (*induction xs*)
case (*Cons a xs*)
then show *?case*
by (*metis le_add_diff_inverse take_add*)
qed *simp*

lemma *well_valued0_take_r*: *⟦well_shaped t; well_valued0 as t⟧ ⟹ well_valued0 (take (r t) as) t*
proof (*induction t*)
case (*Node i j a t1 t2*)
from *Node* **have** *well_valued0_t1*: *well_valued0 (take j as) t1*
proof −
from *Node* **have** *r t1 ≤ j*
using *r_lchild_le_r* **by** (*metis tree.sel(4) tree.sel(8)*)
with *Node* **have** *take j as = take (r t1) as @ take (j − r t1) (drop (r t1) as)*
using *take_eq_append_take_take_drop*[*of r t1 j as*] **by** *simp*
with *Node* **show** *?thesis*
by (*auto intro*!: *well_valued0_append*)
qed
from *Node* **have** *well_valued0_t2*: *well_valued0 (take j as) t2*
by *auto*
from *Node* **have** *sum_eq*: *fold (+) (rev (map ((!) as) [l t1 − Suc 0..<r t2 − Suc 0])) (as ! (r t2 − Suc 0)) =*
fold (+) (rev (map ((!) (take (r t2) as)) [l t1 − Suc 0..<r t2 − Suc 0])) (as ! (r t2 − Suc 0))
by (*intro arg_cong*[**where** *f*=*λxs. fold _ xs _*]) *auto*
from *Node well_valued0_t1 well_valued0_t2 sum_eq* **show** *?case*
by *auto*
qed *simp*

lemma *valid_take_r*: *valid as t ⟹ valid (take (r t) as) t*
unfolding *valid_def*
by (*auto intro*: *well_valued0_take_r*)

lemma *well_valued0_butlast*: *⟦well_shaped t; well_valued0 as t; r t < length as⟧ ⟹ well_valued0 (butlast as) t*
proof (*induction t*)
case (*Node i j a t1 t2*)
then have *r_le_length*: *j ≤ length (butlast as)*
by *simp*
from *Node* **have** *i > 0*

```
    by simp
  with r_le_length Node have sum_eq: sum as i j = sum (butlast as) i j
    by (metis append_butlast_last_id le_zero_eq less_imp_le_nat list.size(3) neq_iff
      sum_eq_sum_append well_shaped.simps(2))
  from Node have r t1 < length as
    by (metis dual_order.strict_trans2 r_lchild_le_r tree.sel(8))
  with Node r_le_length show ?case
    by (metis (no_types, lifting) dual_order.strict_iff_order sum_eq tree.sel(10) tree.sel(4)
      well_shaped.simps(2) well_shaped_rchild well_valued0.simps(2))
qed simp

lemma well_valued0_append_butlast_lchild: ⟦well_shaped t; well_valued0 as t⟧ ⟹
  well_valued0 (butlast as @ [last as + x]) (lchild t)
proof (cases t)
  case (Node i j a t1 t2)
  assume assms: well_shaped t well_valued0 as t
  from Node assms have r t1 < length as
    by (fastforce dest: well_shaped_lr)
  with Node assms show ?thesis
    by (auto simp: well_valued0_butlast well_valued0_append)
qed simp

lemma sum_update_rightmost: ⟦0 < i; i ≤ j; length as = j⟧ ⟹
  sum as i j + x = sum (butlast as @ [last as + x]) i j
  by (cases as)
    (auto simp: nth_append[abs_def] fold_add_add last_conv_nth nth_Cons' nth_butlast
     intro!: arg_cong2[where f=(+)] arg_cong[where f=λxs. fold _ xs _])

lemma well_valued0_update_rightmost: ⟦well_shaped t; well_valued0 as t; length as = r t⟧ ⟹
  well_valued0 (butlast as @ [last as + x]) (update_rightmost (λa. a + x) t)
proof (induction t)
  case Leaf
  then show ?case
    by (auto simp add: valid_Leaf)
next
  case (Node i j a t1 t2)
  moreover
  from Node have well_valued0_t1: well_valued0 (butlast as @ [last as + x]) t1
    using well_valued0_append_butlast_lchild by (metis tree.sel(8))
  moreover
  from Node have well_valued0_t2:
    well_valued0 (butlast as @ [last as + x]) (update_rightmost ((λa. a + x)) t2)
    by (metis ‹well_valued0 (butlast as @ [last as + x]) t1› dual_order.strict_iff_order
      tree.sel(4) update_rightmost.simps(1) well_shaped.simps(2) well_valued0.simps(2))
  ultimately show ?case
    using sum_update_rightmost
    by (cases a) (auto simp: val_update_rightmost_neq_None)
qed


lemma valid_update_rightmost: ⟦valid as t; length as = r t⟧ ⟹
  valid (butlast as @ [last as + x]) (update_rightmost (λa. a + x) t)
  unfolding valid_def
  using well_valued0_update_rightmost
 by (metis update_rightmost.simps(1) val_update_rightmost_neq_None well_shaped_update_rightmost)
```

References

[1] D. Basin, F. Klaedtke, and E. Zălinescu. Greedily computing associative aggregations on sliding windows. *Information Processing Letters*, 115(2):186 – 192, 2015.