A Formal Development of a Polychronous Polytimed Coordination Language

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Chapter 1

A Gentle Introduction to TESL

1.1 Context

The design of complex systems involves different formalisms for modeling their different parts or aspects. The global model of a system may therefore consist of a coordination of concurrent sub-models that use different paradigms such as differential equations, state machines, synchronous data-flow networks, discrete event models and so on, as illustrated in Figure 1.1. This raises the interest in architectural composition languages that allow for "bolting the respective sub-models together", along their various interfaces, and specifying the various ways of collaboration and coordination [2].

We are interested in languages that allow for specifying the timed coordination of subsystems by addressing the following conceptual issues:

- events may occur in different sub-systems at unrelated times, leading to *polychronous* systems, which do not necessarily have a common base clock,

- the behavior of the sub-systems is observed only at a series of discrete instants, and time coordination has to take this *discretization* into account,

- the instants at which a system is observed may be arbitrary and should not change its behavior (*stuttering invariance*),

- coordination between subsystems involves causality, so the occurrence of an event may enforce the occurrence of other events, possibly after a certain duration has elapsed or an event has occurred a given number of times,

- the domain of time (discrete, rational, continuous. . .) may be different in the subsystems, leading to *polytimed* systems,

- the time frames of different sub-systems may be related (for instance, time in a GPS satellite and in a GPS receiver on Earth are related although they are not the same).

In order to tackle the heterogeneous nature of the subsystems, we abstract their behavior as clocks. Each clock models an event, i.e., something that can occur or not at a given time. This time is measured in a time frame associated with each clock, and the nature of time (integer, rational, real, or any type with a linear order) is specific to each clock. When the event associated

Timed Finite State Machine

Lustre/SCADE

Ordinary Differential Equations

$$\frac{\partial Q}{\partial t} = \frac{\partial^2 s}{\partial t} + 2\frac{\partial r}{\partial x}$$
$$\frac{\partial Q}{\partial x} = \frac{\partial r}{\partial t \partial x} - \frac{\partial s}{\partial x}$$
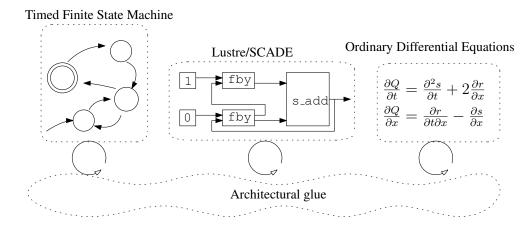
Architectural glue

Figure 1.1: A Heterogeneous Timed System Model

with a clock occurs, the clock ticks. In order to support any kind of behavior for the subsystems, we are only interested in specifying what we can observe at a series of discrete instants. There are two constraints on observations: a clock may tick only at an observation instant, and the time on any clock cannot decrease from an instant to the next one. However, it is always possible to add arbitrary observation instants, which allows for stuttering and modular composition of systems. As a consequence, the key concept of our setting is the notion of a clock-indexed Kripke model: $\Sigma^\infty = \mathbb{N} \to \mathcal{K} \to (\mathbb{B} \times \mathcal{T})$, where $\mathcal{K}$ is an enumerable set of clocks, $\mathbb{B}$ is the set of booleans – used to indicate that a clock ticks at a given instant – and $\mathcal{T}$ is a universal metric time space for which we only assume that it is large enough to contain all individual time spaces of clocks and that it is ordered by some linear ordering ($\leq_\mathcal{T}$).

The elements of Σ^∞ are called runs. A specification language is a set of operators that constrains the set of possible monotonic runs. Specifications are composed by intersecting the denoted run sets of constraint operators. Consequently, such specification languages do not limit the number of clocks used to model a system (as long as it is finite) and it is always possible to add clocks to a specification. Moreover, they are *compositional* by construction since the composition of specifications consists of the conjunction of their constraints.

This work provides the following contributions:

- defining the non-trivial language TESL* in terms of clock-indexed Kripke models,

- proving that this denotational semantics is stuttering invariant,

- defining an adapted form of symbolic primitives and presenting the set of operational semantic rules,

- presenting formal proofs for soundness, completeness, and progress of the latter.

1.2   The TESL Language

The TESL language [1] was initially designed to coordinate the execution of heterogeneous components during the simulation of a system. We define here a minimal kernel of operators that

will form the basis of a family of specification languages, including the original TESL language, which is described at http://wdi.supelec.fr/software/TESL/.

1.2.1 Instantaneous Causal Operators

TESL has operators to deal with instantaneous causality, i.e., to react to an event occurrence in the very same observation instant.

- `c1 implies c2` means that at any instant where `c1` ticks, `c2` has to tick too.

- `c1 implies not c2` means that at any instant where `c1` ticks, `c2` cannot tick.

- `c1 kills c2` means that at any instant where `c1` ticks, and at any future instant, `c2` cannot tick.

1.2.2 Temporal Operators

TESL also has chronometric temporal operators that deal with dates and chronometric delays.

- `c sporadic t` means that clock `c` must have a tick at time `t` on its own time scale.

- `c1 sporadic t on c2` means that clock `c1` must have a tick at an instant where the time on `c2` is `t`.

- `c1 time delayed by d on m implies c2` means that every time clock `c1` ticks, `c2` must have a tick at the first instant where the time on `m` is `d` later than it was when `c1` had ticked. This means that every tick on `c1` is followed by a tick on `c2` after a delay `d` measured on the time scale of clock `m`.

- `time relation (c1, c2) in R` means that at every instant, the current time on clocks `c1` and `c2` must be in relation `R`. By default, the time lines of different clocks are independent. This operator allows us to link two time lines, for instance to model the fact that time in a GPS satellite and time in a GPS receiver on Earth are not the same but are related. Time being polymorphic in TESL, this can also be used to model the fact that the angular position on the camshaft of an engine moves twice as fast as the angular position on the crankshaft [1]. We may consider only linear arithmetic relations to restrict the problem to a domain where the resolution is decidable.

1.2.3 Asynchronous Operators

The last category of TESL operators allows the specification of asynchronous relations between event occurrences. They do not specify the precise instants at which ticks have to occur, they only put bounds on the set of instants at which they should occur.

- `c1 weakly precedes c2` means that for each tick on `c2`, there must be at least one tick on `c1` at a previous or at the same instant. This can also be expressed by stating that at each instant, the number of ticks since the beginning of the run must be lower or equal on `c2` than on `c1`.

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[1]See http://wdi.supelec.fr/software/TESL/GalleryEngine for more details

- `c1 strictly precedes c2` means that for each tick on `c2`, there must be at least one tick on `c1` at a previous instant. This can also be expressed by saying that at each instant, the number of ticks on `c2` from the beginning of the run to this instant, must be lower or equal to the number of ticks on `c1` from the beginning of the run to the previous instant.

Chapter 2

The Core of the TESL Language: Syntax and Basics

theory TESL
imports Main

begin

2.1 Syntactic Representation

We define here the syntax of TESL specifications.

2.1.1 Basic elements of a specification

The following items appear in specifications:

- Clocks, which are identified by a name.

- Tag constants are just constants of a type which denotes the metric time space.

datatype   clock   = Clk ⟨string⟩
type_synonym instant_index = ⟨nat⟩

datatype   'τ tag_const = TConst   (the_tag_const : 'τ)   ("$τ_{cst}$")

2.1.2 Operators for the TESL language

The type of atomic TESL constraints, which can be combined to form specifications.

```
datatype 'τ TESL_atomic =
    SporadicOn       ⟨clock⟩ ⟨'τ tag_const⟩ ⟨clock⟩  ("_ sporadic _ on _" 55)
  | TagRelation      ⟨clock⟩ ⟨clock⟩ ⟨('τ tag_const × 'τ tag_const) ⇒ bool⟩
                                                    ("time-relation ⌊_, _⌋ ∈ _" 55)
  | Implies          ⟨clock⟩ ⟨clock⟩                (infixr "implies" 55)
  | ImpliesNot       ⟨clock⟩ ⟨clock⟩                (infixr "implies not" 55)
  | TimeDelayedBy    ⟨clock⟩ ⟨'τ tag_const⟩ ⟨clock⟩ ⟨clock⟩
                                                    ("_ time-delayed by _ on _ implies _" 55)
```

```
| WeaklyPrecedes   ⟨clock⟩ ⟨clock⟩              (infixr "weakly precedes" 55)
| StrictlyPrecedes ⟨clock⟩ ⟨clock⟩              (infixr "strictly precedes" 55)
| Kills            ⟨clock⟩ ⟨clock⟩              (infixr "kills" 55)
```

A TESL formula is just a list of atomic constraints, with implicit conjunction for the semantics.

type_synonym 'τ TESL_formula = ⟨'τ TESL_atomic list⟩

We call *positive atoms* the atomic constraints that create ticks from nothing. Only sporadic constraints are positive in the current version of TESL.

fun positive_atom :: ⟨'τ TESL_atomic ⇒ bool⟩ **where**
    ⟨positive_atom (_ sporadic _ on _) = True⟩
  | ⟨positive_atom _   = False⟩

The `NoSporadic` function removes sporadic constraints from a TESL formula.

abbreviation NoSporadic :: ⟨'τ TESL_formula ⇒ 'τ TESL_formula⟩
where
  ⟨NoSporadic f ≡ (List.filter (λf$_{atom}$. case f$_{atom}$ of
      _ sporadic _ on _ ⇒ False
    | _ ⇒ True) f)⟩

2.1.3   Field Structure of the Metric Time Space

In order to handle tag relations and delays, tags must belong to a field. We show here that this is the case when the type parameter of 'τ `tag_const` is itself a field.

instantiation tag_const ::(field)field
begin
  fun inverse_tag_const
  where ⟨inverse (τ_{cst} t) = τ_{cst} (inverse t)⟩

  fun divide_tag_const
    where ⟨divide (τ_{cst} t$_1$) (τ_{cst} t$_2$) = τ_{cst} (divide t$_1$ t$_2$)⟩

  fun uminus_tag_const
    where ⟨uminus (τ_{cst} t) = τ_{cst} (uminus t)⟩

fun minus_tag_const
  where ⟨minus (τ_{cst} t$_1$) (τ_{cst} t$_2$) = τ_{cst} (minus t$_1$ t$_2$)⟩

definition ⟨one_tag_const ≡ τ_{cst} 1⟩

fun times_tag_const
  where ⟨times (τ_{cst} t$_1$) (τ_{cst} t$_2$) = τ_{cst} (times t$_1$ t$_2$)⟩

definition ⟨zero_tag_const ≡ τ_{cst} 0⟩

fun plus_tag_const
  where ⟨plus (τ_{cst} t$_1$) (τ_{cst} t$_2$) = τ_{cst} (plus t$_1$ t$_2$)⟩

instance proof

Multiplication is associative.

  fix a::⟨'τ::field tag_const⟩ **and** b::⟨'τ::field tag_const⟩
                            and c::⟨'τ::field tag_const⟩
  obtain u v w **where** ⟨a = τ_{cst} u⟩ **and** ⟨b = τ_{cst} v⟩ **and** ⟨c = τ_{cst} w⟩
    using tag_const.exhaust **by** metis

```
    thus ⟨a * b * c = a * (b * c)⟩
      by (simp add: TESL.times_tag_const.simps)
next
```

Multiplication is commutative.

```
  fix a::⟨'τ::field tag_const⟩ and b::⟨'τ::field tag_const⟩
  obtain u v where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ using tag_const.exhaust by metis
  thus ⟨ a * b = b * a⟩
    by (simp add: TESL.times_tag_const.simps)
next
```

One is neutral for multiplication.

```
  fix a::⟨'τ::field tag_const⟩
  obtain u where ⟨a = τ_cst u⟩ using tag_const.exhaust by blast
  thus ⟨1 * a = a⟩
    by (simp add: TESL.times_tag_const.simps one_tag_const_def)
next
```

Addition is associative.

```
  fix a::⟨'τ::field tag_const⟩ and b::⟨'τ::field tag_const⟩
                             and c::⟨'τ::field tag_const⟩
  obtain u v w where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ and ⟨c = τ_cst w⟩
    using tag_const.exhaust by metis
  thus ⟨a + b + c = a + (b + c)⟩
    by (simp add: TESL.plus_tag_const.simps)
next
```

Addition is commutative.

```
  fix a::⟨'τ::field tag_const⟩ and b::⟨'τ::field tag_const⟩
  obtain u v where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ using tag_const.exhaust by metis
  thus ⟨a + b = b + a⟩
    by (simp add: TESL.plus_tag_const.simps)
next
```

Zero is neutral for addition.

```
  fix a::⟨'τ::field tag_const⟩
  obtain u where ⟨a = τ_cst u⟩ using tag_const.exhaust by blast
  thus ⟨0 + a = a⟩
    by (simp add: TESL.plus_tag_const.simps zero_tag_const_def)
next
```

The sum of an element and its opposite is zero.

```
  fix a::⟨'τ::field tag_const⟩
  obtain u where ⟨a = τ_cst u⟩ using tag_const.exhaust by blast
  thus ⟨-a + a = 0⟩
    by (simp add: TESL.plus_tag_const.simps
                  TESL.uminus_tag_const.simps
                  zero_tag_const_def)
next
```

Subtraction is adding the opposite.

```
  fix a::⟨'τ::field tag_const⟩ and b::⟨'τ::field tag_const⟩
  obtain u v where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ using tag_const.exhaust by metis
  thus ⟨a - b = a + -b⟩
    by (simp add: TESL.minus_tag_const.simps
```

```
                      TESL.plus_tag_const.simps
                      TESL.uminus_tag_const.simps)
next
```

Distributive property of multiplication over addition.

```
  fix a::⟨′τ::field tag_const⟩ and b::⟨′τ::field tag_const⟩
                          and c::⟨′τ::field tag_const⟩
  obtain u v w where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ and ⟨c = τ_cst w⟩
    using tag_const.exhaust by metis
  thus ⟨(a + b) * c = a * c + b * c⟩
    by (simp add: TESL.plus_tag_const.simps
                  TESL.times_tag_const.simps
                  ring_class.ring_distribs(2))
next
```

The neutral elements are distinct.

```
  show ⟨(0::(′τ::field tag_const)) ≠ 1⟩
    by (simp add: one_tag_const_def zero_tag_const_def)
next
```

The product of an element and its inverse is 1.

```
  fix a::⟨′τ::field tag_const⟩ assume h:⟨a ≠ 0⟩
  obtain u where ⟨a = τ_cst u⟩ using tag_const.exhaust by blast
  moreover with h have ⟨u ≠ 0⟩ by (simp add: zero_tag_const_def)
  ultimately show ⟨inverse a * a = 1⟩
    by (simp add: TESL.inverse_tag_const.simps
                  TESL.times_tag_const.simps
                  one_tag_const_def)
next
```

Dividing is multiplying by the inverse.

```
  fix a::⟨′τ::field tag_const⟩ and b::⟨′τ::field tag_const⟩
  obtain u v where ⟨a = τ_cst u⟩ and ⟨b = τ_cst v⟩ using tag_const.exhaust by metis
  thus ⟨a div b = a * inverse b⟩
    by (simp add: TESL.divide_tag_const.simps
                  TESL.inverse_tag_const.simps
                  TESL.times_tag_const.simps
                  divide_inverse)
next
```

Zero is its own inverse.

```
  show ⟨inverse (0::(′τ::field tag_const)) = 0⟩
    by (simp add: TESL.inverse_tag_const.simps zero_tag_const_def)
qed

end
```

For comparing dates (which are represented by tags) on clocks, we need an order on tags.

```
instantiation tag_const :: (order)order
begin
  inductive less_eq_tag_const :: ⟨′a tag_const ⇒ ′a tag_const ⇒ bool⟩
  where
    Int_less_eq[simp]:      ⟨n ≤ m ⟹ (TConst n) ≤ (TConst m)⟩

  definition less_tag: ⟨(x::′a tag_const) < y ⟷ (x ≤ y) ∧ (x ≠ y)⟩
```

```
instance proof
  show ⟨⋀x y :: 'a tag_const. (x < y) = (x ≤ y ∧ ¬ y ≤ x)⟩
    using less_eq_tag_const.simps less_tag by auto
next
  fix x::⟨'a tag_const⟩
  from tag_const.exhaust obtain x₀::'a where ⟨x = TConst x₀⟩ by blast
  with Int_less_eq show ⟨x ≤ x⟩ by simp
next
  show ⟨⋀x y z  :: 'a tag_const. x ≤ y ⟹ y ≤ z ⟹ x ≤ z⟩
    using less_eq_tag_const.simps by auto
next
  show ⟨⋀x y  :: 'a tag_const. x ≤ y ⟹ y ≤ x ⟹ x = y⟩
    using less_eq_tag_const.simps by auto
qed
```

end

For ensuring that time does never flow backwards, we need a total order on tags.

```
instantiation tag_const :: (linorder)linorder
begin
  instance proof
    fix x::⟨'a tag_const⟩ and y::⟨'a tag_const⟩
    from tag_const.exhaust obtain x₀::'a where ⟨x = TConst x₀⟩ by blast
    moreover from tag_const.exhaust obtain y₀::'a where ⟨y = TConst y₀⟩ by blast
    ultimately show ⟨x ≤ y ∨ y ≤ x⟩ using less_eq_tag_const.simps by fastforce
  qed
```

end

end

2.2 Defining Runs

```
theory Run
imports TESL
```

begin

Runs are sequences of instants, and each instant maps a clock to a pair `(h, t)` where `h` indicates whether the clock ticks or not, and `t` is the current time on this clock. The first element of the pair is called the *hamlet* of the clock (to tick or not to tick), the second element is called the *time*.

```
abbreviation hamlet where ⟨hamlet ≡ fst⟩
abbreviation time    where ⟨time ≡ snd⟩
```

```
type_synonym 'τ instant = ⟨clock ⟹ (bool × 'τ tag_const)⟩
```

Runs have the additional constraint that time cannot go backwards on any clock in the sequence of instants. Therefore, for any clock, the time projection of a run is monotonous.

```
typedef (overloaded) 'τ::linordered_field run =
  ⟨{ ϱ::nat ⟹ 'τ instant. ∀c. mono (λn. time (ϱ n c)) }⟩
proof
  show ⟨(λ_ _. (True, τ_cst 0)) ∈ {ϱ. ∀c. mono (λn. time (ϱ n c))}⟩
    unfolding mono_def by blast
qed
```

lemma `Abs_run_inverse_rewrite`:
  ⟨∀c. mono (λn. time (ϱ n c)) ⟹ Rep_run (Abs_run ϱ) = ϱ⟩
by (simp add: Abs_run_inverse)

A *dense* run is a run in which something happens (at least one clock ticks) at every instant.

definition ⟨dense_run ϱ ≡ (∀n. ∃c. hamlet ((Rep_run ϱ) n c))⟩

`run_tick_count` ϱ K n counts the number of ticks on clock K in the interval [0, n] of run ϱ.

fun `run_tick_count` :: ⟨('τ::linordered_field) run ⇒ clock ⇒ nat ⇒ nat⟩
  ("#$_\leq$ _ _ _")
where
  ⟨(#$_\leq$ ϱ K 0)   = (if hamlet ((Rep_run ϱ) 0 K)
                            then 1
                            else 0)⟩
| ⟨(#$_\leq$ ϱ K (Suc n)) = (if hamlet ((Rep_run ϱ) (Suc n) K)
                            then 1 + (#$_\leq$ ϱ K n)
                            else (#$_\leq$ ϱ K n))⟩

`run_tick_count_strictly` ϱ K n counts the number of ticks on clock K in the interval [0, n[of run ϱ.

fun `run_tick_count_strictly` :: ⟨('τ::linordered_field) run ⇒ clock ⇒ nat ⇒ nat⟩
  ("#$_<$ _ _ _")
where
  ⟨(#$_<$ ϱ K 0)   = 0⟩
| ⟨(#$_<$ ϱ K (Suc n)) = #$_\leq$ ϱ K n⟩

`first_time` ϱ K n τ tells whether instant n in run ϱ is the first one where the time on clock K reaches τ.

definition `first_time` :: ⟨'a::linordered_field run ⇒ clock ⇒ nat ⇒ 'a tag_const
                        ⇒ bool⟩
where
  ⟨first_time ϱ K n τ ≡ (time ((Rep_run ϱ) n K) = τ)
                      ∧ (∄n'. n' < n ∧ time ((Rep_run ϱ) n' K) = τ)⟩

The time on a clock is necessarily less than τ before the first instant at which it reaches τ.

lemma `before_first_time`:
  assumes ⟨first_time ϱ K n τ⟩
      and ⟨m < n⟩
    shows ⟨time ((Rep_run ϱ) m K) < τ⟩
proof -
  have ⟨mono (λn. time (Rep_run ϱ n K))⟩ **using** Rep_run **by** blast
  moreover from assms(2) **have** ⟨m ≤ n⟩ **using** less_imp_le **by** simp
  moreover have ⟨mono (λn. time (Rep_run ϱ n K))⟩ **using** Rep_run **by** blast
  ultimately have ⟨time ((Rep_run ϱ) m K) ≤ time ((Rep_run ϱ) n K)⟩
    by (simp add:mono_def)
  moreover from assms(1) **have** ⟨time ((Rep_run ϱ) n K) = τ⟩
    using first_time_def **by** blast
  moreover from assms **have** ⟨time ((Rep_run ϱ) m K) ≠ τ⟩
    using first_time_def **by** blast
  ultimately show ?thesis **by** simp
qed

This leads to an alternate definition of `first_time`:

lemma `alt_first_time_def`:
  assumes ⟨∀m < n. time ((Rep_run ϱ) m K) < τ⟩

```
      and ⟨time ((Rep_run ϱ) n K) = τ⟩
    shows ⟨first_time ϱ K n τ⟩
proof -
  from assms(1) have ⟨∀m < n. time ((Rep_run ϱ) m K) ≠ τ⟩
    by (simp add: less_le)
  with assms(2) show ?thesis by (simp add: first_time_def)
qed

end
```

Chapter 3

Denotational Semantics

theory Denotational
imports
    TESL
    Run

begin

The denotational semantics maps TESL formulae to sets of satisfying runs. Firstly, we define the semantics of atomic formulae (basic constructs of the TESL language), then we define the semantics of compound formulae as the intersection of the semantics of their components: a run must satisfy all the individual formulae of a compound formula.

3.1   Denotational interpretation for atomic TESL formulae

fun TESL_interpretation_atomic
    :: ⟨('τ::linordered_field) TESL_atomic ⇒ 'τ run set⟩ ("⟦ _ ⟧$_{TESL}$")
where
  — K$_1$ sporadic τ on K$_2$ means that K$_1$ should tick at an instant where the time on K$_2$ is τ.

  ⟨⟦ K$_1$ sporadic τ on K$_2$ ⟧$_{TESL}$ =
      {ϱ. ∃n::nat. hamlet ((Rep_run ϱ) n K$_1$) ∧ time ((Rep_run ϱ) n K$_2$) = τ}⟩
  — time-relation ⌊K$_1$, K$_2$⌋ ∈ R means that at each instant, the time on K$_1$ and the time on K$_2$ are in relation R.

  | ⟨⟦ time-relation ⌊K$_1$, K$_2$⌋ ∈ R ⟧$_{TESL}$ =
      {ϱ. ∀n::nat. R (time ((Rep_run ϱ) n K$_1$), time ((Rep_run ϱ) n K$_2$))}⟩
  — master implies slave means that at each instant at which master ticks, slave also ticks.

  | ⟨⟦ master implies slave ⟧$_{TESL}$ =
      {ϱ. ∀n::nat. hamlet ((Rep_run ϱ) n master) ⟶ hamlet ((Rep_run ϱ) n slave)}⟩
  — master implies not slave means that at each instant at which master ticks, slave does not tick.

  | ⟨⟦ master implies not slave ⟧$_{TESL}$ =
      {ϱ. ∀n::nat. hamlet ((Rep_run ϱ) n master) ⟶ ¬hamlet ((Rep_run ϱ) n slave)}⟩
  — master time-delayed by $\delta\tau$ on measuring implies slave means that at each instant at which master ticks, slave will tick after a delay $\delta\tau$ measured on the time scale of measuring.

  | ⟨⟦ master time-delayed by $\delta\tau$ on measuring implies slave ⟧$_{TESL}$ =
    — When master ticks, let's call t$_0$ the current date on measuring. Then, at the first instant when the date on measuring is t$_0$ + δt, slave has to tick.

        {ϱ. ∀n. hamlet ((Rep_run ϱ) n master) ⟶
                (let measured_time = time ((Rep_run ϱ) n measuring) in
                  ∀m ≥ n. first_time ϱ measuring m (measured_time + $\delta\tau$)

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```
                        ⟶ hamlet ((Rep_run ϱ) m slave)
                )
        }⟩
```
— K_1 weakly precedes K_2 means that each tick on K_2 must be preceded by or coincide with at least one tick on K_1. Therefore, at each instant n, the number of ticks on K_2 must be less or equal to the number of ticks on K_1.

| ⟨⟦ K_1 weakly precedes K_2 ⟧$_{TESL}$ =
        {ϱ. ∀n::nat. (run_tick_count ϱ K_2 n) ≤ (run_tick_count ϱ K_1 n)}⟩

— K_1 strictly precedes K_2 means that each tick on K_2 must be preceded by at least one tick on K_1 at a previous instant. Therefore, at each instant n, the number of ticks on K_2 must be less or equal to the number of ticks on K_1 at instant n - 1.

| ⟨⟦ K_1 strictly precedes K_2 ⟧$_{TESL}$ =
        {ϱ. ∀n::nat. (run_tick_count ϱ K_2 n) ≤ (run_tick_count_strictly ϱ K_1 n)}⟩

— K_1 kills K_2 means that when K_1 ticks, K_2 cannot tick and is not allowed to tick at any further instant.

| ⟨⟦ K_1 kills K_2 ⟧$_{TESL}$ =
        {ϱ. ∀n::nat. hamlet ((Rep_run ϱ) n K_1)
                        ⟶ (∀m≥n. ¬ hamlet ((Rep_run ϱ) m K_2))}⟩

3.2   Denotational interpretation for TESL formulae

To satisfy a formula, a run has to satisfy the conjunction of its atomic formulae. Therefore, the interpretation of a formula is the intersection of the interpretations of its components.

fun TESL_interpretation :: ⟨('τ::linordered_field) TESL_formula ⇒ 'τ run set⟩
  ("⟦⟦ _ ⟧⟧$_{TESL}$")
where
  ⟨⟦⟦ [] ⟧⟧$_{TESL}$ = {_. True}⟩
| ⟨⟦⟦ φ # Φ ⟧⟧$_{TESL}$ = ⟦ φ ⟧$_{TESL}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$⟩

lemma TESL_interpretation_homo:
  ⟨⟦ φ ⟧$_{TESL}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$ = ⟦⟦ φ # Φ ⟧⟧$_{TESL}$⟩
by simp

3.2.1   Image interpretation lemma

theorem TESL_interpretation_image:
  ⟨⟦⟦ Φ ⟧⟧$_{TESL}$ = ⋂ ((λφ. ⟦ φ ⟧$_{TESL}$) ' set Φ)⟩
by (induction Φ, simp+)

3.2.2   Expansion law

Similar to the expansion laws of lattices.

theorem TESL_interp_homo_append:
  ⟨⟦⟦ Φ_1 @ Φ_2 ⟧⟧$_{TESL}$ = ⟦⟦ Φ_1 ⟧⟧$_{TESL}$ ∩ ⟦⟦ Φ_2 ⟧⟧$_{TESL}$⟩
by (induction Φ_1, simp, auto)

3.3   Equational laws for the denotation of TESL formulae

lemma TESL_interp_assoc:
  ⟨⟦⟦ (Φ_1 @ Φ_2) @ Φ_3 ⟧⟧$_{TESL}$ = ⟦⟦ Φ_1 @ (Φ_2 @ Φ_3) ⟧⟧$_{TESL}$⟩
by auto

lemma TESL_interp_commute:
  shows ⟨⟦⟦ Φ_1 @ Φ_2 ⟧⟧$_{TESL}$ = ⟦⟦ Φ_2 @ Φ_1 ⟧⟧$_{TESL}$⟩
by (simp add: TESL_interp_homo_append inf_sup_aci(1))

```
lemma TESL_interp_left_commute:
  ⟨[[ Φ₁ @ (Φ₂ @ Φ₃) ]]_TESL = [[ Φ₂ @ (Φ₁ @ Φ₃) ]]_TESL⟩
unfolding TESL_interp_homo_append by auto

lemma TESL_interp_idem:
  ⟨[[ Φ @ Φ ]]_TESL = [[ Φ ]]_TESL⟩
using TESL_interp_homo_append by auto

lemma TESL_interp_left_idem:
  ⟨[[ Φ₁ @ (Φ₁ @ Φ₂) ]]_TESL = [[ Φ₁ @ Φ₂ ]]_TESL⟩
using TESL_interp_homo_append by auto

lemma TESL_interp_right_idem:
  ⟨[[ (Φ₁ @ Φ₂) @ Φ₂ ]]_TESL = [[ Φ₁ @ Φ₂ ]]_TESL⟩
unfolding TESL_interp_homo_append by auto

lemmas TESL_interp_aci = TESL_interp_commute
                         TESL_interp_assoc
                         TESL_interp_left_commute
                         TESL_interp_left_idem
```

The empty formula is the identity element.

```
lemma TESL_interp_neutral1:
  ⟨[[ [] @ Φ ]]_TESL = [[ Φ ]]_TESL⟩
by simp

lemma TESL_interp_neutral2:
  ⟨[[ Φ @ [] ]]_TESL = [[ Φ ]]_TESL⟩
by simp
```

3.4   Decreasing interpretation of TESL formulae

Adding constraints to a TESL formula reduces the number of satisfying runs.

```
lemma TESL_sem_decreases_head:
  ⟨[[ Φ ]]_TESL ⊇ [[ φ # Φ ]]_TESL⟩
by simp

lemma TESL_sem_decreases_tail:
  ⟨[[ Φ ]]_TESL ⊇ [[ Φ @ [φ] ]]_TESL⟩
by (simp add: TESL_interp_homo_append)
```

Repeating a formula in a specification does not change the specification.

```
lemma TESL_interp_formula_stuttering:
  assumes ⟨φ ∈ set Φ⟩
    shows ⟨[[ φ # Φ ]]_TESL = [[ Φ ]]_TESL⟩
proof -
  have ⟨φ # Φ = [φ] @ Φ⟩ by simp
  hence ⟨[[ φ # Φ ]]_TESL = [[ [φ] ]]_TESL ∩ [[ Φ ]]_TESL⟩
    using TESL_interp_homo_append by simp
  thus ?thesis using assms TESL_interpretation_image by fastforce
qed
```

Removing duplicate formulae in a specification does not change the specification.

```
lemma TESL_interp_remdups_absorb:
  ⟨[[ Φ ]]_TESL = [[ remdups Φ ]]_TESL⟩
```

```
proof (induction Φ)
  case Cons
    thus ?case using TESL_interp_formula_stuttering by auto
qed simp
```

Specifications that contain the same formulae have the same semantics.

```
lemma TESL_interp_set_lifting:
  assumes ⟨set Φ = set Φ'⟩
    shows ⟨[[ Φ ]]_TESL = [[ Φ' ]]_TESL⟩
proof -
  have ⟨set (remdups Φ) = set (remdups Φ')⟩
    by (simp add: assms)
  moreover have fxpntΦ: ⟨⋂ ((λφ. [ φ ]_TESL) ' set Φ) = [[ Φ ]]_TESL⟩
    by (simp add: TESL_interpretation_image)
  moreover have fxpntΦ': ⟨⋂ ((λφ. [ φ ]_TESL) ' set Φ') = [[ Φ' ]]_TESL⟩
    by (simp add: TESL_interpretation_image)
  moreover have ⟨⋂ ((λφ. [ φ ]_TESL) ' set Φ) = ⋂ ((λφ. [ φ ]_TESL) ' set Φ')⟩
    by (simp add: assms)
  ultimately show ?thesis using TESL_interp_remdups_absorb by auto
qed
```

The semantics of specifications is contravariant with respect to their inclusion.

```
theorem TESL_interp_decreases_setinc:
  assumes ⟨set Φ ⊆ set Φ'⟩
    shows ⟨[[ Φ ]]_TESL ⊇ [[ Φ' ]]_TESL⟩
proof -
  obtain Φ_r where decompose: ⟨set (Φ @ Φ_r) = set Φ'⟩ using assms by auto
  hence ⟨set (Φ @ Φ_r) = set Φ'⟩ using assms by blast
  moreover have ⟨(set Φ) ∪ (set Φ_r) = set Φ'⟩
    using assms decompose by auto
  moreover have ⟨[[ Φ' ]]_TESL = [[ Φ @ Φ_r ]]_TESL⟩
    using TESL_interp_set_lifting decompose by blast
  moreover have ⟨[[ Φ @ Φ_r ]]_TESL = [[ Φ ]]_TESL ∩ [[ Φ_r ]]_TESL⟩
    by (simp add: TESL_interp_homo_append)
  moreover have ⟨[[ Φ ]]_TESL ⊇ [[ Φ ]]_TESL ∩ [[ Φ_r ]]_TESL⟩ by simp
  ultimately show ?thesis by simp
qed
```

```
lemma TESL_interp_decreases_add_head:
  assumes ⟨set Φ ⊆ set Φ'⟩
    shows ⟨[[ φ # Φ ]]_TESL ⊇ [[ φ # Φ' ]]_TESL⟩
using assms TESL_interp_decreases_setinc by auto
```

```
lemma TESL_interp_decreases_add_tail:
  assumes ⟨set Φ ⊆ set Φ'⟩
    shows ⟨[[ Φ @ [φ] ]]_TESL ⊇ [[ Φ' @ [φ] ]]_TESL⟩
using TESL_interp_decreases_setinc[OF assms]
  by (simp add: TESL_interpretation_image dual_order.trans)
```

```
lemma TESL_interp_absorb1:
  assumes ⟨set Φ_1 ⊆ set Φ_2⟩
    shows ⟨[[ Φ_1 @ Φ_2 ]]_TESL = [[ Φ_2 ]]_TESL⟩
by (simp add: Int_absorb1 TESL_interp_decreases_setinc
                          TESL_interp_homo_append assms)
```

```
lemma TESL_interp_absorb2:
  assumes ⟨set Φ_2 ⊆ set Φ_1⟩
    shows ⟨[[ Φ_1 @ Φ_2 ]]_TESL = [[ Φ_1 ]]_TESL⟩
```

using `TESL_interp_absorb1 TESL_interp_commute assms` **by** `blast`

3.5   Some special cases

lemma `NoSporadic_stable` `[simp]`:
  ⟨$[\![\ \Phi\ ]\!]_{TESL} \subseteq [\![\ $`NoSporadic` $\Phi\ ]\!]_{TESL}$⟩
proof -
  from `filter_is_subset` **have** ⟨`set (NoSporadic` Φ`)` $\subseteq$ `set` Φ⟩ .
  from `TESL_interp_decreases_setinc`[OF this] **show** ?thesis .
qed

lemma `NoSporadic_idem` `[simp]`:
  ⟨$[\![\ \Phi\ ]\!]_{TESL} \cap [\![\ $`NoSporadic` $\Phi\ ]\!]_{TESL} = [\![\ \Phi\ ]\!]_{TESL}$⟩
using `NoSporadic_stable` **by** `blast`

lemma `NoSporadic_setinc`:
  ⟨`set (NoSporadic` Φ`)` $\subseteq$ `set` Φ⟩
by (**rule** `filter_is_subset`)

end

Chapter 4

Symbolic Primitives for Building Runs

theory `SymbolicPrimitive`
  imports `Run`

begin

We define here the primitive constraints on runs, towards which we translate TESL specifications in the operational semantics. These constraints refer to a specific symbolic run and can therefore access properties of the run at particular instants (for instance, the fact that a clock ticks at instant `n` of the run, or the time on a given clock at that instant).

In the previous chapters, we had no reference to particular instants of a run because the TESL language should be invariant by stuttering in order to allow the composition of specifications: adding an instant where no clock ticks to a run that satisfies a formula should yield another run that satisfies the same formula. However, when constructing runs that satisfy a formula, we need to be able to refer to the time or hamlet of a clock at a given instant.

Counter expressions are used to get the number of ticks of a clock up to (strictly or not) a given instant index.

datatype `cnt_expr =`
  `TickCountLess` ⟨clock⟩ ⟨instant_index⟩ `("#`$^<$`")`
`| TickCountLeq` ⟨clock⟩ ⟨instant_index⟩ `("#`$^\le$`")`

4.0.1 Symbolic Primitives for Runs

Tag values are used to refer to the time on a clock at a given instant index.

datatype `tag_val =`
  `TSchematic` ⟨clock * instant_index⟩ `("`τ_{var}`")`

datatype `'`τ` constr =`
— c $\Downarrow$ n @ τ constrains clock c to have time τ at instant n of the run.

  `Timestamp`   ⟨clock⟩   ⟨instant_index⟩ ⟨'τ tag_const⟩   `("_ `$\Downarrow$` _ @ _")`
— m @ n $\oplus$ δt $\Rightarrow$ s constrains clock s to tick at the first instant at which the time on m has increased by δt from the value it had at instant n of the run.
`| TimeDelay`   ⟨clock⟩   ⟨instant_index⟩ ⟨'τ tag_const⟩ ⟨clock⟩ `("_ @ _ `$\oplus$` _ `$\Rightarrow$` _")`
— c $\Uparrow$ n constrains clock c to tick at instant n of the run.

```
| Ticks          ⟨clock⟩   ⟨instant_index⟩                    ("_ ⇑ _")
```
— c ¬⇑ n constrains clock c not to tick at instant n of the run.
```
| NotTicks       ⟨clock⟩   ⟨instant_index⟩                    ("_ ¬⇑ _")
```
— c ¬⇑ < n constrains clock c not to tick before instant n of the run.
```
| NotTicksUntil ⟨clock⟩    ⟨instant_index⟩                    ("_ ¬⇑ < _")
```
— c ¬⇑ ≥ n constrains clock c not to tick at and after instant n of the run.
```
| NotTicksFrom  ⟨clock⟩    ⟨instant_index⟩                    ("_ ¬⇑ ≥ _")
```
— ⌊τ_1, τ_2⌋ ∈ R constrains tag variables τ_1 and τ_2 to be in relation R.
```
| TagArith      ⟨tag_val⟩ ⟨tag_val⟩ ⟨('τ tag_const × 'τ tag_const) ⇒ bool⟩ ("⌊_, _⌋ ∈ _")
```
— ⌈k_1, k_2⌉ ∈ R constrains counter expressions k_1 and k_2 to be in relation R.
```
| TickCntArith  ⟨cnt_expr⟩ ⟨cnt_expr⟩ ⟨(nat × nat) ⇒ bool⟩    ("⌈_, _⌉ ∈ _")
```
— k_1 ⪯ k_2 constrains counter expression k_1 to be less or equal to counter expression k_2.
```
| TickCntLeq    ⟨cnt_expr⟩ ⟨cnt_expr⟩                         ("_ ⪯ _")
```

```
type_synonym 'τ system = ⟨'τ constr list⟩
```

The abstract machine has configurations composed of:

- the past Γ, which captures choices that have already be made as a list of symbolic primitive constraints on the run;

- the current index n, which is the index of the present instant;

- the present Ψ, which captures the formulae that must be satisfied in the current instant;

- the future Φ, which captures the constraints on the future of the run.

```
type_synonym 'τ config =
                ⟨'τ system * instant_index * 'τ TESL_formula * 'τ TESL_formula⟩
```

4.1   Semantics of Primitive Constraints

The semantics of the primitive constraints is defined in a way similar to the semantics of TESL formulae.

```
fun counter_expr_eval :: ⟨('τ::linordered_field) run ⇒ cnt_expr ⇒ nat⟩
  ("⟦ _ ⊢ _ ⟧_{cntexpr}")
where
  ⟨⟦ ϱ ⊢ #< clk indx ⟧_{cntexpr} = run_tick_count_strictly ϱ clk indx⟩
| ⟨⟦ ϱ ⊢ #≤ clk indx ⟧_{cntexpr} = run_tick_count ϱ clk indx⟩
```


```
fun symbolic_run_interpretation_primitive
  ::⟨('τ::linordered_field) constr ⇒ 'τ run set⟩ ("⟦ _ ⟧_{prim}")
where
  ⟨⟦ K ⇑ n  ⟧_{prim}     = {ϱ. hamlet ((Rep_run ϱ) n K) }⟩
| ⟨⟦ K @ n_0 ⊕ δt ⇒ K' ⟧_{prim} =
                {ϱ. ∀n ≥ n_0. first_time ϱ K n (time ((Rep_run ϱ) n_0 K) + δt)
                        ⟶ hamlet ((Rep_run ϱ) n K')}⟩
| ⟨⟦ K ¬⇑ n ⟧_{prim}     = {ϱ. ¬hamlet ((Rep_run ϱ) n K) }⟩
| ⟨⟦ K ¬⇑ < n ⟧_{prim}   = {ϱ. ∀i < n. ¬ hamlet ((Rep_run ϱ) i K)}⟩
| ⟨⟦ K ¬⇑ ≥ n ⟧_{prim}   = {ϱ. ∀i ≥ n. ¬ hamlet ((Rep_run ϱ) i K) }⟩
| ⟨⟦ K ⇓ n @ τ ⟧_{prim} = {ϱ. time ((Rep_run ϱ) n K) = τ }⟩
| ⟨⟦ ⌊τ_{var}(K_1, n_1), τ_{var}(K_2, n_2)⌋ ∈ R ⟧_{prim} =
    { ϱ. R (time ((Rep_run ϱ) n_1 K_1), time ((Rep_run ϱ) n_2 K_2)) }⟩
```

| ⟨⟦ ⌈e$_1$, e$_2$⌉ ∈ R ⟧$_{prim}$ = { ϱ. R (⟦ ϱ ⊢ e$_1$ ⟧$_{cntexpr}$, ⟦ ϱ ⊢ e$_2$ ⟧$_{cntexpr}$) }⟩
| ⟨⟦ cnt_e$_1$ ⪯ cnt_e$_2$ ⟧$_{prim}$ = { ϱ. ⟦ ϱ ⊢ cnt_e$_1$ ⟧$_{cntexpr}$ ≤ ⟦ ϱ ⊢ cnt_e$_2$ ⟧$_{cntexpr}$ }⟩

The composition of primitive constraints is their conjunction, and we get the set of satisfying runs by intersection.

fun symbolic_run_interpretation
  ::⟨('τ::linordered_field) constr list ⇒ ('τ::linordered_field) run set⟩
  ("⟦⟦ _ ⟧⟧$_{prim}$")
where
  ⟨⟦⟦ [] ⟧⟧$_{prim}$ = {ϱ. True }⟩
| ⟨⟦⟦ γ # Γ ⟧⟧$_{prim}$ = ⟦ γ ⟧$_{prim}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}$⟩

lemma symbolic_run_interp_cons_morph:
  ⟨⟦ γ ⟧$_{prim}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}$ = ⟦⟦ γ # Γ ⟧⟧$_{prim}$⟩
by auto

definition consistent_context :: ⟨('τ::linordered_field) constr list ⇒ bool⟩
where
  ⟨consistent_context Γ ≡ (⟦⟦ Γ ⟧⟧$_{prim}$ ≠ {}) ⟩

4.1.1 Defining a method for witness construction

In order to build a run, we can start from an initial run in which no clock ticks and the time is always 0 on any clock.

abbreviation initial_run :: ⟨('τ::linordered_field) run⟩ ("ϱ$_⊙$") **where**
  ⟨ϱ$_⊙$ ≡ Abs_run ((λ_ _. (False, τ$_{cst}$ 0)) ::nat ⇒ clock ⇒ (bool × 'τ tag_const))⟩

To help avoiding that time flows backward, setting the time on a clock at a given instant sets it for the future instants too.

fun time_update
  :: ⟨nat ⇒ clock ⇒ ('τ::linordered_field) tag_const ⇒ (nat ⇒ 'τ instant)
      ⇒ (nat ⇒ 'τ instant)⟩
where
  ⟨time_update n K τ ϱ = (λn' K'. if K = K' ∧ n ≤ n'
                                   then (hamlet (ϱ n K), τ)
                                   else ϱ n' K')⟩

4.2 Rules and properties of consistence

lemma context_consistency_preservationI:
  ⟨consistent_context ((γ::('τ::linordered_field) constr)#Γ) ⟹ consistent_context Γ⟩
unfolding consistent_context_def **by** auto

— This is very restrictive

inductive context_independency
  ::⟨('τ::linordered_field) constr ⇒ 'τ constr list ⇒ bool⟩ ("_ ⋈ _")
where
  NotTicks_independency:
  ⟨(K ⇑ n) ∉ set Γ ⟹ (K ¬⇑ n) ⋈ Γ⟩
| Ticks_independency:
  ⟨(K ¬⇑ n) ∉ set Γ ⟹ (K ⇑ n) ⋈ Γ⟩
| Timestamp_independency:
  ⟨(∄τ'. τ' = τ ∧ (K ⇓ n @ τ) ∈ set Γ) ⟹ (K ⇓ n @ τ) ⋈ Γ⟩

4.3 Major Theorems

4.3.1 Interpretation of a context

The interpretation of a context is the intersection of the interpretation of its components.

```
theorem symrun_interp_fixpoint:
  ⟨⋂ ((λγ. ⟦ γ ⟧_prim) ' set Γ) = ⟦⟦ Γ ⟧⟧_prim⟩
by (induction Γ, simp+)
```

4.3.2 Expansion law

Similar to the expansion laws of lattices

```
theorem symrun_interp_expansion:
  ⟨⟦⟦ Γ_1 @ Γ_2 ⟧⟧_prim = ⟦⟦ Γ_1 ⟧⟧_prim ∩ ⟦⟦ Γ_2 ⟧⟧_prim⟩
by (induction Γ_1, simp, auto)
```

4.4 Equations for the interpretation of symbolic primitives

4.4.1 General laws

```
lemma symrun_interp_assoc:
  ⟨⟦⟦ (Γ_1 @ Γ_2) @ Γ_3 ⟧⟧_prim = ⟦⟦ Γ_1 @ (Γ_2 @ Γ_3) ⟧⟧_prim⟩
by auto
```

```
lemma symrun_interp_commute:
  ⟨⟦⟦ Γ_1 @ Γ_2 ⟧⟧_prim = ⟦⟦ Γ_2 @ Γ_1 ⟧⟧_prim⟩
by (simp add: symrun_interp_expansion inf_sup_aci(1))
```

```
lemma symrun_interp_left_commute:
  ⟨⟦⟦ Γ_1 @ (Γ_2 @ Γ_3) ⟧⟧_prim = ⟦⟦ Γ_2 @ (Γ_1 @ Γ_3) ⟧⟧_prim⟩
unfolding symrun_interp_expansion by auto
```

```
lemma symrun_interp_idem:
  ⟨⟦⟦ Γ @ Γ ⟧⟧_prim = ⟦⟦ Γ ⟧⟧_prim⟩
using symrun_interp_expansion by auto
```

```
lemma symrun_interp_left_idem:
  ⟨⟦⟦ Γ_1 @ (Γ_1 @ Γ_2) ⟧⟧_prim = ⟦⟦ Γ_1 @ Γ_2 ⟧⟧_prim⟩
using symrun_interp_expansion by auto
```

```
lemma symrun_interp_right_idem:
  ⟨⟦⟦ (Γ_1 @ Γ_2) @ Γ_2 ⟧⟧_prim = ⟦⟦ Γ_1 @ Γ_2 ⟧⟧_prim⟩
unfolding symrun_interp_expansion by auto
```

```
lemmas symrun_interp_aci =  symrun_interp_commute
                            symrun_interp_assoc
                            symrun_interp_left_commute
                            symrun_interp_left_idem
```

— Identity element

```
lemma symrun_interp_neutral1:
  ⟨⟦⟦ [] @ Γ ⟧⟧_prim = ⟦⟦ Γ ⟧⟧_prim⟩
by simp
```

```
lemma symrun_interp_neutral2:
  ⟨⟦⟦ Γ @ [] ⟧⟧_prim = ⟦⟦ Γ ⟧⟧_prim⟩
```

by simp

4.4.2 Decreasing interpretation of symbolic primitives

Adding constraints to a context reduces the number of satisfying runs.

lemma TESL_sem_decreases_head:
 ⟨[[Γ]]$_{prim}$ ⊇ [[γ # Γ]]$_{prim}$⟩
by simp

lemma TESL_sem_decreases_tail:
 ⟨[[Γ]]$_{prim}$ ⊇ [[Γ @ [γ]]]$_{prim}$⟩
by (simp add: symrun_interp_expansion)

Adding a constraint that is already in the context does not change the interpretation of the context.

lemma symrun_interp_formula_stuttering:
  assumes ⟨γ ∈ set Γ⟩
    shows ⟨[[γ # Γ]]$_{prim}$ = [[Γ]]$_{prim}$⟩
proof -
  have ⟨γ # Γ = [γ] @ Γ⟩ **by** simp
  hence ⟨[[γ # Γ]]$_{prim}$ = [[[γ]]]$_{prim}$ ∩ [[Γ]]$_{prim}$⟩
    using symrun_interp_expansion **by** simp
  thus ?thesis **using** assms symrun_interp_fixpoint **by** fastforce
qed

Removing duplicate constraints from a context does not change the interpretation of the context.

lemma symrun_interp_remdups_absorb:
 ⟨[[Γ]]$_{prim}$ = [[remdups Γ]]$_{prim}$⟩
proof (induction Γ)
  case Cons
    thus ?case **using** symrun_interp_formula_stuttering **by** auto
qed simp

Two identical sets of constraints have the same interpretation, the order in the context does not matter.

lemma symrun_interp_set_lifting:
  assumes ⟨set Γ = set Γ'⟩
    shows ⟨[[Γ]]$_{prim}$ = [[Γ']]$_{prim}$⟩
proof -
  have ⟨set (remdups Γ) = set (remdups Γ')⟩
    by (simp add: assms)
  moreover have fxpntΓ: ⟨⋂ ((λγ. [γ]$_{prim}$) ' set Γ) = [[Γ]]$_{prim}$⟩
    by (simp add: symrun_interp_fixpoint)
  moreover have fxpntΓ': ⟨⋂ ((λγ. [γ]$_{prim}$) ' set Γ') = [[Γ']]$_{prim}$⟩
    by (simp add: symrun_interp_fixpoint)
  moreover have ⟨⋂ ((λγ. [γ]$_{prim}$) ' set Γ) = ⋂ ((λγ. [γ]$_{prim}$) ' set Γ')⟩
    by (simp add: assms)
  ultimately show ?thesis **using** symrun_interp_remdups_absorb **by** auto
qed

The interpretation of contexts is contravariant with regard to set inclusion.

theorem symrun_interp_decreases_setinc:
  assumes ⟨set Γ ⊆ set Γ'⟩
    shows ⟨[[Γ]]$_{prim}$ ⊇ [[Γ']]$_{prim}$⟩
proof -

```
      obtain Γ_r where decompose: ‹set (Γ @ Γ_r) = set Γ'› using assms by auto
      hence ‹set (Γ @ Γ_r) = set Γ'› using assms by blast
      moreover have ‹(set Γ) ∪ (set Γ_r) = set Γ'› using assms decompose by auto
      moreover have ‹[[ Γ' ]]_prim = [[ Γ @ Γ_r ]]_prim›
        using symrun_interp_set_lifting decompose by blast
      moreover have ‹[[ Γ @ Γ_r ]]_prim = [[ Γ ]]_prim ∩ [[ Γ_r ]]_prim›
        by (simp add: symrun_interp_expansion)
      moreover have ‹[[ Γ ]]_prim ⊇ [[ Γ ]]_prim ∩ [[ Γ_r ]]_prim› by simp
      ultimately show ?thesis by simp
qed

lemma symrun_interp_decreases_add_head:
  assumes ‹set Γ ⊆ set Γ'›
    shows ‹[[ γ # Γ ]]_prim ⊇ [[ γ # Γ' ]]_prim›
using symrun_interp_decreases_setinc assms by auto

lemma symrun_interp_decreases_add_tail:
  assumes ‹set Γ ⊆ set Γ'›
    shows ‹[[ Γ @ [γ] ]]_prim ⊇ [[ Γ' @ [γ] ]]_prim›
proof -
  from symrun_interp_decreases_setinc[OF assms] have ‹[[ Γ' ]]_prim ⊆ [[ Γ ]]_prim› .
  thus ?thesis by (simp add: symrun_interp_expansion dual_order.trans)
qed

lemma symrun_interp_absorb1:
  assumes ‹set Γ_1 ⊆ set Γ_2›
    shows ‹[[ Γ_1 @ Γ_2 ]]_prim = [[ Γ_2 ]]_prim›
by (simp add: Int_absorb1 symrun_interp_decreases_setinc
                       symrun_interp_expansion assms)

lemma symrun_interp_absorb2:
  assumes ‹set Γ_2 ⊆ set Γ_1›
    shows ‹[[ Γ_1 @ Γ_2 ]]_prim = [[ Γ_1 ]]_prim›
using symrun_interp_absorb1 symrun_interp_commute assms by blast

end
```

Chapter 5

Operational Semantics

```
theory Operational
imports
  SymbolicPrimitive

begin
```

The operational semantics defines rules to build symbolic runs from a TESL specification (a set of TESL formulae). Symbolic runs are described using the symbolic primitives presented in the previous chapter. Therefore, the operational semantics compiles a set of constraints on runs, as defined by the denotational semantics, into a set of symbolic constraints on the instants of the runs. Concrete runs can then be obtained by solving the constraints at each instant.

5.1 Operational steps

We introduce a notation to describe configurations:

- Γ is the context, the set of symbolic constraints on past instants of the run;

- n is the index of the current instant, the present;

- Ψ is the TESL formula that must be satisfied at the current instant (present);

- Φ is the TESL formula that must be satisfied for the following instants (the future).

```
abbreviation uncurry_conf
  ::⟨('τ::linordered_field) system ⇒ instant_index ⇒ 'τ TESL_formula ⇒ 'τ TESL_formula
      ⇒ 'τ config⟩                                          ("_, _ ⊢ _ ▷ _" 80)
where
  ⟨Γ, n ⊢ Ψ ▷ Φ ≡ (Γ, n, Ψ, Φ)⟩
```

The only introduction rule allows us to progress to the next instant when there are no more constraints to satisfy for the present instant.

```
inductive operational_semantics_intro
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩           ("_ ↪ᵢ _" 70)
where
  instant_i:
```

⟨(Γ, n ⊢ [] ▷ Φ) ↪$_i$ (Γ, Suc n ⊢ Φ ▷ [])⟩

The elimination rules describe how TESL formulae for the present are transformed into constraints on the past and on the future.

inductive operational_semantics_elim
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩   ("_ ↪$_e$ _" 70)
where
  sporadic_on_e1:
— A sporadic constraint can be ignored in the present and rejected into the future.

    ⟨(Γ, n ⊢ ((K$_1$ sporadic τ on K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (Γ, n ⊢ Ψ ▷ ((K$_1$ sporadic τ on K$_2$) # Φ))⟩
| sporadic_on_e2:
— It can also be handled in the present by making the clock tick and have the expected time. Once it has been handled, it is no longer a constraint to satisfy, so it disappears from the future.

    ⟨(Γ, n ⊢ ((K$_1$ sporadic τ on K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ⇑ n) # (K$_2$ ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ)⟩
| tagrel_e:
— A relation between time scales has to be obeyed at every instant.

    ⟨(Γ, n ⊢ ((time-relation ⌊K$_1$, K$_2$⌋ ∈ R) # Ψ) ▷ Φ)
      ↪$_e$ (((⌊τ$_{var}$(K$_1$, n), τ$_{var}$(K$_2$, n)⌋ ∈ R) # Γ), n
              ⊢ Ψ ▷ ((time-relation ⌊K$_1$, K$_2$⌋ ∈ R) # Φ))⟩
| implies_e1:
— An implication can be handled in the present by forbidding a tick of the master clock. The implication is copied back into the future because it holds for the whole run.

    ⟨(Γ, n ⊢ ((K$_1$ implies K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies K$_2$) # Φ))⟩
| implies_e2:
— It can also be handled in the present by making both the master and the slave clocks tick.

    ⟨(Γ, n ⊢ ((K$_1$ implies K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ⇑ n) # (K$_2$ ⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies K$_2$) # Φ))⟩
| implies_not_e1:
— A negative implication can be handled in the present by forbidding a tick of the master clock. The implication is copied back into the future because it holds for the whole run.

    ⟨(Γ, n ⊢ ((K$_1$ implies not K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies not K$_2$) # Φ))⟩
| implies_not_e2:
— It can also be handled in the present by making the master clock ticks and forbidding a tick on the slave clock.

    ⟨(Γ, n ⊢ ((K$_1$ implies not K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ⇑ n) # (K$_2$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies not K$_2$) # Φ))⟩
| timedelayed_e1:
— A timed delayed implication can be handled by forbidding a tick on the master clock.

    ⟨(Γ, n ⊢ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ))⟩
| timedelayed_e2:
— It can also be handled by making the master clock tick and adding a constraint that makes the slave clock tick when the delay has elapsed on the measuring clock.

    ⟨(Γ, n ⊢ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ) ▷ Φ)
      ↪$_e$ (((K$_1$ ⇑ n) # (K$_2$ @ n ⊕ δτ ⇒ K$_3$) # Γ), n
              ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ))⟩
| weakly_precedes_e:
— A weak precedence relation has to hold at every instant.

    ⟨(Γ, n ⊢ ((K$_1$ weakly precedes K$_2$) # Ψ) ▷ Φ)
      ↪$_e$ ((((⌈#$^≤$ K$_2$ n, #$^≤$ K$_1$ n⌉ ∈ (λ(x,y). x≤y)) # Γ), n
              ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ))⟩
| strictly_precedes_e:
— A strict precedence relation has to hold at every instant.

```
⟨(Γ, n ⊢ ((K₁ strictly precedes K₂) # Ψ) ▷ Φ)
    ↪ₑ  (((⌈#≤ K₂ n, #< K₁ n⌉ ∈ (λ(x,y). x≤y)) # Γ), n
           ⊢ Ψ ▷ ((K₁ strictly precedes K₂) # Φ))⟩
| kills_e1:
```
— A kill can be handled by forbidding a tick of the triggering clock.

```
  ⟨(Γ, n ⊢ ((K₁ kills K₂) # Ψ) ▷ Φ)
      ↪ₑ  (((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ))⟩
| kills_e2:
```
— It can also be handled by making the triggering clock tick and by forbidding any further tick of the killed
  clock.
```
  ⟨(Γ, n ⊢ ((K₁ kills K₂) # Ψ) ▷ Φ)
      ↪ₑ  (((K₁ ⇑ n) # (K₂ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ))⟩
```

A step of the operational semantics is either the application of the introduction rule or the
application of an elimination rule.

```
inductive operational_semantics_step
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩              ("_ ↪ _" 70)
where
  intro_part:
  ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁)  ↪ᵢ  (Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂)
    ⟹ (Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁)  ↪  (Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂)⟩
| elims_part:
  ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁)  ↪ₑ  (Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂)
    ⟹ (Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁)  ↪  (Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂)⟩
```

We introduce notations for the reflexive transitive closure of the operational semantic step, its
transitive closure and its reflexive closure.

```
abbreviation operational_semantics_step_rtranclp
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩              ("_ ↪** _" 70)
where
  ⟨C₁ ↪** C₂ ≡ operational_semantics_step** C₁ C₂⟩


abbreviation operational_semantics_step_tranclp
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩              ("_ ↪++ _" 70)
where
  ⟨C₁ ↪++ C₂ ≡ operational_semantics_step++ C₁ C₂⟩


abbreviation operational_semantics_step_reflclp
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩              ("_ ↪== _" 70)
where
  ⟨C₁ ↪== C₂ ≡ operational_semantics_step== C₁ C₂⟩


abbreviation operational_semantics_step_relpowp
  ::⟨('τ::linordered_field) config ⇒ nat ⇒ 'τ config ⇒ bool⟩        ("_ ↪- _" 70)
where
  ⟨C₁ ↪ⁿ C₂ ≡ (operational_semantics_step ^^ n) C₁ C₂⟩


definition operational_semantics_elim_inv
  ::⟨('τ::linordered_field) config ⇒ 'τ config ⇒ bool⟩              ("_ ↪ₑ← _" 70)
where
  ⟨C₁ ↪ₑ← C₂ ≡ C₂ ↪ₑ C₁⟩
```

5.2 Basic Lemmas

If a configuration can be reached in m steps from a configuration that can be reached in n
steps from an original configuration, then it can be reached in n + m steps from the original

configuration.

```
lemma operational_semantics_trans_generalized:
  assumes ⟨C₁ ↪ⁿ C₂⟩
  assumes ⟨C₂ ↪ᵐ C₃⟩
    shows ⟨C₁ ↪ⁿ ⁺ ᵐ C₃⟩
using relcompp.relcompI[of  ⟨operational_semantics_step ^^ n⟩ _ _
                            ⟨operational_semantics_step ^^ m⟩, OF assms]
by (simp add: relpowp_add)
```

We consider the set of configurations that can be reached in one operational step from a given configuration.

```
abbreviation Cnext_solve
  ::⟨('τ::linordered_field) config ⇒ 'τ config set⟩ ("𝒞ₙₑₓₜ _")
where
  ⟨𝒞ₙₑₓₜ 𝒮 ≡ { 𝒮'. 𝒮 ↪ 𝒮' }⟩
```

Advancing to the next instant is possible when there are no more constraints on the current instant.

```
lemma Cnext_solve_instant:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ [] ▷ Φ)) ⊇ { Γ, Suc n ⊢ Φ ▷ [] }⟩
by (simp add: operational_semantics_step.simps operational_semantics_intro.instant_i)
```

The following lemmas state that the configurations produced by the elimination rules of the operational semantics belong to the configurations that can be reached in one step.

```
lemma Cnext_solve_sporadicon:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ sporadic τ on K₂) # Ψ) ▷ Φ))
    ⊇ { Γ, n ⊢ Ψ ▷ ((K₁ sporadic τ on K₂) # Φ),
        ((K₁ ⇑ n) # (K₂ ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ }⟩
by (simp add: operational_semantics_step.simps
              operational_semantics_elim.sporadic_on_e1
              operational_semantics_elim.sporadic_on_e2)
```

```
lemma Cnext_solve_tagrel:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((time-relation ⌊K₁, K₂⌋ ∈ R) # Ψ) ▷ Φ))
    ⊇ { ((⌊τᵥₐᵣ(K₁, n), τᵥₐᵣ(K₂, n)⌋ ∈ R) # Γ),n
          ⊢ Ψ ▷ ((time-relation ⌊K₁, K₂⌋ ∈ R) # Φ) }⟩
by (simp add: operational_semantics_step.simps operational_semantics_elim.tagrel_e)
```

```
lemma Cnext_solve_implies:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ implies K₂) # Ψ) ▷ Φ))
    ⊇ { ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies K₂) # Φ),
        ((K₁ ⇑ n) # (K₂ ⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies K₂) # Φ) }⟩
by (simp add: operational_semantics_step.simps operational_semantics_elim.implies_e1
              operational_semantics_elim.implies_e2)
```

```
lemma Cnext_solve_implies_not:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ))
    ⊇ { ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ),
        ((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) }⟩
by (simp add: operational_semantics_step.simps
              operational_semantics_elim.implies_not_e1
              operational_semantics_elim.implies_not_e2)
```

```
lemma Cnext_solve_timedelayed:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ time-delayed by δτ on K₂ implies K₃) # Ψ) ▷ Φ))
    ⊇ { ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ time-delayed by δτ on K₂ implies K₃) # Φ),
```

```
            ((K₁ ⇑ n) # (K₂ @ n ⊕ δτ ⇒ K₃) # Γ), n
                ⊢ Ψ ▷ ((K₁ time-delayed by δτ on K₂ implies K₃) # Φ) })
by (simp add: operational_semantics_step.simps
                operational_semantics_elim.timedelayed_e1
                operational_semantics_elim.timedelayed_e2)


lemma Cnext_solve_weakly_precedes:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ weakly precedes K₂) # Ψ) ▷ Φ))
    ⊇ { ((⌈#≤ K₂ n, #≤ K₁ n⌉ ∈ (λ(x,y). x≤y)) # Γ), n
          ⊢ Ψ ▷ ((K₁ weakly precedes K₂) # Φ) }⟩
by (simp add: operational_semantics_step.simps
                operational_semantics_elim.weakly_precedes_e)


lemma Cnext_solve_strictly_precedes:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ strictly precedes K₂) # Ψ) ▷ Φ))
    ⊇ { ((⌈#≤ K₂ n, #< K₁ n⌉ ∈ (λ(x,y). x≤y)) # Γ), n
          ⊢ Ψ ▷ ((K₁ strictly precedes K₂) # Φ) }⟩
by (simp add: operational_semantics_step.simps
                operational_semantics_elim.strictly_precedes_e)


lemma Cnext_solve_kills:
  ⟨(𝒞ₙₑₓₜ (Γ, n ⊢ ((K₁ kills K₂) # Ψ) ▷ Φ))
    ⊇ { ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ),
        ((K₁ ⇑ n) # (K₂ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ) }⟩
by (simp add: operational_semantics_step.simps operational_semantics_elim.kills_e1
                operational_semantics_elim.kills_e2)
```

An empty specification can be reduced to an empty specification for an arbitrary number of
steps.

```
lemma empty_spec_reductions:
  ⟨([], 0 ⊢ [] ▷ []) ↪ᵏ ([], k ⊢ [] ▷ [])⟩
proof (induct k)
  case 0 thus ?case by simp
next
  case Suc thus ?case
    using instant_i operational_semantics_step.simps by fastforce
qed


end
```

Chapter 6

Equivalence of the Operational and Denotational Semantics

```
theory Corecursive_Prop
  imports
    SymbolicPrimitive
    Operational
    Denotational

begin
```

6.1 Stepwise denotational interpretation of TESL atoms

In order to prove the equivalence of the denotational and operational semantics, we need to be able to ignore the past (for which the constraints are encoded in the context) and consider only the satisfaction of the constraints from a given instant index. For this purpose, we define an interpretation of TESL formulae for a suffix of a run. That interpretation is closely related to the denotational semantics as defined in the preceding chapters.

fun `TESL_interpretation_atomic_stepwise`
    :: ⟨('τ::linordered_field) TESL_atomic ⇒ nat ⇒ 'τ run set⟩ ("⟦ _ ⟧$_{TESL}^{\geq}$ -")
where
  ⟨⟦ K$_1$ sporadic τ on K$_2$ ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∃n≥i. hamlet ((Rep_run ϱ) n K$_1$) ∧ time ((Rep_run ϱ) n K$_2$) = τ}⟩
| ⟨⟦ time-relation ⌊K$_1$, K$_2$⌋ ∈ R ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∀n≥i. R (time ((Rep_run ϱ) n K$_1$), time ((Rep_run ϱ) n K$_2$))}⟩
| ⟨⟦ master implies slave ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∀n≥i. hamlet ((Rep_run ϱ) n master) ⟶ hamlet ((Rep_run ϱ) n slave)}⟩
| ⟨⟦ master implies not slave ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∀n≥i. hamlet ((Rep_run ϱ) n master) ⟶ ¬ hamlet ((Rep_run ϱ) n slave)}⟩
| ⟨⟦ master time-delayed by $\delta\tau$ on measuring implies slave ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∀n≥i. hamlet ((Rep_run ϱ) n master) ⟶
                (let measured_time = time ((Rep_run ϱ) n measuring) in
                 ∀m ≥ n. first_time ϱ measuring m (measured_time + $\delta\tau$)
                        ⟶ hamlet ((Rep_run ϱ) m slave)
)
      }⟩
| ⟨⟦ K$_1$ weakly precedes K$_2$ ⟧$_{TESL}^{\geq\ i}$ =
      {ϱ. ∀n≥i. (run_tick_count ϱ K$_2$ n) ≤ (run_tick_count ϱ K$_1$ n)}⟩
```

```
| ⟨⟦ K₁ strictly precedes K₂ ⟧_TESL^≥ i =
      {ϱ. ∀n≥i. (run_tick_count ϱ K₂ n) ≤ (run_tick_count_strictly ϱ K₁ n)}⟩
| ⟨⟦ K₁ kills K₂ ⟧_TESL^≥ i =
      {ϱ. ∀n≥i. hamlet ((Rep_run ϱ) n K₁) ⟶ (∀m≥n. ¬ hamlet ((Rep_run ϱ) m K₂))}⟩
```

The denotational interpretation of TESL formulae can be unfolded into the stepwise interpretation.

```
lemma TESL_interp_unfold_stepwise_sporadicon:
  ⟨⟦ K₁ sporadic τ on K₂ ⟧_TESL = ⋃ {Y. ∃n::nat. Y = ⟦ K₁ sporadic τ on K₂ ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_tagrelgen:
  ⟨⟦ time-relation ⌊K₁, K₂⌋ ∈ R ⟧_TESL
    = ⋂ {Y. ∃n::nat. Y = ⟦ time-relation ⌊K₁, K₂⌋ ∈ R ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_implies:
  ⟨⟦ master implies slave ⟧_TESL
    = ⋂ {Y. ∃n::nat. Y = ⟦ master implies slave ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_implies_not:
  ⟨⟦ master implies not slave ⟧_TESL
    = ⋂ {Y. ∃n::nat. Y = ⟦ master implies not slave ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_timedelayed:
  ⟨⟦ master time-delayed by δτ on measuring implies slave ⟧_TESL
    = ⋂ {Y. ∃n::nat.
           Y = ⟦ master time-delayed by δτ on measuring implies slave ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_weakly_precedes:
  ⟨⟦ K₁ weakly precedes K₂ ⟧_TESL
    = ⋂ {Y. ∃n::nat. Y = ⟦ K₁ weakly precedes K₂ ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_strictly_precedes:
  ⟨⟦ K₁ strictly precedes K₂ ⟧_TESL
    = ⋂ {Y. ∃n::nat. Y = ⟦ K₁ strictly precedes K₂ ⟧_TESL^≥ ⁿ}⟩
by auto


lemma TESL_interp_unfold_stepwise_kills:
  ⟨⟦ master kills slave ⟧_TESL = ⋂ {Y. ∃n::nat. Y = ⟦ master kills slave ⟧_TESL^≥ ⁿ}⟩
by auto
```

Positive atomic formulae (the ones that create ticks from nothing) are unfolded as the union of the stepwise interpretations.

```
theorem TESL_interp_unfold_stepwise_positive_atoms:
  assumes ⟨positive_atom φ⟩
    shows ⟨⟦ φ::'τ::linordered_field TESL_atomic ⟧_TESL
            = ⋃ {Y. ∃n::nat. Y = ⟦ φ ⟧_TESL^≥ ⁿ}⟩
proof -
  from positive_atom.elims(2)[OF assms]
    obtain u v w where ⟨φ = (u sporadic v on w)⟩ by blast
  with TESL_interp_unfold_stepwise_sporadicon show ?thesis by simp
qed
```

Negative atomic formulae are unfolded as the intersection of the stepwise interpretations.

theorem TESL_interp_unfold_stepwise_negative_atoms:
  assumes ⟨¬ positive_atom φ⟩
    shows ⟨⟦ φ ⟧$_{TESL}$ = ⋂ {Y. ∃n::nat. Y = ⟦ φ ⟧$_{TESL}^{\geq\, n}$}⟩
proof (cases φ)
  case SporadicOn **thus** ?thesis **using** assms **by** simp
next
  case TagRelation
    thus ?thesis **using** TESL_interp_unfold_stepwise_tagrelgen **by** simp
next
  case Implies
    thus ?thesis **using** TESL_interp_unfold_stepwise_implies **by** simp
next
  case ImpliesNot
    thus ?thesis **using** TESL_interp_unfold_stepwise_implies_not **by** simp
next
  case TimeDelayedBy
    thus ?thesis **using** TESL_interp_unfold_stepwise_timedelayed **by** simp
next
  case WeaklyPrecedes
    thus ?thesis
      using TESL_interp_unfold_stepwise_weakly_precedes **by** simp
next
  case StrictlyPrecedes
    thus ?thesis
      using TESL_interp_unfold_stepwise_strictly_precedes **by** simp
next
  case Kills
    thus ?thesis
      using TESL_interp_unfold_stepwise_kills **by** simp
qed

Some useful lemmas for reasoning on properties of sequences.

lemma forall_nat_expansion:
  ⟨(∀n ≥ (n_0::nat). P n) = (P n_0 ∧ (∀n ≥ Suc n_0. P n))⟩
proof -
  have ⟨(∀n ≥ (n_0::nat). P n) = (∀n. (n = n_0 ∨ n > n_0) ⟶ P n)⟩
    using le_less **by** blast
  also have ⟨... = (P n_0 ∧ (∀n > n_0. P n))⟩ **by** blast
  finally show ?thesis **using** Suc_le_eq **by** simp
qed

lemma exists_nat_expansion:
  ⟨(∃n ≥ (n_0::nat). P n) = (P n_0 ∨ (∃n ≥ Suc n_0. P n))⟩
proof -
  have ⟨(∃n ≥ (n_0::nat). P n) = (∃n. (n = n_0 ∨ n > n_0) ∧ P n)⟩
    using le_less **by** blast
  also have ⟨... = (∃n. (P n_0) ∨ (n > n_0 ∧ P n))⟩ **by** blast
  finally show ?thesis **using** Suc_le_eq **by** simp
qed

lemma forall_nat_set_suc:⟨{x. ∀m ≥ n. P x m} = {x. P x n} ∩ {x. ∀m ≥ Suc n. P x m}⟩
proof
  { **fix** x **assume** h:⟨x ∈ {x. ∀m ≥ n. P x m}⟩
    hence ⟨P x n⟩ **by** simp
    moreover from h **have** ⟨x ∈ {x. ∀m ≥ Suc n. P x m}⟩ **by** simp
    ultimately have ⟨x ∈ {x. P x n} ∩ {x. ∀m ≥ Suc n. P x m}⟩ **by** simp
  } **thus** ⟨{x. ∀m ≥ n. P x m} ⊆ {x. P x n} ∩ {x. ∀m ≥ Suc n. P x m}⟩ ..

next
  { fix x   **assume** h:⟨x ∈ {x. P x n} ∩ {x. ∀m ≥ Suc n. P x m}⟩
    hence ⟨P x n⟩ **by simp**
    moreover from h **have** ⟨∀m ≥ Suc n. P x m⟩ **by simp**
    ultimately have ⟨∀m ≥ n. P x m⟩ **using** forall_nat_expansion **by blast**
    hence ⟨x ∈ {x. ∀m ≥ n. P x m}⟩ **by simp**
  } thus ⟨{x. P x n} ∩ {x. ∀m ≥ Suc n. P x m} ⊆ {x. ∀m ≥ n. P x m}⟩ ..
qed

lemma exists_nat_set_suc:⟨{x. ∃m ≥ n. P x m} = {x. P x n} ∪ {x. ∃m ≥ Suc n. P x m}⟩
proof
  { fix x **assume** h:⟨x ∈ {x. ∃m ≥ n. P x m}⟩
    hence ⟨x ∈ {x. ∃m. (m = n ∨ m ≥ Suc n) ∧ P x m}⟩
      using Suc_le_eq antisym_conv2 **by fastforce**
    hence ⟨x ∈ {x. P x n} ∪ {x. ∃m ≥ Suc n. P x m}⟩ **by blast**
  } thus ⟨{x. ∃m ≥ n. P x m} ⊆ {x. P x n} ∪ {x. ∃m ≥ Suc n. P x m}⟩ ..
next
  { fix x   **assume** h:⟨x ∈ {x. P x n} ∪ {x. ∃m ≥ Suc n. P x m}⟩
    hence ⟨x ∈ {x. ∃m ≥ n. P x m}⟩ **using** Suc_leD **by blast**
  } thus ⟨{x. P x n} ∪ {x. ∃m ≥ Suc n. P x m} ⊆ {x. ∃m ≥ n. P x m}⟩ ..
qed

6.2   Coinduction Unfolding Properties

The following lemmas show how to shorten a suffix, i.e. to unfold one instant in the construction of a run. They correspond to the rules of the operational semantics.

lemma TESL_interp_stepwise_sporadicon_coind_unfold:
  ⟨⟦ K_1 sporadic τ on K_2 ⟧$_{TESL}^{\geq\ n}$ =
    ⟦ K_1 ⇑ n ⟧$_{prim}$ ∩ ⟦ K_2 ⇓ n @ τ ⟧$_{prim}$ — rule sporadic_on_e2
    ∪ ⟦ K_1 sporadic τ on K_2 ⟧$_{TESL}^{\geq\ Suc\ n}$⟩   — rule sporadic_on_e1
unfolding TESL_interpretation_atomic_stepwise.simps(1)
          symbolic_run_interpretation_primitive.simps(1,6)
using exists_nat_set_suc[of ⟨n⟩ ⟨λϱ n. hamlet (Rep_run ϱ n K_1)
                                    ∧ time (Rep_run ϱ n K_2) = τ⟩]
by (simp add: Collect_conj_eq)

lemma TESL_interp_stepwise_tagrel_coind_unfold:
  ⟨⟦ time-relation ⌊K_1, K_2⌋ ∈ R ⟧$_{TESL}^{\geq\ n}$ =   — rule tagrel_e
    ⟦ ⌊τ_{var}(K_1, n), τ_{var}(K_2, n)⌋ ∈ R ⟧$_{prim}$
    ∩ ⟦ time-relation ⌊K_1, K_2⌋ ∈ R ⟧$_{TESL}^{\geq\ Suc\ n}$⟩
proof -
  have ⟨{ϱ. ∀m≥n. R (time ((Rep_run ϱ) m K_1), time ((Rep_run ϱ) m K_2))}
      = {ϱ. R (time ((Rep_run ϱ) n K_1), time ((Rep_run ϱ) n K_2))}
      ∩ {ϱ. ∀m≥Suc n. R (time ((Rep_run ϱ) m K_1), time ((Rep_run ϱ) m K_2))}⟩
    using forall_nat_set_suc[of ⟨n⟩ ⟨λx y. R (time ((Rep_run x) y K_1),
                                    time ((Rep_run x) y K_2))⟩] **by simp**
  thus ?thesis **by auto**
qed

lemma TESL_interp_stepwise_implies_coind_unfold:
  ⟨⟦ master implies slave ⟧$_{TESL}^{\geq\ n}$ =
    (⟦ master ¬⇑ n ⟧$_{prim}$ — rule implies_e1
      ∪ ⟦ master ⇑ n ⟧$_{prim}$ ∩ ⟦ slave ⇑ n ⟧$_{prim}$) — rule implies_e2
      ∩ ⟦ master implies slave ⟧$_{TESL}^{\geq\ Suc\ n}$⟩

proof -
  have ⟨{ϱ. ∀m≥n. hamlet ((Rep_run ϱ) m master) ⟶ hamlet ((Rep_run ϱ) m slave)}
        = {ϱ. hamlet ((Rep_run ϱ) n master) ⟶ hamlet ((Rep_run ϱ) n slave)}
        ∩ {ϱ. ∀m≥Suc n. hamlet ((Rep_run ϱ) m master)
                        ⟶ hamlet ((Rep_run ϱ) m slave)}⟩
    using forall_nat_set_suc[of ⟨n⟩ ⟨λx y. hamlet ((Rep_run x) y master)
                                    ⟶ hamlet ((Rep_run x) y slave)⟩] **by** simp
  thus ?thesis **by** auto
qed

lemma TESL_interp_stepwise_implies_not_coind_unfold:
  ⟨⟦ master implies not slave ⟧$_{TESL}^{≥ n}$ =
      (⟦ master ¬⤊ n ⟧$_{prim}$ — rule implies_not_e1
        ∪ ⟦ master ⤊ n ⟧$_{prim}$ ∩ ⟦ slave ¬⤊ n ⟧$_{prim}$)   — rule implies_not_e2
      ∩ ⟦ master implies not slave ⟧$_{TESL}^{≥ Suc n}$⟩
proof -
  have ⟨{ϱ. ∀m≥n. hamlet ((Rep_run ϱ) m master) ⟶ ¬ hamlet ((Rep_run ϱ) m slave)}
        = {ϱ. hamlet ((Rep_run ϱ) n master) ⟶ ¬ hamlet ((Rep_run ϱ) n slave)}
          ∩ {ϱ. ∀m≥Suc n. hamlet ((Rep_run ϱ) m master)
                      ⟶ ¬ hamlet ((Rep_run ϱ) m slave)}⟩
    using forall_nat_set_suc[of ⟨n⟩ ⟨λx y. hamlet ((Rep_run x) y master)
                                    ⟶ ¬hamlet ((Rep_run x) y slave)⟩] **by** simp
  thus ?thesis **by** auto
qed

lemma TESL_interp_stepwise_timedelayed_coind_unfold:
  ⟨⟦ master time-delayed by δτ on measuring implies slave ⟧$_{TESL}^{≥ n}$ =
      (⟦ master ¬⤊ n ⟧$_{prim}$ — rule timedelayed_e1
        ∪ (⟦ master ⤊ n ⟧$_{prim}$ ∩ ⟦ measuring @ n ⊕ δτ ⇒ slave ⟧$_{prim}$))
                                        — rule timedelayed_e2
      ∩ ⟦ master time-delayed by δτ on measuring implies slave ⟧$_{TESL}^{≥ Suc n}$⟩
proof -
  let ?prop = ⟨λϱ m. hamlet ((Rep_run ϱ) m master) ⟶
                    (let measured_time = time ((Rep_run ϱ) m measuring) in
                    ∀p ≥ m. first_time ϱ measuring p (measured_time + δτ)
                          ⟶ hamlet ((Rep_run ϱ) p slave))⟩
  have ⟨{ϱ. ∀m ≥ n. ?prop ϱ m} = {ϱ. ?prop ϱ n} ∩ {ϱ. ∀m ≥ Suc n. ?prop ϱ m}⟩
    using forall_nat_set_suc[of ⟨n⟩ ?prop] **by** blast
  also have ⟨... = {ϱ. ?prop ϱ n}
              ∩ ⟦ master time-delayed by δτ on measuring implies slave ⟧$_{TESL}^{≥ Suc n}$⟩
    by simp
  finally show ?thesis **by** auto
qed

lemma TESL_interp_stepwise_weakly_precedes_coind_unfold:
  ⟨⟦ K$_1$ weakly precedes K$_2$ ⟧$_{TESL}^{≥ n}$ =   — rule weakly_precedes_e
    ⟦ (⌈#$^{≤}$ K$_2$ n, #$^{≤}$ K$_1$ n⌉ ∈ (λ(x,y). x≤y)) ⟧$_{prim}$
    ∩ ⟦ K$_1$ weakly precedes K$_2$ ⟧$_{TESL}^{≥ Suc n}$⟩
proof -
  have ⟨{ϱ. ∀p≥n. (run_tick_count ϱ K$_2$ p) ≤ (run_tick_count ϱ K$_1$ p)}
        = {ϱ. (run_tick_count ϱ K$_2$ n) ≤ (run_tick_count ϱ K$_1$ n)}
        ∩ {ϱ. ∀p≥Suc n. (run_tick_count ϱ K$_2$ p) ≤ (run_tick_count ϱ K$_1$ p)}⟩
    using forall_nat_set_suc[of ⟨n⟩ ⟨λϱ n. (run_tick_count ϱ K$_2$ n)
                                    ≤ (run_tick_count ϱ K$_1$ n)⟩]
    by simp
  thus ?thesis **by** auto
qed

lemma TESL_interp_stepwise_strictly_precedes_coind_unfold:
  ⟨⟦ K$_1$ strictly precedes K$_2$ ⟧$_{TESL}^{\geq n}$ =   — rule strictly_precedes_e
    ⟦ (⌈#$^{\leq}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x,y). x≤y)) ⟧$_{prim}$
    ∩ ⟦ K$_1$ strictly precedes K$_2$ ⟧$_{TESL}^{\geq Suc n}$⟩
proof -
  have ⟨{ϱ. ∀p≥n. (run_tick_count ϱ K$_2$ p) ≤ (run_tick_count_strictly ϱ K$_1$ p)}
        = {ϱ. (run_tick_count ϱ K$_2$ n) ≤ (run_tick_count_strictly ϱ K$_1$ n)}
        ∩ {ϱ. ∀p≥Suc n. (run_tick_count ϱ K$_2$ p) ≤ (run_tick_count_strictly ϱ K$_1$ p)}⟩
    using forall_nat_set_suc[of ⟨n⟩ ⟨λϱ n. (run_tick_count ϱ K$_2$ n)
                              ≤ (run_tick_count_strictly ϱ K$_1$ n)⟩]
    by simp
  thus ?thesis **by** auto
qed

lemma TESL_interp_stepwise_kills_coind_unfold:
  ⟨⟦ K$_1$ kills K$_2$ ⟧$_{TESL}^{\geq n}$ =
    (⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ — rule kills_e1
      ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$ ∩ ⟦ K$_2$ ¬⇑ ≥ n ⟧$_{prim}$)   — rule kills_e2
    ∩ ⟦ K$_1$ kills K$_2$ ⟧$_{TESL}^{\geq Suc n}$⟩
proof -
  let ?kills = ⟨λn ϱ. ∀p≥n. hamlet ((Rep_run ϱ) p K$_1$)
                              ⟶ (∀m≥p. ¬ hamlet ((Rep_run ϱ) m K$_2$))⟩
  let ?ticks = ⟨λn ϱ c. hamlet ((Rep_run ϱ) n c)⟩
  let ?dead = ⟨λn ϱ c. ∀m ≥ n. ¬hamlet ((Rep_run ϱ) m c)⟩
  have ⟨⟦ K$_1$ kills K$_2$ ⟧$_{TESL}^{\geq n}$ = {ϱ. ?kills n ϱ}⟩ **by** simp
  also have ⟨... = ({ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ})
              ∪ ({ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$})⟩
  proof
    { **fix** ϱ::⟨'τ::linordered_field run⟩
      assume ⟨ϱ ∈ {ϱ. ?kills n ϱ}⟩
      hence ⟨?kills n ϱ⟩ **by** simp
      hence ⟨(?ticks n ϱ K$_1$ ∧ ?dead n ϱ K$_2$) ∨ (¬?ticks n ϱ K$_1$ ∧ ?kills (Suc n) ϱ)⟩
        using Suc_leD **by** blast
      hence ⟨ϱ ∈ ({ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$})
            ∪ ({ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ})⟩
        by blast
    } **thus** ⟨{ϱ. ?kills n ϱ}
          ⊆ {ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ}
          ∪ {ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$}⟩ **by** blast
  next
    { **fix** ϱ::⟨'τ::linordered_field run⟩
      assume ⟨ϱ ∈ ({ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ})
            ∪ ({ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$})⟩
      hence ⟨¬ ?ticks n ϱ K$_1$ ∧ ?kills (Suc n) ϱ
            ∨ ?ticks n ϱ K$_1$ ∧ ?dead n ϱ K$_2$⟩ **by** blast
      moreover have ⟨((¬ ?ticks n ϱ K$_1$) ∧ (?kills (Suc n) ϱ)) ⟶ ?kills n ϱ⟩
        using dual_order.antisym not_less_eq_eq **by** blast
      ultimately have ⟨?kills n ϱ ∨ ?ticks n ϱ K$_1$ ∧ ?dead n ϱ K$_2$⟩ **by** blast
      hence ⟨?kills n ϱ⟩ **using** le_trans **by** blast
    } **thus** ⟨({ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ})
            ∪ ({ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$})
          ⊆ {ϱ. ?kills n ϱ}⟩ **by** blast
  qed
  also have ⟨... = {ϱ. ¬ ?ticks n ϱ K$_1$} ∩ {ϱ. ?kills (Suc n) ϱ}
            ∪ {ϱ. ?ticks n ϱ K$_1$} ∩ {ϱ. ?dead n ϱ K$_2$} ∩ {ϱ. ?kills (Suc n) ϱ}⟩
    using Collect_cong Collect_disj_eq **by** auto
  also have ⟨... = ⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∩ ⟦ K$_1$ kills K$_2$ ⟧$_{TESL}^{\geq Suc n}$

$$\cup \; [\![\; \mathtt{K_1} \; \Uparrow \; \mathtt{n} \;]\!]_{prim} \; \cap \; [\![\; \mathtt{K_2} \; \neg\Uparrow \; \geq \; \mathtt{n} \;]\!]_{prim}$$
$$\cap \; [\![\; \mathtt{K_1} \; \mathtt{kills} \; \mathtt{K_2} \;]\!]_{TESL}^{\geq \; \mathtt{Suc \; n}} \rangle \; \textbf{by simp}$$
finally show ?thesis by blast
qed

The stepwise interpretation of a TESL formula is the intersection of the interpretation of its atomic components.

fun `TESL_interpretation_stepwise`
  $::\langle$'τ`::linordered_field TESL_formula` $\Rightarrow$ `nat` $\Rightarrow$ 'τ `run set`$\rangle$
  $("[\![\; \_ \;]\!]_{TESL}^{\geq} \; \text{-}")$
where
  $\langle [\![\; \mathtt{[]} \;]\!]_{TESL}^{\geq \; \mathtt{n}} = \{\varrho. \; \mathtt{True}\}\rangle$
$| \; \langle [\![\; \varphi \; \# \; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{n}} = [\![\; \varphi \;]\!]_{TESL}^{\geq \; \mathtt{n}} \cap [\![\; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{n}} \rangle$

lemma `TESL_interpretation_stepwise_fixpoint`:
  $\langle [\![\; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{n}} = \bigcap \; ((\lambda\varphi. \; [\![\; \varphi \;]\!]_{TESL}^{\geq \; \mathtt{n}}) \; ' \; \mathtt{set} \; \Phi)\rangle$
by (induction Φ, simp, auto)

The global interpretation of a TESL formula is its interpretation starting at the first instant.

lemma `TESL_interpretation_stepwise_zero`:
  $\langle [\![\; \varphi \;]\!]_{TESL} = [\![\; \varphi \;]\!]_{TESL}^{\geq \; 0}\rangle$
by (induction φ, simp+)

lemma `TESL_interpretation_stepwise_zero'`:
  $\langle [\![\; \Phi \;]\!]_{TESL} = [\![\; \Phi \;]\!]_{TESL}^{\geq \; 0}\rangle$
by (induction Φ, simp, simp add: `TESL_interpretation_stepwise_zero`)

lemma `TESL_interpretation_stepwise_cons_morph`:
  $\langle [\![\; \varphi \;]\!]_{TESL}^{\geq \; \mathtt{n}} \cap [\![\; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{n}} = [\![\; \varphi \; \# \; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{n}} \rangle$
by auto

theorem `TESL_interp_stepwise_composition`:
  shows $\langle [\![\; \Phi_1 \; @ \; \Phi_2 \;]\!]_{TESL}^{\geq \; \mathtt{n}} = [\![\; \Phi_1 \;]\!]_{TESL}^{\geq \; \mathtt{n}} \cap [\![\; \Phi_2 \;]\!]_{TESL}^{\geq \; \mathtt{n}} \rangle$
by (induction Φ_1, simp, auto)

6.3 Interpretation of configurations

The interpretation of a configuration of the operational semantics abstract machine is the intersection of:

- the interpretation of its context (the past),

- the interpretation of its present from the current instant,

- the interpretation of its future from the next instant.

fun `HeronConf_interpretation`
  $::\langle$'τ`::linordered_field config` $\Rightarrow$ 'τ `run set`$\rangle$ $("[\![\; \_ \;]\!]_{config}" \; 71)$
where
  $\langle [\![\; \Gamma, \; \mathtt{n} \vdash \Psi \; \triangleright \; \Phi \;]\!]_{config} = [\![\; \Gamma \;]\!]_{prim} \cap [\![\; \Psi \;]\!]_{TESL}^{\geq \; \mathtt{n}} \cap [\![\; \Phi \;]\!]_{TESL}^{\geq \; \mathtt{Suc \; n}} \rangle$

lemma `HeronConf_interp_composition`:
  $\langle [\![\; \Gamma_1, \; \mathtt{n} \vdash \Psi_1 \; \triangleright \; \Phi_1 \;]\!]_{config} \cap [\![\; \Gamma_2, \; \mathtt{n} \vdash \Psi_2 \; \triangleright \; \Phi_2 \;]\!]_{config}$
    $= [\![\; (\Gamma_1 \; @ \; \Gamma_2), \; \mathtt{n} \vdash (\Psi_1 \; @ \; \Psi_2) \; \triangleright \; (\Phi_1 \; @ \; \Phi_2) \;]\!]_{config}\rangle$
  using `TESL_interp_stepwise_composition symrun_interp_expansion`

```
by (simp add: TESL_interp_stepwise_composition
              symrun_interp_expansion inf_assoc inf_left_commute)
```

When there are no remaining constraints on the present, the interpretation of a configuration is the same as the configuration at the next instant of its future. This corresponds to the introduction rule of the operational semantics.

lemma HeronConf_interp_stepwise_instant_cases:
  $\langle$ ⟦ Γ, n ⊢ [] ▷ Φ ⟧$_{config}$ = ⟦ Γ, Suc n ⊢ Φ ▷ [] ⟧$_{config}\rangle$
proof -
  have $\langle$ ⟦ Γ, n ⊢ [] ▷ Φ ⟧$_{config}$ = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ [] ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  moreover have $\langle$ ⟦ Γ, Suc n ⊢ Φ ▷ [] ⟧$_{config}$
                  = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}$ ∩ ⟦⟦ [] ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  moreover have $\langle$⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ [] ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}$
                  = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}$ ∩ ⟦⟦ [] ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  ultimately show ?thesis **by** blast
qed

The following lemmas use the unfolding properties of the stepwise denotational semantics to give rewriting rules for the interpretation of configurations that match the elimination rules of the operational semantics.

lemma HeronConf_interp_stepwise_sporadicon_cases:
  $\langle$ ⟦ Γ, n ⊢ ((K_1 sporadic τ on K_2) # Ψ) ▷ Φ ⟧$_{config}$
  = ⟦ Γ, n ⊢ Ψ ▷ ((K_1 sporadic τ on K_2) # Φ) ⟧$_{config}$
  ∪ ⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ ⟧$_{config}\rangle$
proof -
  have $\langle$ ⟦ Γ, n ⊢ (K_1 sporadic τ on K_2) # Ψ ▷ Φ ⟧$_{config}$
       = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ (K_1 sporadic τ on K_2) # Ψ ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  moreover have $\langle$ ⟦ Γ, n ⊢ Ψ ▷ ((K_1 sporadic τ on K_2) # Φ) ⟧$_{config}$
                  = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$
                  ∩ ⟦⟦ (K_1 sporadic τ on K_2) # Φ ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  moreover have $\langle$ ⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ ⟧$_{config}$
                  = ⟦⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ) ⟧⟧$_{prim}$
                  ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}^{\geq Suc\ n}\rangle$
    by simp
  ultimately show ?thesis
  proof -
    have $\langle$(⟦ K_1 ⇑ n ⟧$_{prim}$ ∩ ⟦ K_2 ⇓ n @ τ ⟧$_{prim}$ ∪ ⟦ K_1 sporadic τ on K_2 ⟧$_{TESL}^{\geq Suc\ n}$)
         ∩ (⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$)
         = ⟦ K_1 sporadic τ on K_2 ⟧$_{TESL}^{\geq n}$ ∩ (⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}$)$\rangle$
      using TESL_interp_stepwise_sporadicon_coind_unfold **by** blast
    hence $\langle$⟦⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ) ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$
         ∪ ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦ K_1 sporadic τ on K_2 ⟧$_{TESL}^{\geq Suc\ n}$
         = ⟦⟦ (K_1 sporadic τ on K_2) # Ψ ⟧⟧$_{TESL}^{\geq n}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}\rangle$ **by** auto
    thus ?thesis **by** auto
  qed
qed

lemma HeronConf_interp_stepwise_tagrel_cases:
  $\langle$ ⟦ Γ, n ⊢ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Ψ) ▷ Φ ⟧$_{config}$
  = ⟦ ((⌊τ_{var}(K_1, n), τ_{var}(K_2, n)⌋ ∈ R) # Γ), n
      ⊢ Ψ ▷ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Φ) ⟧$_{config}\rangle$
proof -

have $\langle [\![$ Γ, n ⊢ (time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R) # Ψ ▷ Φ $]\!]_{config}$
      = $[\![[\![$ Γ $]\!]]\!]_{prim}$ ∩ $[\![[\![$ (time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R) # Ψ $]\!]]\!]_{TESL}{}^{\geq n}$
      ∩ $[\![[\![$ Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$ **by** simp
moreover have $\langle [\![$ (($\lfloor \tau_{var}(K_1, n), \tau_{var}(K_2, n) \rfloor$ ∈ R) # Γ), n
                    ⊢ Ψ ▷ ((time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R) # Φ) $]\!]_{config}$
                  = $[\![(\lfloor \tau_{var}(K_1, n), \tau_{var}(K_2, n) \rfloor$ ∈ R) # Γ $]\!]_{prim}$ ∩ $[\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$
                    ∩ $[\![[\![$ (time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R) # Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$
    by simp
  ultimately show ?thesis
  proof -
    have $\langle [\![$ $\lfloor \tau_{var}(K_1, n), \tau_{var}(K_2, n) \rfloor$ ∈ R $]\!]_{prim}$
          ∩ $[\![$ time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R $]\!]_{TESL}{}^{\geq \text{ Suc } n}$
          ∩ $[\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$ = $[\![[\![$ (time-relation $\lfloor K_1, K_2 \rfloor$ ∈ R) # Ψ $]\!]]\!]_{TESL}{}^{\geq n} \rangle$
      using TESL_interp_stepwise_tagrel_coind_unfold
            TESL_interpretation_stepwise_cons_morph **by** blast
    thus ?thesis **by** auto
  qed
qed

lemma HeronConf_interp_stepwise_implies_cases:
  $\langle [\![$ Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ $]\!]_{config}$
      = $[\![$ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) $]\!]_{config}$
    ∪ $[\![$ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) $]\!]_{config} \rangle$
proof -
  have $\langle [\![$ Γ, n ⊢ (K_1 implies K_2) # Ψ ▷ Φ $]\!]_{config}$
        = $[\![[\![$ Γ $]\!]]\!]_{prim}$ ∩ $[\![[\![$ (K_1 implies K_2) # Ψ $]\!]]\!]_{TESL}{}^{\geq n}$ ∩ $[\![[\![$ Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$
    by simp
  moreover have $\langle [\![$ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) $]\!]_{config}$
              = $[\![$ (K_1 ¬⇑ n) # Γ $]\!]_{prim}$ ∩ $[\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$
              ∩ $[\![[\![$ (K_1 implies K_2) # Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$ **by** simp
  moreover have $\langle [\![$ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) $]\!]_{config}$
              = $[\![$ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ) $]\!]_{prim}$ ∩ $[\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$
              ∩ $[\![[\![$ (K_1 implies K_2) # Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$ **by** simp
  ultimately show ?thesis
  proof -
    have f1: $\langle ([\![$ K_1 ¬⇑ n $]\!]_{prim}$ ∪ $[\![$ K_1 ⇑ n $]\!]_{prim}$ ∩ $[\![$ K_2 ⇑ n $]\!]_{prim})$
            ∩ $[\![$ K_1 implies K_2 $]\!]_{TESL}{}^{\geq \text{ Suc } n}$ ∩ $([\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$
            ∩ $[\![[\![$ Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n})$
          = $[\![[\![$ (K_1 implies K_2) # Ψ $]\!]]\!]_{TESL}{}^{\geq n}$ ∩ $[\![[\![$ Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$
      using TESL_interp_stepwise_implies_coind_unfold
            TESL_interpretation_stepwise_cons_morph **by** blast
    have $\langle [\![$ K_1 ¬⇑ n $]\!]_{prim}$ ∩ $[\![[\![$ Γ $]\!]]\!]_{prim}$ ∪ $[\![$ K_1 ⇑ n $]\!]_{prim}$ ∩ $[\![[\![$ (K_2 ⇑ n) # Γ $]\!]]\!]_{prim}$
        = $([\![$ K_1 ¬⇑ n $]\!]_{prim}$ ∪ $[\![$ K_1 ⇑ n $]\!]_{prim}$ ∩ $[\![$ K_2 ⇑ n $]\!]_{prim}$) ∩ $[\![[\![$ Γ $]\!]]\!]_{prim} \rangle$
      by force
    hence $\langle [\![$ Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ $]\!]_{config}$
      = $([\![$ K_1 ¬⇑ n $]\!]_{prim}$ ∩ $[\![[\![$ Γ $]\!]]\!]_{prim}$ ∪ $[\![$ K_1 ⇑ n $]\!]_{prim}$ ∩ $[\![[\![$ (K_2 ⇑ n) # Γ $]\!]]\!]_{prim})$
      ∩ $([\![[\![$ Ψ $]\!]]\!]_{TESL}{}^{\geq n}$ ∩ $[\![[\![$ (K_1 implies K_2) # Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n}) \rangle$
      using f1 **by** (simp add: inf_left_commute inf_assoc)
    thus ?thesis **by** (simp add: Int_Un_distrib2 inf_assoc)
  qed
qed

lemma HeronConf_interp_stepwise_implies_not_cases:
  $\langle [\![$ Γ, n ⊢ ((K_1 implies not K_2) # Ψ) ▷ Φ $]\!]_{config}$
      = $[\![$ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies not K_2) # Φ) $]\!]_{config}$
    ∪ $[\![$ ((K_1 ⇑ n) # (K_2 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies not K_2) # Φ) $]\!]_{config} \rangle$
proof -
  have $\langle [\![$ Γ, n ⊢ (K_1 implies not K_2) # Ψ ▷ Φ $]\!]_{config}$
        = $[\![[\![$ Γ $]\!]]\!]_{prim}$ ∩ $[\![[\![$ (K_1 implies not K_2) # Ψ $]\!]]\!]_{TESL}{}^{\geq n}$ ∩ $[\![[\![$ Φ $]\!]]\!]_{TESL}{}^{\geq \text{ Suc } n} \rangle$

by simp
moreover have ⟨⟦ ((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies not K$_2$) # Φ) ⟧$_{config}$
                        = ⟦⟦ (K$_1$ ¬⇑ n) # Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
                        ∩ ⟦⟦ (K$_1$ implies not K$_2$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩ **by** simp
moreover have ⟨⟦ ((K$_1$ ⇑ n) # (K$_2$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ implies not K$_2$) # Φ) ⟧$_{config}$
                        = ⟦⟦ ((K$_1$ ⇑ n) # (K$_2$ ¬⇑ n) # Γ) ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
                        ∩ ⟦⟦ (K$_1$ implies not K$_2$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩ **by** simp
ultimately show ?thesis
proof -
  have f1: ⟨(⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$ ∩ ⟦ K$_2$ ¬⇑ n ⟧$_{prim}$)
            ∩ ⟦ K$_1$ implies not K$_2$ ⟧$_{TESL}$$^{\geq Suc\ n}$
            ∩ (⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$)
            = ⟦⟦ (K$_1$ implies not K$_2$) # Ψ ⟧⟧$_{TESL}$$^{\geq n}$ ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩
      using TESL_interp_stepwise_implies_not_coind_unfold
            TESL_interpretation_stepwise_cons_morph **by** blast
  have ⟨⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}$ ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$ ∩ ⟦⟦ (K$_2$ ¬⇑ n) # Γ ⟧⟧$_{prim}$
      = (⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$ ∩ ⟦ K$_2$ ¬⇑ n ⟧$_{prim}$) ∩ ⟦⟦ Γ ⟧⟧$_{prim}$⟩
      by force
  then have ⟨⟦ Γ, n ⊢ ((K$_1$ implies not K$_2$) # Ψ) ▷ Φ ⟧$_{config}$
                    = (⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∩ ⟦⟦ Γ ⟧⟧$_{prim}$ ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$
                    ∩ ⟦⟦ (K$_2$ ¬⇑ n) # Γ ⟧⟧$_{prim}$) ∩ (⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
                    ∩ ⟦⟦ (K$_1$ implies not K$_2$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$)⟩
      using f1 **by** (simp add: inf_left_commute inf_assoc)
  thus ?thesis **by** (simp add: Int_Un_distrib2 inf_assoc)
  qed
qed

lemma HeronConf_interp_stepwise_timedelayed_cases:
  ⟨⟦ Γ, n ⊢ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ) ▷ Φ ⟧$_{config}$
    = ⟦ ((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ) ⟧$_{config}$
    ∪ ⟦ ((K$_1$ ⇑ n) # (K$_2$ @ n ⊕ δτ ⇒ K$_3$) # Γ), n
        ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ) ⟧$_{config}$⟩
proof -
  have 1:⟨⟦ Γ, n ⊢ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ ▷ Φ ⟧$_{config}$
        = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ ⟧⟧$_{TESL}$$^{\geq n}$
        ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩ **by** simp
  moreover have ⟨⟦ ((K$_1$ ¬⇑ n) # Γ), n
                    ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ) ⟧$_{config}$
                    = ⟦⟦ (K$_1$ ¬⇑ n) # Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
                    ∩ ⟦⟦ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩
      by simp
  moreover have ⟨⟦ ((K$_1$ ⇑ n) # (K$_2$ @ n ⊕ δτ ⇒ K$_3$) # Γ), n
                    ⊢ Ψ ▷ ((K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ) ⟧$_{config}$
                    = ⟦⟦ (K$_1$ ⇑ n) # (K$_2$ @ n ⊕ δτ ⇒ K$_3$) # Γ ⟧⟧$_{prim}$ ∩ ⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
                    ∩ ⟦⟦ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$⟩
      by simp
  ultimately show ?thesis
  proof -
    have ⟨⟦ Γ, n ⊢ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ ▷ Φ ⟧$_{config}$
        = ⟦⟦ Γ ⟧⟧$_{prim}$ ∩ (⟦⟦ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ ⟧⟧$_{TESL}$$^{\geq n}$
        ∩ ⟦⟦ Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$)⟩
        using 1 **by** blast
    hence ⟨⟦ Γ, n ⊢ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Ψ ▷ Φ ⟧$_{config}$
        = (⟦ K$_1$ ¬⇑ n ⟧$_{prim}$ ∪ ⟦ K$_1$ ⇑ n ⟧$_{prim}$ ∩ ⟦ K$_2$ @ n ⊕ δτ ⇒ K$_3$ ⟧$_{prim}$)
        ∩ (⟦⟦ Γ ⟧⟧$_{prim}$ ∩ (⟦⟦ Ψ ⟧⟧$_{TESL}$$^{\geq n}$
        ∩ ⟦⟦ (K$_1$ time-delayed by δτ on K$_2$ implies K$_3$) # Φ ⟧⟧$_{TESL}$$^{\geq Suc\ n}$))⟩
        using TESL_interpretation_stepwise_cons_morph
            TESL_interp_stepwise_timedelayed_coind_unfold
      proof -

have $\langle[\![\ ($K$_1$ **time-delayed by** $\delta\tau$ **on** K$_2$ **implies** K$_3) \# \Psi\ ]\!]_{TESL}{}^{\geq\ \text{n}}$
$= ([\![\ K_1\ \neg\Uparrow\ n\ ]\!]_{prim} \cup [\![\ K_1\ \Uparrow\ n\ ]\!]_{prim} \cap [\![\ K_2\ @\ n\ \oplus\ \delta\tau \Rightarrow K_3\ ]\!]_{prim})$
$\cap [\![\ K_1\ $**time-delayed by** $\delta\tau$ **on** K$_2$ **implies** K$_3\ ]\!]_{TESL}{}^{\geq\ \text{Suc n}} \cap [\![\![\ \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}\rangle$
  using TESL_interp_stepwise_timedelayed_coind_unfold
       TESL_interpretation_stepwise_cons_morph **by** blast
    then show ?thesis
       by (simp add: Int_assoc Int_left_commute)
   qed
   then show ?thesis **by** (simp add: inf_assoc inf_sup_distrib2)
 qed
qed

lemma HeronConf_interp_stepwise_weakly_precedes_cases:
  $\langle[\![\ \Gamma,\ n\ \vdash\ ((K_1\ $**weakly precedes** K$_2) \# \Psi) \rhd \Phi\ ]\!]_{config}$
  $= [\![\ ((\lceil\#^{\leq}\ K_2\ n,\ \#^{\leq}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$))\ \#\ \Gamma),\ $n
    $\vdash \Psi \rhd (($K$_1\ $**weakly precedes** K$_2) \# \Phi)\ ]\!]_{config}\rangle$
proof -
 have $\langle[\![\ \Gamma,\ n\ \vdash\ (K_1\ $**weakly precedes** K$_2) \# \Psi \rhd \Phi\ ]\!]_{config}$
    $= [\![\![\ \Gamma\ ]\!]\!]_{prim} \cap [\![\![\ (K_1\ $**weakly precedes** K$_2) \# \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}$
    $\cap [\![\![\ \Phi\ ]\!]\!]_{TESL}{}^{\geq\ \text{Suc n}}\rangle$ **by** simp
 moreover have $\langle[\![\ (($\lceil\#^{\leq}$ K$_2$ n, $\#^{\leq}$ K$_1$ n$\rceil \in (\lambda($x,y$).\ x\leq$y$))\ \#\ \Gamma),\ $n
            $\vdash \Psi \rhd (($K$_1\ $**weakly precedes** K$_2) \# \Phi)\ ]\!]_{config}$
    $= [\![\![\ (\lceil\#^{\leq}\ K_2\ n,\ \#^{\leq}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$))\ \#\ \Gamma\ ]\!]\!]_{prim}$
    $\cap [\![\![\ \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}} \cap [\![\![\ (K_1\ $**weakly precedes** K$_2) \# \Phi\ ]\!]\!]_{TESL}{}^{\geq\ \text{Suc n}}\rangle$
  by simp
 ultimately show ?thesis
 proof -
   have $\langle[\![\ \lceil\#^{\leq}\ K_2\ n,\ \#^{\leq}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$)\ ]\!]_{prim}$
        $\cap [\![\ K_1\ $**weakly precedes** K$_2\ ]\!]_{TESL}{}^{\geq\ \text{Suc n}} \cap [\![\![\ \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}$
      $= [\![\![\ ($K$_1\ $**weakly precedes** K$_2) \# \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}\rangle$
     using TESL_interp_stepwise_weakly_precedes_coind_unfold
          TESL_interpretation_stepwise_cons_morph **by** blast
   thus ?thesis **by** auto
 qed
qed

lemma HeronConf_interp_stepwise_strictly_precedes_cases:
  $\langle[\![\ \Gamma,\ n\ \vdash\ ((K_1\ $**strictly precedes** K$_2) \# \Psi) \rhd \Phi\ ]\!]_{config}$
  $= [\![\ ((\lceil\#^{\leq}\ K_2\ n,\ \#^{<}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$))\ \#\ \Gamma),\ $n
    $\vdash \Psi \rhd (($K$_1\ $**strictly precedes** K$_2) \# \Phi)\ ]\!]_{config}\rangle$
proof -
 have $\langle[\![\ \Gamma,\ n\ \vdash\ (K_1\ $**strictly precedes** K$_2) \# \Psi \rhd \Phi\ ]\!]_{config}$
    $= [\![\![\ \Gamma\ ]\!]\!]_{prim} \cap [\![\![\ (K_1\ $**strictly precedes** K$_2) \# \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}$
    $\cap [\![\![\ \Phi\ ]\!]\!]_{TESL}{}^{\geq\ \text{Suc n}}\rangle$ **by** simp
 moreover have $\langle[\![\ (($\lceil\#^{\leq}$ K$_2$ n, $\#^{<}$ K$_1$ n$\rceil \in (\lambda($x,y$).\ x\leq$y$))\ \#\ \Gamma),\ $n
            $\vdash \Psi \rhd (($K$_1\ $**strictly precedes** K$_2) \# \Phi)\ ]\!]_{config}$
    $= [\![\![\ (\lceil\#^{\leq}\ K_2\ n,\ \#^{<}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$))\ \#\ \Gamma\ ]\!]\!]_{prim}$
    $\cap [\![\![\ \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}$
    $\cap [\![\![\ ($K$_1\ $**strictly precedes** K$_2) \# \Phi\ ]\!]\!]_{TESL}{}^{\geq\ \text{Suc n}}\rangle$ **by** simp
 ultimately show ?thesis
 proof -
   have $\langle[\![\ \lceil\#^{\leq}\ K_2\ n,\ \#^{<}\ K_1\ n\rceil \in (\lambda(x,y).\ x\leq$y$)\ ]\!]_{prim}$
        $\cap [\![\ K_1\ $**strictly precedes** K$_2\ ]\!]_{TESL}{}^{\geq\ \text{Suc n}} \cap [\![\![\ \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}$
      $= [\![\![\ ($K$_1\ $**strictly precedes** K$_2) \# \Psi\ ]\!]\!]_{TESL}{}^{\geq\ \text{n}}\rangle$
     using TESL_interp_stepwise_strictly_precedes_coind_unfold
          TESL_interpretation_stepwise_cons_morph **by** blast
   thus ?thesis **by** auto
 qed
qed

lemma HeronConf_interp_stepwise_kills_cases:
    $\langle \llbracket$ Γ, n $\vdash$ ((K$_1$ kills K$_2$) # Ψ) $\triangleright$ Φ $\rrbracket_{config}$
        = $\llbracket$ ((K$_1$ $\neg\Uparrow$ n) # Γ), n $\vdash$ Ψ $\triangleright$ ((K$_1$ kills K$_2$) # Φ) $\rrbracket_{config}$
        $\cup$ $\llbracket$ ((K$_1$ $\Uparrow$ n) # (K$_2$ $\neg\Uparrow$ $\geq$ n) # Γ), n $\vdash$ Ψ $\triangleright$ ((K$_1$ kills K$_2$) # Φ) $\rrbracket_{config}\rangle$
proof -
    have $\langle \llbracket$ Γ, n $\vdash$ ((K$_1$ kills K$_2$) # Ψ) $\triangleright$ Φ $\rrbracket_{config}$
            = $\llbracket\llbracket$ Γ $\rrbracket\rrbracket_{prim}$ $\cap$ $\llbracket\llbracket$ (K$_1$ kills K$_2$) # Ψ $\rrbracket\rrbracket_{TESL}^{\geq \text{ n}}$ $\cap$ $\llbracket\llbracket$ Φ $\rrbracket\rrbracket_{TESL}^{\geq \text{ Suc n}}\rangle$
        by simp
    moreover have $\langle \llbracket$ ((K$_1$ $\neg\Uparrow$ n) # Γ), n $\vdash$ Ψ $\triangleright$ ((K$_1$ kills K$_2$) # Φ) $\rrbracket_{config}$
                    = $\llbracket\llbracket$ (K$_1$ $\neg\Uparrow$ n) # Γ $\rrbracket\rrbracket_{prim}$ $\cap$ $\llbracket\llbracket$ Ψ $\rrbracket\rrbracket_{TESL}^{\geq \text{ n}}$
                    $\cap$ $\llbracket\llbracket$ (K$_1$ kills K$_2$) # Φ $\rrbracket\rrbracket_{TESL}^{\geq \text{ Suc n}}\rangle$ **by** simp
    moreover have $\langle \llbracket$ ((K$_1$ $\Uparrow$ n) # (K$_2$ $\neg\Uparrow$ $\geq$ n) # Γ), n $\vdash$ Ψ $\triangleright$ ((K$_1$ kills K$_2$) # Φ) $\rrbracket_{config}$
                    = $\llbracket\llbracket$ (K$_1$ $\Uparrow$ n) # (K$_2$ $\neg\Uparrow$ $\geq$ n) # Γ $\rrbracket\rrbracket_{prim}$ $\cap$ $\llbracket\llbracket$ Ψ $\rrbracket\rrbracket_{TESL}^{\geq \text{ n}}$
                    $\cap$ $\llbracket\llbracket$ (K$_1$ kills K$_2$) # Φ $\rrbracket\rrbracket_{TESL}^{\geq \text{ Suc n}}\rangle$ **by** simp
    ultimately show ?thesis
        proof -
            have $\langle\llbracket\llbracket$ (K$_1$ kills K$_2$) # Ψ $\rrbracket\rrbracket_{TESL}^{\geq \text{ n}}$
                    = ($\llbracket$ (K$_1$ $\neg\Uparrow$ n) $\rrbracket_{prim}$ $\cup$ $\llbracket$ (K$_1$ $\Uparrow$ n) $\rrbracket_{prim}$ $\cap$ $\llbracket$ (K$_2$ $\neg\Uparrow$ $\geq$ n) $\rrbracket_{prim}$)
                    $\cap$ $\llbracket$ (K$_1$ kills K$_2$) $\rrbracket_{TESL}^{\geq \text{ Suc n}}$ $\cap$ $\llbracket\llbracket$ Ψ $\rrbracket\rrbracket_{TESL}^{\geq \text{ n}}\rangle$
                using TESL_interp_stepwise_kills_coind_unfold
                        TESL_interpretation_stepwise_cons_morph **by** blast
            thus ?thesis **by** auto
        qed
qed

end

Chapter 7

Main Theorems

theory Hygge_Theory
imports
  Corecursive_Prop

begin

Using the properties we have shown about the interpretation of configurations and the stepwise unfolding of the denotational semantics, we can now prove several important results about the construction of runs from a specification.

7.1 Initial configuration

The denotational semantics of a specification Ψ is the interpretation at the first instant of a configuration which has Ψ as its present. This means that we can start to build a run that satisfies a specification by starting from this configuration.

theorem solve_start:
  shows $\langle [\![\ \Psi\ ]\!]_{TESL} = [\![\ []\ ,\ 0 \vdash \Psi \rhd []\ ]\!]_{config} \rangle$
  proof -
    have $\langle [\![\ \Psi\ ]\!]_{TESL} = [\![\ \Psi\ ]\!]_{TESL}^{\geq 0} \rangle$
    by (simp add: TESL_interpretation_stepwise_zero')
    moreover have $\langle [\![\ []\ ,\ 0 \vdash \Psi \rhd []\ ]\!]_{config} =$
                        $[\![\ []\ ]\!]_{prim} \cap [\![\ \Psi\ ]\!]_{TESL}^{\geq 0} \cap [\![\ []\ ]\!]_{TESL}^{\geq \text{Suc } 0} \rangle$
    by simp
    ultimately show ?thesis **by** auto
  qed

7.2 Soundness

The interpretation of a configuration $\mathcal{S}_2$ that is a refinement of a configuration $\mathcal{S}_1$ is contained in the interpretation of $\mathcal{S}_1$. This means that by making successive choices in building the instants of a run, we preserve the soundness of the constructed run with regard to the original specification.

lemma sound_reduction:
  assumes $\langle (\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1)\ \hookrightarrow\ (\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) \rangle$
  shows $\langle [\![\ \Gamma_1\ ]\!]_{prim} \cap [\![\ \Psi_1\ ]\!]_{TESL}^{\geq n_1} \cap [\![\ \Phi_1\ ]\!]_{TESL}^{\geq \text{Suc } n_1}$
          $\supseteq\ [\![\ \Gamma_2\ ]\!]_{prim} \cap [\![\ \Psi_2\ ]\!]_{TESL}^{\geq n_2} \cap [\![\ \Phi_2\ ]\!]_{TESL}^{\geq \text{Suc } n_2} \rangle$ **(is** ?P**)**
proof -

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from assms **consider**
  (a) $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1)\ \hookrightarrow_i\ (\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2)\rangle$
| (b) $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1)\ \hookrightarrow_e\ (\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2)\rangle$
  using operational_semantics_step.simps **by** blast
thus ?thesis
proof (cases)
  case a
    thus ?thesis **by** (simp add: operational_semantics_intro.simps)
next
  case b **thus** ?thesis
  proof (rule operational_semantics_elim.cases)
    fix Γ n K_1 τ K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash (K_1$ sporadic τ on $K_2)$ # $\Psi \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (\Gamma,\ n \vdash \Psi \rhd ((K_1$ sporadic τ on $K_2)$ # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_sporadicon_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 τ K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash (K_1$ sporadic τ on $K_2)$ # $\Psi \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((K_1 \Uparrow n)$ # $(K_2 \Downarrow n$ @ $\tau)$ # $\Gamma),\ n \vdash \Psi \rhd \Phi)\rangle$
    thus ?P **using** HeronConf_interp_stepwise_sporadicon_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 K_2 R Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash$ (time-relation $\lfloor K_1,\ K_2 \rfloor \in$ R) # $\Psi \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((\lfloor \tau_{var}\ (K_1,\ n),\ \tau_{var}\ (K_2,\ n)\rfloor \in$ R) # $\Gamma),$ n
                              $\vdash \Psi \rhd$ ((time-relation $\lfloor K_1,\ K_2 \rfloor \in$ R) # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_tagrel_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash (K_1$ implies $K_2)$ # $\Psi \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((K_1 \neg\Uparrow n)$ # $\Gamma),\ n \vdash \Psi \rhd ((K_1$ implies $K_2)$ # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_implies_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash ((K_1$ implies $K_2)$ # $\Psi) \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((K_1 \Uparrow n)$ # $(K_2 \Uparrow n)$ # $\Gamma),$ n
                        $\vdash \Psi \rhd ((K_1$ implies $K_2)$ # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_implies_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash ((K_1$ implies not $K_2)$ # $\Psi) \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((K_1 \neg\Uparrow n)$ # $\Gamma),\ n \vdash \Psi \rhd ((K_1$ implies not $K_2)$ # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_implies_not_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 K_2 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) = (\Gamma,\ n \vdash ((K_1$ implies not $K_2)$ # $\Psi) \rhd \Phi)\rangle$
    and $\langle(\Gamma_2,\ n_2 \vdash \Psi_2 \rhd \Phi_2) = (((K_1 \Uparrow n)$ # $(K_2 \neg\Uparrow n)$ # $\Gamma),$ n
                      $\vdash \Psi \rhd ((K_1$ implies not $K_2)$ # $\Phi))\rangle$
    thus ?P **using** HeronConf_interp_stepwise_implies_not_cases
                HeronConf_interpretation.simps **by** blast
  next
    fix Γ n K_1 $\delta\tau$ K_2 K_3 Ψ Φ
    assume $\langle(\Gamma_1,\ n_1 \vdash \Psi_1 \rhd \Phi_1) =$
             $(\Gamma,\ n \vdash ((K_1$ time-delayed by $\delta\tau$ on K_2 implies $K_3)$ # $\Psi) \rhd \Phi)\rangle$

```
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) =
              (((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ time-delayed by δτ on K₂ implies K₃) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_timedelayed_cases
                    HeronConf_interpretation.simps by blast
  next
    fix Γ n K₁ δτ K₂ K₃ Ψ Φ
    assume ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁) =
            (Γ, n ⊢ ((K₁ time-delayed by δτ on K₂ implies K₃) # Ψ) ▷ Φ)⟩
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂)
          = (((K₁ ⇑ n) # (K₂ @ n ⊕ δτ ⇒ K₃) # Γ), n
              ⊢ Ψ ▷ ((K₁ time-delayed by δτ on K₂ implies K₃) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_timedelayed_cases
                    HeronConf_interpretation.simps by blast
  next
    fix Γ n K₁ K₂ Ψ Φ
    assume ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁) = (Γ, n ⊢ ((K₁ weakly precedes K₂) # Ψ) ▷ Φ)⟩
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) = (((⌈#≤ K₂ n, #≤ K₁ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
                                  ⊢ Ψ ▷ ((K₁ weakly precedes K₂) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_weakly_precedes_cases
                    HeronConf_interpretation.simps by blast
  next
    fix Γ n K₁ K₂ Ψ Φ
    assume ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁) = (Γ, n ⊢ ((K₁ strictly precedes K₂) # Ψ) ▷ Φ)⟩
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) = (((⌈#≤ K₂ n, #< K₁ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
                                  ⊢ Ψ ▷ ((K₁ strictly precedes K₂) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_strictly_precedes_cases
                    HeronConf_interpretation.simps by blast
  next
    fix Γ n K₁ K₂ Ψ Φ
    assume ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁) = (Γ, n ⊢ ((K₁ kills K₂) # Ψ) ▷ Φ)⟩
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) = (((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_kills_cases
                    HeronConf_interpretation.simps by blast
  next
    fix Γ n K₁ K₂ Ψ Φ
    assume ⟨(Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁) = (Γ, n ⊢ ((K₁ kills K₂) # Ψ) ▷ Φ)⟩
      and ⟨(Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) =
              (((K₁ ⇑ n) # (K₂ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K₁ kills K₂) # Φ))⟩
      thus ?P using HeronConf_interp_stepwise_kills_cases
                    HeronConf_interpretation.simps by blast
    qed
  qed
qed

inductive_cases step_elim:⟨S₁ ↪ S₂⟩

lemma sound_reduction':
  assumes ⟨S₁ ↪ S₂⟩
  shows ⟨⟦ S₁ ⟧config ⊇ ⟦ S₂ ⟧config⟩
proof -
  have ⟨∀ s₁ s₂. (⟦ s₂ ⟧config ⊆ ⟦ s₁ ⟧config) ∨ ¬(s₁ ↪ s₂)⟩
    using sound_reduction by fastforce
  thus ?thesis using assms by blast
qed

lemma sound_reduction_generalized:
  assumes ⟨S₁ ↪ᵏ S₂⟩
    shows ⟨⟦ S₁ ⟧config ⊇ ⟦ S₂ ⟧config⟩
proof -
```

```
  from assms show ?thesis
  proof (induction k arbitrary: 𝒮₂)
    case 0
      hence *: ⟨𝒮₁ ↪⁰ 𝒮₂ ⟹ 𝒮₁ = 𝒮₂⟩ by auto
      moreover have ⟨𝒮₁ = 𝒮₂⟩ using * "0.prems" by linarith
      ultimately show ?case by auto
  next
    case (Suc k)
      thus ?case
      proof -
        fix k :: nat
        assume ff: ⟨𝒮₁ ↪^Suc k 𝒮₂⟩
        assume hi: ⟨⋀𝒮₂. 𝒮₁ ↪ᵏ 𝒮₂ ⟹ ⟦ 𝒮₂ ⟧_config ⊆ ⟦ 𝒮₁ ⟧_config⟩
        obtain 𝒮ₙ where red_decomp: ⟨(𝒮₁ ↪ᵏ 𝒮ₙ) ∧ (𝒮ₙ ↪ 𝒮₂)⟩ using ff by auto
        hence ⟨⟦ 𝒮₁ ⟧_config ⊇ ⟦ 𝒮ₙ ⟧_config⟩ using hi by simp
        also have ⟨⟦ 𝒮ₙ ⟧_config ⊇ ⟦ 𝒮₂ ⟧_config⟩ by (simp add: red_decomp sound_reduction')
        ultimately show ⟨⟦ 𝒮₁ ⟧_config ⊇ ⟦ 𝒮₂ ⟧_config⟩ by simp
      qed
  qed
qed
```

From the initial configuration, a configuration $\mathcal{S}$ obtained after any number k of reduction steps denotes runs from the initial specification Ψ.

```
theorem soundness:
  assumes ⟨([], 0 ⊢ Ψ ▷ []) ↪ᵏ 𝒮⟩
    shows ⟨⟦ Ψ ⟧_TESL ⊇ ⟦ 𝒮 ⟧_config⟩
  using assms sound_reduction_generalized solve_start by blast
```

7.3 Completeness

We will now show that any run that satisfies a specification can be derived from the initial configuration, at any number of steps.

We start by proving that any run that is denoted by a configuration $\mathcal{S}$ is necessarily denoted by at least one of the configurations that can be reached from $\mathcal{S}$.

```
lemma complete_direct_successors:
  shows ⟨⟦ Γ, n ⊢ Ψ ▷ Φ ⟧_config ⊆ (⋃X∈𝒞_next (Γ, n ⊢ Ψ ▷ Φ). ⟦ X ⟧_config)⟩
  proof (induct Ψ)
    case Nil
    show ?case
      using HeronConf_interp_stepwise_instant_cases operational_semantics_step.simps
            operational_semantics_intro.instant_i
      by fastforce
  next
    case (Cons ψ Ψ)  thus ?case
      proof (cases ψ)
        case (SporadicOn K1 τ K2) thus ?thesis
          using HeronConf_interp_stepwise_sporadicon_cases
                                    [of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨τ⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                Cnext_solve_sporadicon[of ⟨Γ⟩ ⟨n⟩ ⟨Ψ⟩ ⟨K1⟩ ⟨τ⟩ ⟨K2⟩ ⟨Φ⟩] by blast
      next
        case (TagRelation K₁ K₂ R) thus ?thesis
          using HeronConf_interp_stepwise_tagrel_cases
                                    [of ⟨Γ⟩ ⟨n⟩ ⟨K₁⟩ ⟨K₂⟩ ⟨R⟩ ⟨Ψ⟩ ⟨Φ⟩]
                Cnext_solve_tagrel[of ⟨K₁⟩ ⟨n⟩ ⟨K₂⟩ ⟨R⟩ ⟨Γ⟩ ⟨Ψ⟩ ⟨Φ⟩] by blast
      next
        case (Implies K1 K2) thus ?thesis
```

```
                  using HeronConf_interp_stepwise_implies_cases
                                      [of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                        Cnext_solve_implies[of ⟨K1⟩ ⟨n⟩ ⟨Γ⟩ ⟨Ψ⟩ ⟨K2⟩ ⟨Φ⟩] by blast
      next
        case (ImpliesNot K1 K2) thus ?thesis
          using HeronConf_interp_stepwise_implies_not_cases
                                      [of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                        Cnext_solve_implies_not[of ⟨K1⟩ ⟨n⟩ ⟨Γ⟩ ⟨Ψ⟩ ⟨K2⟩ ⟨Φ⟩] by blast
      next
        case (TimeDelayedBy Kmast τ Kmeas Kslave) thus ?thesis
          using HeronConf_interp_stepwise_timedelayed_cases
                          [of ⟨Γ⟩ ⟨n⟩ ⟨Kmast⟩ ⟨τ⟩ ⟨Kmeas⟩ ⟨Kslave⟩ ⟨Ψ⟩ ⟨Φ⟩]
                    Cnext_solve_timedelayed
                          [of ⟨Kmast⟩ ⟨n⟩ ⟨Γ⟩ ⟨Ψ⟩ ⟨τ⟩ ⟨Kmeas⟩ ⟨Kslave⟩ ⟨Φ⟩] by blast
      next
        case (WeaklyPrecedes K1 K2) thus ?thesis
          using HeronConf_interp_stepwise_weakly_precedes_cases
                                        [of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                        Cnext_solve_weakly_precedes[of ⟨K2⟩ ⟨n⟩ ⟨K1⟩ ⟨Γ⟩ ⟨Ψ⟩  ⟨Φ⟩]
          by blast
      next
        case (StrictlyPrecedes K1 K2)  thus ?thesis
          using HeronConf_interp_stepwise_strictly_precedes_cases
                                        [of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                        Cnext_solve_strictly_precedes[of ⟨K2⟩ ⟨n⟩ ⟨K1⟩ ⟨Γ⟩ ⟨Ψ⟩  ⟨Φ⟩]
          by blast
      next
        case (Kills K1 K2) thus ?thesis
          using HeronConf_interp_stepwise_kills_cases[of ⟨Γ⟩ ⟨n⟩ ⟨K1⟩ ⟨K2⟩ ⟨Ψ⟩ ⟨Φ⟩]
                  Cnext_solve_kills[of ⟨K1⟩ ⟨n⟩ ⟨Γ⟩ ⟨Ψ⟩ ⟨K2⟩ ⟨Φ⟩] by blast
      qed
  qed
```

```
lemma complete_direct_successors':
  shows ⟨⟦ 𝒮 ⟧config ⊆ (⋃X∈𝒞next 𝒮. ⟦ X ⟧config)⟩
proof -
  from HeronConf_interpretation.cases obtain Γ n Ψ Φ
    where ⟨𝒮 = (Γ, n ⊢ Ψ ⊳ Φ)⟩ by blast
  with complete_direct_successors[of ⟨Γ⟩ ⟨n⟩ ⟨Ψ⟩ ⟨Φ⟩] show ?thesis by simp
qed
```

Therefore, if a run belongs to a configuration, it necessarily belongs to a configuration derived from it.

```
lemma branch_existence:
  assumes ⟨ϱ ∈ ⟦ 𝒮₁ ⟧config⟩
  shows ⟨∃𝒮₂. (𝒮₁ ↪ 𝒮₂) ∧ (ϱ ∈ ⟦ 𝒮₂ ⟧config)⟩
proof -
  from assms complete_direct_successors' have ⟨ϱ ∈ (⋃X∈𝒞next 𝒮₁. ⟦ X ⟧config)⟩ by blast
  hence ⟨∃s∈𝒞next 𝒮₁. ϱ ∈ ⟦ s ⟧config⟩ by simp
  thus ?thesis by blast
qed
```

```
lemma branch_existence':
  assumes ⟨ϱ ∈ ⟦ 𝒮₁ ⟧config⟩
  shows ⟨∃𝒮₂. (𝒮₁ ↪ᵏ 𝒮₂) ∧ (ϱ ∈ ⟦ 𝒮₂ ⟧config)⟩
proof (induct k)
  case 0
    thus ?case by (simp add: assms)
```

next
  case (Suc k)
    thus ?case
      using branch_existence relpowp_Suc_I[of ⟨k⟩ ⟨operational_semantics_step⟩]
    by blast
qed

Any run that belongs to the original specification Ψ has a corresponding configuration $\mathcal{S}$ at any number k of reduction steps from the initial configuration. Therefore, any run that satisfies a specification can be derived from the initial configuration at any level of reduction.

theorem completeness:
  assumes ⟨$\varrho \in [\![\, \Psi\,]\!]_{TESL}$⟩
  shows ⟨$\exists \mathcal{S}.\ (([], 0 \vdash \Psi \rhd []) \hookrightarrow^{k}\ \mathcal{S})$
        $\wedge\ \varrho \in [\![\ \mathcal{S}\ ]\!]_{config}$⟩
  using assms branch_existence' solve_start **by** blast

7.4   Progress

Reduction steps do not guarantee that the construction of a run progresses in the sequence of instants. We need to show that it is always possible to reach the next instant, and therefore any future instant, through a number of steps.

lemma instant_index_increase:
  assumes ⟨$\varrho \in [\![\ \Gamma,\ n \vdash \Psi \rhd \Phi\ ]\!]_{config}$⟩
  shows   ⟨$\exists \Gamma_k\ \Psi_k\ \Phi_k\ k.\ ((\Gamma,\ n \vdash \Psi \rhd \Phi)\ \hookrightarrow^{k}\ (\Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k))$
                            $\wedge\ \varrho \in [\![\ \Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k\ ]\!]_{config}$⟩
proof (insert assms, induct Ψ arbitrary: Γ Φ)
  case (Nil Γ Φ)
    then show ?case
    proof -
      have ⟨$(\Gamma,\ n \vdash [] \rhd \Phi)\ \hookrightarrow^{1}\ (\Gamma,\ \text{Suc } n \vdash \Phi \rhd [])$⟩
        using instant_i intro_part **by** fastforce
      moreover have ⟨$[\![\ \Gamma,\ n \vdash [] \rhd \Phi\ ]\!]_{config} = [\![\ \Gamma,\ \text{Suc } n \vdash \Phi \rhd []\ ]\!]_{config}$⟩
        by auto
      moreover have ⟨$\varrho \in [\![\ \Gamma,\ \text{Suc } n \vdash \Phi \rhd []\ ]\!]_{config}$⟩
        using assms Nil.prems calculation(2) **by** blast
      ultimately show ?thesis **by** blast
    qed
next
  case (Cons ψ Ψ)
    then show ?case
    proof (induct ψ)
      case (SporadicOn K_1 τ K_2)
        have branches: ⟨$[\![\ \Gamma,\ n \vdash ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Psi) \rhd \Phi\ ]\!]_{config}$
              $= [\![\ \Gamma,\ n \vdash \Psi \rhd ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Phi)\ ]\!]_{config}$
              $\cup\ [\![\ ((K_1 \Uparrow n)\ \#\ (K_2 \Downarrow n\ @\ \tau)\ \#\ \Gamma),\ n \vdash \Psi \rhd \Phi\ ]\!]_{config}$⟩
          using HeronConf_interp_stepwise_sporadicon_cases **by** simp
        have br1: ⟨$\varrho \in [\![\ \Gamma,\ n \vdash \Psi \rhd ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Phi)\ ]\!]_{config}$
              $\implies \exists \Gamma_k\ \Psi_k\ \Phi_k\ k.$
                  $((\Gamma,\ n \vdash ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Psi) \rhd \Phi)$
                      $\hookrightarrow^{k}\ (\Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k))$
                $\wedge\ \varrho \in [\![\ \Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k\ ]\!]_{config}$⟩
        proof -
          assume h1: ⟨$\varrho \in [\![\ \Gamma,\ n \vdash \Psi \rhd ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Phi)\ ]\!]_{config}$⟩
         hence ⟨$\exists \Gamma_k\ \Psi_k\ \Phi_k\ k.\ ((\Gamma,\ n \vdash \Psi \rhd ((K_1 \text{ sporadic } \tau \text{ on } K_2)\ \#\ \Phi))$
                       $\hookrightarrow^{k}\ (\Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k))$
                  $\wedge\ (\varrho \in [\![\ \Gamma_k,\ \text{Suc } n \vdash \Psi_k \rhd \Phi_k\ ]\!]_{config})$⟩

         using h1 SporadicOn.prems **by** simp
       from this obtain Γ_k Ψ_k Φ_k k **where**
            fp:⟨(((Γ, n ⊢ Ψ ▷ ((K_1 sporadic τ on K_2) # Φ))
                    ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
             ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
       have
         ⟨(Γ, n ⊢ ((K_1 sporadic τ on K_2) # Ψ) ▷ Φ)
          ↪ (Γ, n ⊢ Ψ ▷ ((K_1 sporadic τ on K_2) # Φ))⟩
        by (simp add: elims_part sporadic_on_e1)
       with fp relpowp_Suc_I2 **have**
         ⟨((Γ, n ⊢ ((K_1 sporadic τ on K_2) # Ψ) ▷ Φ)
          ↪$^{Suc\ k}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))⟩ **by** auto
       thus ?thesis **using** fp **by** blast
     qed
     have br2: ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ ⟧$_{config}$
            ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K_1 sporadic τ on K_2) # Ψ) ▷ Φ)
                         ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
                 ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
     proof -
       assume h2: ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ ⟧$_{config}$⟩
       hence ⟨(∃Γ_k Ψ_k Φ_k k. ((((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ)
                          ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
                  ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
        using h2 SporadicOn.prems **by** simp

        from this obtain Γ_k Ψ_k Φ_k k
        where fp:⟨((((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ)
                ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))⟩
         and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
        have pc:⟨(Γ, n ⊢ ((K_1 sporadic τ on K_2) # Ψ) ▷ Φ)
        ↪ (((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ)⟩
        by (simp add: elims_part sporadic_on_e2)
        hence ⟨(Γ, n ⊢ (K_1 sporadic τ on K_2) # Ψ ▷ Φ)
          ↪$^{Suc\ k}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
         using fp relpowp_Suc_I2 **by** auto
        with rc **show** ?thesis **by** blast
     qed
     from branches SporadicOn.prems(2) **have**
      ⟨ϱ ∈ ⟦ Γ, n ⊢ Ψ ▷ ((K_1 sporadic τ on K_2) # Φ) ⟧$_{config}$
      ∪ ⟦ ((K_1 ⇑ n) # (K_2 ⇓ n @ τ) # Γ), n ⊢ Ψ ▷ Φ ⟧$_{config}$⟩
     by simp
     with br1 br2 **show** ?case **by** blast
 next
  case (TagRelation K_1 K_2 R)
    have branches: ⟨⟦ Γ, n ⊢ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Ψ) ▷ Φ ⟧$_{config}$
      = ⟦ ((⌊τ_{var}(K_1, n), τ_{var}(K_2, n)⌋ ∈ R) # Γ), n
        ⊢ Ψ ▷ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Φ) ⟧$_{config}$⟩
    using HeronConf_interp_stepwise_tagrel_cases **by** simp
   thus ?case
   proof -
     have ⟨∃Γ_k Ψ_k Φ_k k.
       ((((⌊τ_{var}(K_1, n), τ_{var}(K_2, n)⌋ ∈ R) # Γ), n
         ⊢ Ψ ▷ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Φ))
       ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)) ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
     using TagRelation.prems **by** simp

     from this obtain Γ_k Ψ_k Φ_k k
      where fp:⟨(((((⌊τ_{var}(K_1, n), τ_{var}(K_2, n)⌋ ∈ R) # Γ), n
         ⊢ Ψ ▷ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Φ))

$\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)))⟩
  and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
have pc:⟨(Γ, n ⊢ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Ψ) ▷ Φ)
  ↪ (((⌊τ_{var} (K_1, n), τ_{var} (K_2, n)⌋ ∈ R) # Γ), n
    ⊢ Ψ ▷ ((time-relation ⌊K_1, K_2⌋ ∈ R) # Φ)))⟩
  by (simp add: elims_part tagrel_e)
hence ⟨(Γ, n ⊢ (time-relation ⌊K_1, K_2⌋ ∈ R) # Ψ ▷ Φ)
   $\hookrightarrow^{\mathrm{Suc\ k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
  using fp relpowp_Suc_I2 **by** auto
with rc **show** ?thesis **by** blast
 qed
next
 case (Implies K_1 K_2)
  have branches: ⟨⟦ Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ ⟧$_{config}$
   = ⟦ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$
   ∪ ⟦ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$⟩
  using HeronConf_interp_stepwise_implies_cases **by** simp
  moreover have br1: ⟨ϱ ∈ ⟦ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$
    ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ)
        $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
    ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
  proof -
   assume h1: ⟨ϱ ∈ ⟦ ((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$⟩
   then have ⟨∃Γ_k Ψ_k Φ_k k.
     (((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ))
      $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
    ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
   using h1 Implies.prems **by** simp
   from this obtain Γ_k Ψ_k Φ_k k **where**
   fp:⟨(((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ))
    $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))⟩
   and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
   have pc:⟨(Γ, n ⊢ (K_1 implies K_2) # Ψ ▷ Φ)
     ↪ (((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ)))⟩
   by (simp add: elims_part implies_e1)
   hence ⟨(Γ, n ⊢ (K_1 implies K_2) # Ψ ▷ Φ) $\hookrightarrow^{\mathrm{Suc\ k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
    using fp relpowp_Suc_I2 **by** auto
   with rc **show** ?thesis **by** blast
  qed
  moreover have br2: ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n
       ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$
    ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ)
          $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
      ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
  proof -
   assume h2: ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n
      ⊢ Ψ ▷ ((K_1 implies K_2) # Φ) ⟧$_{config}$⟩
   then have ⟨∃Γ_k Ψ_k Φ_k k. (
      ((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ))
      $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)
) ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
   using h2 Implies.prems **by** simp
   from this obtain Γ_k Ψ_k Φ_k k **where**
    fp:⟨(((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ))
    $\hookrightarrow^{\mathrm{k}}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
   and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
   have ⟨(Γ, n ⊢ ((K_1 implies K_2) # Ψ) ▷ Φ)
    ↪ (((K_1 ⇑ n) # (K_2 ⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 implies K_2) # Φ)))⟩
   by (simp add: elims_part implies_e2)

      hence ⟨(Γ, n ⊢ ((K₁ implies K₂) # Ψ) ▷ Φ) ↪^{Suc k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
        using fp relpowp_Suc_I2 by auto
      with rc show ?thesis by blast
    qed
    ultimately show ?case using Implies.prems(2) by blast
next
  case (ImpliesNot K₁ K₂)
    have branches: ⟨⟦ Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ ⟧_{config}
      = ⟦ ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}
      ∪ ⟦ ((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}⟩
    using HeronConf_interp_stepwise_implies_not_cases by simp
    moreover have br1: ⟨ϱ ∈ ⟦ ((K₁ ¬⇑ n) # Γ), n
                ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}
       ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ)
                 ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
         ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩
    proof -
      assume h1: ⟨ϱ ∈ ⟦ ((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}⟩
      then have ⟨∃Γ_k Ψ_k Φ_k k.
          ((((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ))
         ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
         ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩
      using h1 ImpliesNot.prems by simp
      from this obtain Γ_k Ψ_k Φ_k k **where**
        fp:⟨((((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ))
          ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)))⟩
        and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩ **by blast**
      have pc:⟨(Γ, n ⊢ (K₁ implies not K₂) # Ψ ▷ Φ)
         ↪ (((K₁ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ))⟩
        by (simp add: elims_part implies_not_e1)
      hence ⟨(Γ, n ⊢ (K₁ implies not K₂) # Ψ ▷ Φ) ↪^{Suc k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
        using fp relpowp_Suc_I2 by auto
      with rc show ?thesis by blast
    qed
    moreover have br2: ⟨ϱ ∈ ⟦ ((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n
                ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}
         ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ)
                 ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
            ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩
    proof -
      assume h2: ⟨ϱ ∈ ⟦ ((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n
                ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ) ⟧_{config}⟩
      then have ⟨∃Γ_k Ψ_k Φ_k k. (
          (((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n
          ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ)) ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)
) ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩
      using h2 ImpliesNot.prems by simp
      from this obtain Γ_k Ψ_k Φ_k k **where**
        fp:⟨(((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ))
          ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
      and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_{config}⟩ **by blast**
      have ⟨(Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ)
        ↪ (((K₁ ⇑ n) # (K₂ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K₁ implies not K₂) # Φ))⟩
        by (simp add: elims_part implies_not_e2)
      hence ⟨(Γ, n ⊢ ((K₁ implies not K₂) # Ψ) ▷ Φ)
        ↪^{Suc k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
        using fp relpowp_Suc_I2 by auto
      with rc show ?thesis by blast
    qed

    ultimately show ?case using ImpliesNot.prems(2) **by blast**
next
 case (TimeDelayedBy K_1 $\delta\tau$ K_2 K_3)
  have branches:
   ⟨⟦ Γ, n ⊢ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Ψ) ▷ Φ ⟧$_{config}$
    = ⟦ ((K_1 ¬⇑ n) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$
    ∪ ⟦ ((K_1 ⇑ n) # (K_2 @ n ⊕ $\delta\tau$ ⇒ K_3) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$⟩
   using HeronConf_interp_stepwise_timedelayed_cases **by simp**
  moreover have br1:
   ⟨ϱ ∈ ⟦ ((K_1 ¬⇑ n) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$
   ⟹ ∃Γ_k Ψ_k Φ_k k.
    ((Γ, n ⊢ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Ψ) ▷ Φ)
      ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
    ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
  proof -
   assume h1: ⟨ϱ ∈ ⟦ ((K_1 ¬⇑ n) # Γ), n
       ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$⟩
   then have ⟨∃Γ_k Ψ_k Φ_k k.
    ((((K_1 ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ))
      ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
    ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
   using h1 TimeDelayedBy.prems **by simp**
   from this obtain Γ_k Ψ_k Φ_k k
    where fp:⟨((((K_1 ¬⇑ n) # Γ), n
       ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ))
      ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
    and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by blast**
   have ⟨(Γ, n ⊢ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Ψ) ▷ Φ)
    ↪ ((((K_1 ¬⇑ n) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ))⟩
    by (simp add: elims_part timedelayed_e1)
   hence ⟨(Γ, n ⊢ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Ψ) ▷ Φ)
    ↪$^{Suc\ k}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
    using fp relpowp_Suc_I2 **by auto**
   with rc **show ?thesis by blast**
  qed
  moreover have br2:
   ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 @ n ⊕ $\delta\tau$ ⇒ K_3) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$
   ⟹ ∃Γ_k Ψ_k Φ_k k.
    ((Γ, n ⊢ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Ψ) ▷ Φ)
      ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
    ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
  proof -
   assume h2: ⟨ϱ ∈ ⟦ ((K_1 ⇑ n) # (K_2 @ n ⊕ $\delta\tau$ ⇒ K_3) # Γ), n
      ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ) ⟧$_{config}$⟩
   then have ⟨∃Γ_k Ψ_k Φ_k k. ((((K_1 ⇑ n) # (K_2 @ n ⊕ $\delta\tau$ ⇒ K_3) # Γ), n
       ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ))
       ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
       ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
   using h2 TimeDelayedBy.prems **by simp**
   from this obtain Γ_k Ψ_k Φ_k k
    where fp:⟨((((K_1 ⇑ n) # (K_2 @ n ⊕ $\delta\tau$ ⇒ K_3) # Γ), n
       ⊢ Ψ ▷ ((K_1 time-delayed by $\delta\tau$ on K_2 implies K_3) # Φ))
      ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
    and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by blast**

   have ⟨(Γ, n ⊢ ((K$_1$ time-delayed by $\delta\tau$ on K$_2$ implies K$_3$) # Ψ) ▷ Φ)
     ↪ (((K$_1$ ⇑ n) # (K$_2$ @ n ⊕ $\delta\tau$ ⇒ K$_3$) # Γ), n
       ⊢ Ψ ▷ ((K$_1$ time-delayed by $\delta\tau$ on K$_2$ implies K$_3$) # Φ))⟩
    by (simp add: elims_part timedelayed_e2)
   with fp relpowp_Suc_I2 **have**
    ⟨(Γ, n ⊢ ((K$_1$ time-delayed by $\delta\tau$ on K$_2$ implies K$_3$) # Ψ) ▷ Φ)
     ↪$^{\text{Suc k}}$ (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$)⟩
    by auto
   with rc **show** ?thesis **by** blast
  qed
  ultimately show ?case **using** TimeDelayedBy.prems(2) **by** blast
next
 case (WeaklyPrecedes K$_1$ K$_2$)
  have ⟨⟦ Γ, n ⊢ ((K$_1$ weakly precedes K$_2$) # Ψ) ▷ Φ ⟧$_{config}$ =
  ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
   ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ) ⟧$_{config}$⟩
   using HeronConf_interp_stepwise_weakly_precedes_cases **by** simp
  moreover have ⟨ϱ ∈ ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
      ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ) ⟧$_{config}$
   ⟹ (∃Γ$_k$ Ψ$_k$ Φ$_k$ k. ((Γ, n ⊢ ((K$_1$ weakly precedes K$_2$) # Ψ) ▷ Φ)
        ↪^{k} (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$))
     ∧ (ϱ ∈ ⟦ Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$ ⟧$_{config}$))⟩
  proof -
   assume ⟨ϱ ∈ ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
      ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ) ⟧$_{config}$⟩
   hence ⟨∃Γ$_k$ Ψ$_k$ Φ$_k$ k. ((((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
       ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ))
     ↪^{k} (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$))
      ∧ (ϱ ∈ ⟦ Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$ ⟧$_{config}$)⟩
   using WeaklyPrecedes.prems **by** simp
   from this obtain Γ$_k$ Ψ$_k$ Φ$_k$ k
    where fp:⟨((((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
       ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ))
     ↪^{k} (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$)⟩
    and rc:⟨ϱ ∈ ⟦ Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$ ⟧$_{config}$⟩ **by** blast
   have ⟨(Γ, n ⊢ ((K$_1$ weakly precedes K$_2$) # Ψ) ▷ Φ)
     ↪ (((⌈#$^{\le}$ K$_2$ n, #$^{\le}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
    ⊢ Ψ ▷ ((K$_1$ weakly precedes K$_2$) # Φ))⟩
    by (simp add: elims_part weakly_precedes_e)
   with fp relpowp_Suc_I2 **have** ⟨(Γ, n ⊢ ((K$_1$ weakly precedes K$_2$) # Ψ) ▷ Φ)
        ↪$^{\text{Suc k}}$ (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$)⟩
    by auto
   with rc **show** ?thesis **by** blast
  qed
  ultimately show ?case **using** WeaklyPrecedes.prems(2) **by** blast
next
 case (StrictlyPrecedes K$_1$ K$_2$)
  have ⟨⟦ Γ, n ⊢ ((K$_1$ strictly precedes K$_2$) # Ψ) ▷ Φ ⟧$_{config}$ =
  ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
   ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ) ⟧$_{config}$⟩
   using HeronConf_interp_stepwise_strictly_precedes_cases **by** simp
  moreover have ⟨ϱ ∈ ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
      ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ) ⟧$_{config}$
   ⟹ (∃Γ$_k$ Ψ$_k$ Φ$_k$ k. ((Γ, n ⊢ ((K$_1$ strictly precedes K$_2$) # Ψ) ▷ Φ)
        ↪^{k} (Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$))
    ∧ (ϱ ∈ ⟦ Γ$_k$, Suc n ⊢ Ψ$_k$ ▷ Φ$_k$ ⟧$_{config}$))⟩
  proof -
   assume ⟨ϱ ∈ ⟦ ((⌈#$^{\le}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
      ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ) ⟧$_{config}$⟩

hence ⟨∃Γ_k Ψ_k Φ_k k. ((((⌈#$^{\leq}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
                            ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ))
                    ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
           ∧ (ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$)⟩
      using StrictlyPrecedes.prems **by** simp
    from this obtain Γ_k Ψ_k Φ_k k
      where fp:⟨((((⌈#$^{\leq}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
                            ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ))
                    ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
        and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
    have ⟨(Γ, n ⊢ ((K$_1$ strictly precedes K$_2$) # Ψ) ▷ Φ)
          ↪ ((((⌈#$^{\leq}$ K$_2$ n, #$^{<}$ K$_1$ n⌉ ∈ (λ(x, y). x ≤ y)) # Γ), n
        ⊢ Ψ ▷ ((K$_1$ strictly precedes K$_2$) # Φ))⟩
      by (simp add: elims_part strictly_precedes_e)
    with fp relpowp_Suc_I2 **have** ⟨(Γ, n ⊢ ((K$_1$ strictly precedes K$_2$) # Ψ) ▷ Φ)
                            ↪$^{Suc\ k}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
      by auto
    with rc **show** ?thesis **by** blast
  qed
  ultimately show ?case **using** StrictlyPrecedes.prems(2) **by** blast
next
  case (Kills K$_1$ K$_2$)
    have branches: ⟨⟦ Γ, n ⊢ ((K$_1$ kills K$_2$) # Ψ) ▷ Φ ⟧$_{config}$
      = ⟦ ((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ) ⟧$_{config}$
      ∪ ⟦ ((K$_1$ ⇑ n) # (K$_2$ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ) ⟧$_{config}$⟩
      using HeronConf_interp_stepwise_kills_cases **by** simp
    moreover have br1: ⟨ϱ ∈ ⟦ ((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ) ⟧$_{config}$
              ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K$_1$ kills K$_2$) # Ψ) ▷ Φ)
                            ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
                ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
    proof -
      assume h1: ⟨ϱ ∈ ⟦ ((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ) ⟧$_{config}$⟩
      then have ⟨∃Γ_k Ψ_k Φ_k k.
              ((((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ))
              ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
              ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
        using h1 Kills.prems **by** simp
      from this obtain Γ_k Ψ_k Φ_k k **where**
        fp:⟨((((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ))
            ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))⟩
          and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩ **by** blast
      have pc:⟨(Γ, n ⊢ (K$_1$ kills K$_2$) # Ψ ▷ Φ)
            ↪ (((K$_1$ ¬⇑ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ))⟩
        by (simp add: elims_part kills_e1)
      hence ⟨(Γ, n ⊢ (K$_1$ kills K$_2$) # Ψ ▷ Φ) ↪$^{Suc\ k}$ (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
        using fp relpowp_Suc_I2 **by** auto
      with rc **show** ?thesis **by** blast
    qed
    moreover have br2:
      ⟨ϱ ∈ ⟦ ((K$_1$ ⇑ n) # (K$_2$ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ) ⟧$_{config}$
        ⟹ ∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ ((K$_1$ kills K$_2$) # Ψ) ▷ Φ)
                            ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k))
                ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩
    proof -
      assume h2: ⟨ϱ ∈ ⟦((K$_1$ ⇑ n)#(K$_2$ ¬⇑ ≥ n)#Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$)#Φ)⟧$_{config}$⟩
      then have ⟨∃Γ_k Ψ_k Φ_k k. (
              (((K$_1$ ⇑ n) # (K$_2$ ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K$_1$ kills K$_2$) # Φ))
              ↪^{k} (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)
) ∧ ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧$_{config}$⟩

```
            using h2 Kills.prems by simp
          from this obtain Γ_k Ψ_k Φ_k k where
              fp:⟨(((K_1 ⇑ n) # (K_2 ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K_1 kills K_2) # Φ))
                      ↪^k (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
          and rc:⟨ϱ ∈ ⟦ Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k ⟧_config⟩ by blast
          have ⟨(Γ, n ⊢ ((K_1 kills K_2) # Ψ) ▷ Φ)
                  ↪ (((K_1 ⇑ n) # (K_2 ¬⇑ ≥ n) # Γ), n ⊢ Ψ ▷ ((K_1 kills K_2) # Φ))⟩
            by (simp add: elims_part kills_e2)
          hence ⟨(Γ, n ⊢ ((K_1 kills K_2) # Ψ) ▷ Φ) ↪^(Suc k) (Γ_k, Suc n ⊢ Ψ_k ▷ Φ_k)⟩
            using fp relpowp_Suc_I2 by auto
          with rc show ?thesis by blast
        qed
        ultimately show ?case using Kills.prems(2) by blast
    qed
qed


lemma instant_index_increase_generalized:
  assumes ⟨n < n_k⟩
  assumes ⟨ϱ ∈ ⟦ Γ, n ⊢ Ψ ▷ Φ ⟧_config⟩
  shows    ⟨∃Γ_k Ψ_k Φ_k k. ((Γ, n ⊢ Ψ ▷ Φ) ↪^k (Γ_k, n_k ⊢ Ψ_k ▷ Φ_k))
                      ∧ ϱ ∈ ⟦ Γ_k, n_k ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
proof -
  obtain δk where diff: ⟨n_k = δk + Suc n⟩
    using add.commute assms(1) less_iff_Suc_add by auto
  show ?thesis
    proof (subst diff, subst diff, insert assms(2), induct δk)
      case 0  thus ?case
        using instant_index_increase assms(2) by simp
    next
      case (Suc δk)
        have f0: ⟨ϱ ∈ ⟦ Γ, n ⊢ Ψ ▷ Φ ⟧_config ⟹ ∃Γ_k Ψ_k Φ_k k.
                    ((Γ, n ⊢ Ψ ▷ Φ) ↪^k (Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k))
                  ∧ ϱ ∈ ⟦ Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
          using Suc.hyps by blast
        obtain Γ_k Ψ_k Φ_k k
          where cont: ⟨((Γ, n ⊢ Ψ ▷ Φ) ↪^k (Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k))
                      ∧ ϱ ∈ ⟦ Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
          using f0 assms(1) Suc.prems by blast
        then have fcontinue: ⟨∃Γ_k' Ψ_k' Φ_k' k'. ((Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k)
                              ↪^k' (Γ_k', Suc (δk + Suc n) ⊢ Ψ_k' ▷ Φ_k'))
                            ∧ ϱ ∈ ⟦ Γ_k', Suc (δk + Suc n) ⊢ Ψ_k' ▷ Φ_k' ⟧_config⟩
          using f0 cont instant_index_increase by blast
        obtain Γ_k' Ψ_k' Φ_k' k'
          where cont2: ⟨((Γ_k, δk + Suc n ⊢ Ψ_k ▷ Φ_k)
                        ↪^k' (Γ_k', Suc (δk + Suc n) ⊢ Ψ_k' ▷ Φ_k'))
                      ∧ ϱ ∈ ⟦ Γ_k', Suc (δk + Suc n) ⊢ Ψ_k' ▷ Φ_k' ⟧_config⟩
          using Suc.prems using fcontinue cont by blast
        have trans: ⟨(Γ, n ⊢ Ψ ▷ Φ) ↪^(k + k') (Γ_k', Suc (δk + Suc n) ⊢ Ψ_k' ▷ Φ_k')⟩
          using operational_semantics_trans_generalized cont cont2 by blast
        moreover have suc_assoc: ⟨Suc δk + Suc n = Suc (δk + Suc n)⟩ by arith
        ultimately show ?case
          proof (subst suc_assoc)
            show ⟨∃Γ_k Ψ_k Φ_k k.
                    ((Γ, n ⊢ Ψ ▷ Φ) ↪^k (Γ_k, Suc (δk + Suc n) ⊢ Ψ_k ▷ Φ_k))
                  ∧ ϱ ∈ ⟦ Γ_k, Suc δk + Suc n ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
            using cont2 local.trans by auto
          qed
    qed
qed
```

Any run that belongs to a specification Ψ has a corresponding configuration that develops it up to the nth instant.

```
theorem progress:
  assumes ⟨ϱ ∈ ⟦⟦ Ψ ⟧⟧_TESL⟩
    shows ⟨∃k Γ_k Ψ_k Φ_k. (([], 0 ⊢ Ψ ▷ []) ↪^k (Γ_k, n ⊢ Ψ_k ▷ Φ_k))
                          ∧ ϱ ∈ ⟦ Γ_k, n ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
proof -
  have 1:⟨∃Γ_k Ψ_k Φ_k k. (([], 0 ⊢ Ψ ▷ []) ↪^k (Γ_k, 0 ⊢ Ψ_k ▷ Φ_k))
                         ∧ ϱ ∈ ⟦ Γ_k, 0 ⊢ Ψ_k ▷ Φ_k ⟧_config⟩
    using assms relpowp_0_I solve_start by fastforce
  show ?thesis
  proof (cases ⟨n = 0⟩)
    case True
      thus ?thesis using assms relpowp_0_I solve_start by fastforce
  next
    case False hence pos:⟨n > 0⟩ by simp
      from assms solve_start have ⟨ϱ ∈ ⟦ [], 0 ⊢ Ψ ▷ [] ⟧_config ⟩ by blast
      from instant_index_increase_generalized[OF pos this] show ?thesis by blast
  qed
qed
```

7.5   Local termination

Here, we prove that the computation of an instant in a run always terminates. Since this computation terminates when the list of constraints for the present instant becomes empty, we introduce a measure for this formula.

```
primrec measure_interpretation :: ⟨'τ::linordered_field TESL_formula ⇒ nat⟩ ("μ")
where
  ⟨μ [] = (0::nat)⟩
| ⟨μ (φ # Φ) = (case φ of
                  _ sporadic _ on _ ⇒ 1 + μ Φ
                | _                 ⇒ 2 + μ Φ)⟩

fun measure_interpretation_config :: ⟨'τ::linordered_field config ⇒ nat⟩ ("μ_config")
where
  ⟨μ_config (Γ, n ⊢ Ψ ▷ Φ) = μ Ψ⟩
```

We then show that the elimination rules make this measure decrease.

```
lemma elimation_rules_strictly_decreasing:
  assumes ⟨(Γ_1, n_1 ⊢ Ψ_1 ▷ Φ_1) ↪_e (Γ_2, n_2 ⊢ Ψ_2 ▷ Φ_2)⟩
    shows ⟨μ Ψ_1 > μ Ψ_2⟩
using assms by (auto elim: operational_semantics_elim.cases)


lemma elimation_rules_strictly_decreasing_meas:
  assumes ⟨(Γ_1, n_1 ⊢ Ψ_1 ▷ Φ_1) ↪_e (Γ_2, n_2 ⊢ Ψ_2 ▷ Φ_2)⟩
    shows ⟨(Ψ_2, Ψ_1) ∈ measure μ⟩
using assms by (auto elim: operational_semantics_elim.cases)


lemma elimation_rules_strictly_decreasing_meas':
  assumes ⟨S_1 ↪_e S_2⟩
  shows ⟨(S_2, S_1) ∈ measure μ_config⟩
proof -
  from assms obtain Γ_1 n_1 Ψ_1 Φ_1 where p1:⟨S_1 = (Γ_1, n_1 ⊢ Ψ_1 ▷ Φ_1)⟩
    using measure_interpretation_config.cases by blast
  from assms obtain Γ_2 n_2 Ψ_2 Φ_2 where p2:⟨S_2 = (Γ_2, n_2 ⊢ Ψ_2 ▷ Φ_2)⟩
```

```
      using measure_interpretation_config.cases by blast
    from elimation_rules_strictly_decreasing_meas assms p1 p2
      have ⟨(Ψ₂, Ψ₁) ∈ measure μ⟩ by blast
    hence ⟨μ Ψ₂ < μ Ψ₁⟩ by simp
    hence ⟨μ_config (Γ₂, n₂ ⊢ Ψ₂ ▷ Φ₂) < μ_config (Γ₁, n₁ ⊢ Ψ₁ ▷ Φ₁)⟩ by simp
    with p1 p2 show ?thesis by simp
qed
```

Therefore, the relation made up of elimination rules is well-founded and the computation of an instant terminates.

```
theorem instant_computation_termination:
  ⟨wfP (λ(S₁::'a::linordered_field config) S₂. (S₁ ↪ₑ⁺ S₂))⟩
proof (simp add: wfP_def)
  show ⟨wf {((S₁::'a::linordered_field config), S₂). S₁ ↪ₑ⁺ S₂}⟩
  proof (rule wf_subset)
    have ⟨measure μ_config = {(S₂, (S₁::'a::linordered_field config)).
                              μ_config S₂ < μ_config S₁}⟩
      by (simp add: inv_image_def less_eq measure_def)
    thus ⟨{((S₁::'a::linordered_field config), S₂). S₁ ↪ₑ⁺ S₂} ⊆ (measure μ_config)⟩
      using elimation_rules_strictly_decreasing_meas'
            operational_semantics_elim_inv_def by blast
  next
    show ⟨wf (measure measure_interpretation_config)⟩ by simp
  qed
qed


end
```

Chapter 8

Properties of TESL

8.1 Stuttering Invariance

theory `StutteringDefs`

imports `Denotational`

begin

When composing systems into more complex systems, it may happen that one system has to perform some action while the rest of the complex system does nothing. In order to support the composition of TESL specifications, we want to be able to insert stuttering instants in a run without breaking the conformance of a run to its specification. This is what we call the *stuttering invariance* of TESL.

8.1.1 Definition of stuttering

We consider stuttering as the insertion of empty instants (instants at which no clock ticks) in a run. We caracterize this insertion with a dilating function, which maps the instant indices of the original run to the corresponding instant indices of the dilated run. The properties of a dilating function are:

- it is strictly increasing because instants are inserted into the run,

- the image of an instant index is greater than it because stuttering instants can only delay the original instants of the run,

- no instant is inserted before the first one in order to have a well defined initial date on each clock,

- if n is not in the image of the function, no clock ticks at instant n and the date on the clocks do not change.

definition `dilating_fun`
where
  ⟨`dilating_fun (f::nat ⇒ nat) (r::'a::linordered_field run)`
    `≡ strict_mono f ∧ (f 0 = 0) ∧ (∀n. f n ≥ n`
    `∧ ((∄`n_0`. f `n_0` = n) ⟶ (∀c. ¬(hamlet ((Rep_run r) n c))))`⟩

Figure 8.1: Dilating and contracting functions

```
∧ ((∄n₀. f n₀ = (Suc n))  ⟶  (∀c. time ((Rep_run r) (Suc n) c)
                                       = time ((Rep_run r) n c)))
)⟩
```

A run `r` is a dilation of a run `sub` by function `f` if:

- `f` is a dilating function for `r`

- the time in `r` is the time in `sub` dilated by `f`

- the hamlet in `r` is the hamlet in sub dilated by `f`

definition `dilating`
where
  ⟨`dilating f sub r ≡ dilating_fun f r`
                     ∧ (∀n c. `time ((Rep_run sub) n c) = time ((Rep_run r) (f n) c)`)
                     ∧ (∀n c. `hamlet ((Rep_run sub) n c) = hamlet ((Rep_run r) (f n) c)`)⟩

A *run* is a *subrun* of another run if there exists a dilation between them.

definition `is_subrun ::⟨'a::linordered_field run ⇒ 'a run ⇒ bool⟩` (**infixl** "≪" 60)
where
  ⟨`sub ≪ r ≡ (∃f. dilating f sub r)`⟩

A contracting function is the reverse of a dilating fun, it maps an instant index of a dilated run to the index of the last instant of a non stuttering run that precedes it. Since several successive stuttering instants are mapped to the same instant of the non stuttering run, such a function is monotonous, but not strictly. The image of the first instant of the dilated run is necessarily the first instant of the non stuttering run, and the image of an instant index is less that this index because we remove stuttering instants.

definition `contracting_fun`
  where ⟨`contracting_fun g ≡ mono g ∧ g 0 = 0 ∧ (∀n. g n ≤ n)`⟩

Figure 8.1 illustrates the relations between the instants of a run and the instants of a dilated run, with the mappings by the dilating function `f` and the contracting function `g`:

A function `g` is contracting with respect to the dilation of run `sub` into run `r` by the dilating function `f` if:

- it is a contracting function ;

- (f ∘ g) n is the index of the last original instant before instant n in run r, therefore:

    - (f ∘ g) n ≤ n
    - the time does not change on any clock between instants (f ∘ g) n and n of run r;
    - no clock ticks before n strictly after (f ∘ g) n in run r. See Figure 8.1 for a better understanding. Notice that in this example, 2 is equal to (f ∘ g) 2, (f ∘ g) 3, and (f ∘ g) 4.

definition contracting
where
⟨contracting g r sub f ≡ contracting_fun g
                        ∧ (∀n. f (g n) ≤ n)
                        ∧ (∀n c k. f (g n) ≤ k ∧ k ≤ n
                            ⟶ time ((Rep_run r) k c) = time ((Rep_run sub) (g n) c))
                        ∧ (∀n c k. f (g n) < k ∧ k ≤ n
                            ⟶ ¬ hamlet ((Rep_run r) k c))⟩

For any dilating function, we can build its *inverse*, as illustrated on Figure 8.1, which is a contracting function:

definition ⟨dil_inverse f::(nat ⇒ nat) ≡ (λn. Max {i. f i ≤ n})⟩

8.1.2 Alternate definitions for counting ticks.

For proving the stuttering invariance of TESL specifications, we will need these alternate definitions for counting ticks, which are based on sets.

tick_count r c n is the number of ticks of clock c in run r upto instant n.

definition tick_count :: ⟨'a::linordered_field run ⇒ clock ⇒ nat ⇒ nat⟩
where
  ⟨tick_count r c n = card {i. i ≤ n ∧ hamlet ((Rep_run r) i c)}⟩

tick_count_strict r c n is the number of ticks of clock c in run r upto but excluding instant n.

definition tick_count_strict :: ⟨'a::linordered_field run ⇒ clock ⇒ nat ⇒ nat⟩
where
  ⟨tick_count_strict r c n = card {i. i < n ∧ hamlet ((Rep_run r) i c)}⟩

end

8.1.3 Stuttering Lemmas

theory StutteringLemmas

imports StutteringDefs

begin

In this section, we prove several lemmas that will be used to show that TESL specifications are invariant by stuttering.

The following one will be useful in proving properties over a sequence of stuttering instants.

lemma `bounded_suc_ind`:
  assumes ⟨⋀k. k < m ⟹ P (Suc (z + k)) = P (z + k)⟩
    shows ⟨k < m ⟹ P (Suc (z + k)) = P z⟩
proof (induction k)
  case 0
    with `assms(1)[of 0]` **show** `?case` **by** simp
next
  case (Suc k')
    with `assms[of ⟨Suc k'⟩]` **show** `?case` **by** force
qed

8.1.4   Lemmas used to prove the invariance by stuttering

Since a dilating function is strictly monotonous, it is injective.

lemma `dilating_fun_injects`:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨inj_on f A⟩
using assms dilating_fun_def strict_mono_imp_inj_on **by** blast

lemma `dilating_injects`:
  assumes ⟨dilating f sub r⟩
  shows   ⟨inj_on f A⟩
using assms dilating_def dilating_fun_injects **by** blast

If a clock ticks at an instant in a dilated run, that instant is the image by the dilating function of an instant of the original run.

lemma `ticks_image`:
  assumes ⟨dilating_fun f r⟩
  and   ⟨hamlet ((Rep_run r) n c)⟩
  shows   ⟨∃n_0. f n_0 = n⟩
using dilating_fun_def assms **by** blast

lemma `ticks_image_sub`:
  assumes ⟨dilating f sub r⟩
  and   ⟨hamlet ((Rep_run r) n c)⟩
  shows   ⟨∃n_0. f n_0 = n⟩
using assms dilating_def ticks_image **by** blast

lemma `ticks_image_sub'`:
  assumes ⟨dilating f sub r⟩
  and   ⟨∃c. hamlet ((Rep_run r) n c)⟩
  shows   ⟨∃n_0. f n_0 = n⟩
using ticks_image_sub[OF assms(1)] assms(2) **by** blast

The image of the ticks in an interval by a dilating function is the interval bounded by the image of the bounds of the original interval. This is proven for all 4 kinds of intervals: `]m, n[`, `[m, n[`, `]m, n]` and `[m, n]`.

lemma `dilating_fun_image_strict`:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨{k. f m < k ∧ k < f n ∧ hamlet ((Rep_run r) k c)}
         = image f {k. m < k ∧ k < n ∧ hamlet ((Rep_run r) (f k) c)}⟩
  (**is** ⟨?IMG = image f ?SET⟩)
proof
  { **fix** k **assume** h:⟨k ∈ ?IMG⟩
    from h **obtain** k_0 **where** k0prop:⟨f k_0 = k ∧ hamlet ((Rep_run r) (f k_0) c)⟩

```
        using ticks_image[OF assms] by blast
      with h have ⟨k ∈ image f ?SET⟩
        using assms dilating_fun_def strict_mono_less by blast
    } thus ⟨?IMG ⊆ image f ?SET⟩ ..
next
    { fix k assume h:⟨k ∈ image f ?SET⟩
      from h obtain k₀ where k0prop:⟨k = f k₀ ∧ k₀ ∈ ?SET⟩ by blast
      hence ⟨k ∈ ?IMG⟩ using assms by (simp add: dilating_fun_def strict_mono_less)
    } thus ⟨image f ?SET ⊆ ?IMG⟩ ..
qed
```

lemma dilating_fun_image_left:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨{k. f m ≤ k ∧ k < f n ∧ hamlet ((Rep_run r) k c)}
             = image f {k. m ≤ k ∧ k < n ∧ hamlet ((Rep_run r) (f k) c)}⟩
  (**is** ⟨?IMG = image f ?SET⟩)
proof

```
    { fix k assume h:⟨k ∈ ?IMG⟩
      from h obtain k₀ where k0prop:⟨f k₀ = k ∧ hamlet ((Rep_run r) (f k₀) c)⟩
        using ticks_image[OF assms] by blast
      with h have ⟨k ∈ image f ?SET⟩
        using assms dilating_fun_def strict_mono_less strict_mono_less_eq by fastforce
    } thus ⟨?IMG ⊆ image f ?SET⟩ ..
next
    { fix k assume h:⟨k ∈ image f ?SET⟩
      from h obtain k₀ where k0prop:⟨k = f k₀ ∧ k₀ ∈ ?SET⟩ by blast
      hence ⟨k ∈ ?IMG⟩
        using assms dilating_fun_def strict_mono_less strict_mono_less_eq by fastforce
    } thus ⟨image f ?SET ⊆ ?IMG⟩ ..
qed
```

lemma dilating_fun_image_right:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨{k. f m < k ∧ k ≤ f n ∧ hamlet ((Rep_run r) k c)}
             = image f {k. m < k ∧ k ≤ n ∧ hamlet ((Rep_run r) (f k) c)}⟩
  (**is** ⟨?IMG = image f ?SET⟩)
proof

```
    { fix k assume h:⟨k ∈ ?IMG⟩
      from h obtain k₀ where k0prop:⟨f k₀ = k ∧ hamlet ((Rep_run r) (f k₀) c)⟩
        using ticks_image[OF assms] by blast
      with h have ⟨k ∈ image f ?SET⟩
        using assms dilating_fun_def strict_mono_less strict_mono_less_eq by fastforce
    } thus ⟨?IMG ⊆ image f ?SET⟩ ..
next
    { fix k assume h:⟨k ∈ image f ?SET⟩
      from h obtain k₀ where k0prop:⟨k = f k₀ ∧ k₀ ∈ ?SET⟩ by blast
      hence ⟨k ∈ ?IMG⟩
        using assms dilating_fun_def strict_mono_less strict_mono_less_eq by fastforce
    } thus ⟨image f ?SET ⊆ ?IMG⟩ ..
qed
```

lemma dilating_fun_image:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨{k. f m ≤ k ∧ k ≤ f n ∧ hamlet ((Rep_run r) k c)}
             = image f {k. m ≤ k ∧ k ≤ n ∧ hamlet ((Rep_run r) (f k) c)}⟩
  (**is** ⟨?IMG = image f ?SET⟩)
proof

```
    { fix k assume h:⟨k ∈ ?IMG⟩
      from h obtain k₀ where k0prop:⟨f k₀ = k ∧ hamlet ((Rep_run r) (f k₀) c)⟩
```

```
        using ticks_image[OF assms] by blast
      with h have ⟨k ∈ image f ?SET⟩
        using assms dilating_fun_def strict_mono_less_eq by blast
    } thus ⟨?IMG ⊆ image f ?SET⟩ ..
next
  { fix k assume h:⟨k ∈ image f ?SET⟩
    from h obtain k₀ where k0prop:⟨k = f k₀ ∧ k₀ ∈ ?SET⟩ by blast
    hence ⟨k ∈ ?IMG⟩ using assms by (simp add: dilating_fun_def strict_mono_less_eq)
  } thus ⟨image f ?SET ⊆ ?IMG⟩ ..
qed
```

On any clock, the number of ticks in an interval is preserved by a dilating function.

```
lemma ticks_as_often_strict:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨card {p. n < p ∧ p < m ∧ hamlet ((Rep_run r) (f p) c)}
          = card {p. f n < p ∧ p < f m ∧ hamlet ((Rep_run r) p c)}⟩
    (is ⟨card ?SET = card ?IMG⟩)
proof -
  from dilating_fun_injects[OF assms] have ⟨inj_on f ?SET⟩ .
  moreover have ⟨finite ?SET⟩ by simp
  from inj_on_iff_eq_card[OF this] calculation
    have ⟨card (image f ?SET) = card ?SET⟩ by blast
  moreover from dilating_fun_image_strict[OF assms] have ⟨?IMG = image f ?SET⟩ .
  ultimately show ?thesis by auto
qed
```

```
lemma ticks_as_often_left:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨card {p. n ≤ p ∧ p < m ∧ hamlet ((Rep_run r) (f p) c)}
          = card {p. f n ≤ p ∧ p < f m ∧ hamlet ((Rep_run r) p c)}⟩
    (is ⟨card ?SET = card ?IMG⟩)
proof -
  from dilating_fun_injects[OF assms] have ⟨inj_on f ?SET⟩ .
  moreover have ⟨finite ?SET⟩ by simp
  from inj_on_iff_eq_card[OF this] calculation
    have ⟨card (image f ?SET) = card ?SET⟩ by blast
  moreover from dilating_fun_image_left[OF assms] have ⟨?IMG = image f ?SET⟩ .
  ultimately show ?thesis by auto
qed
```

```
lemma ticks_as_often_right:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨card {p. n < p ∧ p ≤ m ∧ hamlet ((Rep_run r) (f p) c)}
          = card {p. f n < p ∧ p ≤ f m ∧ hamlet ((Rep_run r) p c)}⟩
    (is ⟨card ?SET = card ?IMG⟩)
proof -
  from dilating_fun_injects[OF assms] have ⟨inj_on f ?SET⟩ .
  moreover have ⟨finite ?SET⟩ by simp
  from inj_on_iff_eq_card[OF this] calculation
    have ⟨card (image f ?SET) = card ?SET⟩ by blast
  moreover from dilating_fun_image_right[OF assms] have ⟨?IMG = image f ?SET⟩ .
  ultimately show ?thesis by auto
qed
```

```
lemma ticks_as_often:
  assumes ⟨dilating_fun f r⟩
  shows   ⟨card {p. n ≤ p ∧ p ≤ m ∧ hamlet ((Rep_run r) (f p) c)}
          = card {p. f n ≤ p ∧ p ≤ f m ∧ hamlet ((Rep_run r) p c)}⟩
```

```
      (is ⟨card ?SET = card ?IMG⟩)
proof -
  from dilating_fun_injects[OF assms] have ⟨inj_on f ?SET⟩ .
  moreover have ⟨finite ?SET⟩ by simp
  from inj_on_iff_eq_card[OF this] calculation
    have ⟨card (image f ?SET) = card ?SET⟩ by blast
  moreover from dilating_fun_image[OF assms] have ⟨?IMG = image f ?SET⟩ .
  ultimately show ?thesis by auto
qed
```

The date of an event is preserved by dilation.

```
lemma ticks_tag_image:
  assumes ⟨dilating f sub r⟩
  and     ⟨∃c. hamlet ((Rep_run r) k c)⟩
  and     ⟨time ((Rep_run r) k c) = τ⟩
  shows   ⟨∃k₀. f k₀ = k ∧ time ((Rep_run sub) k₀ c) = τ⟩
proof -
  from ticks_image_sub'[OF assms(1,2)] have ⟨∃k₀. f k₀ = k⟩ .
  from this obtain k₀ where ⟨f k₀ = k⟩ by blast
  moreover with assms(1,3) have ⟨time ((Rep_run sub) k₀ c) = τ⟩
    by (simp add: dilating_def)
  ultimately show ?thesis by blast
qed
```

TESL operators are invariant by dilation.

```
lemma ticks_sub:
  assumes ⟨dilating f sub r⟩
  shows   ⟨hamlet ((Rep_run sub) n a) = hamlet ((Rep_run r) (f n) a)⟩
using assms by (simp add: dilating_def)

lemma no_tick_sub:
  assumes ⟨dilating f sub r⟩
  shows   ⟨(∄n₀. f n₀ = n) ⟶ ¬hamlet ((Rep_run r) n a)⟩
using assms dilating_def dilating_fun_def by blast
```

Lifting a total function to a partial function on an option domain.

```
definition opt_lift::⟨('a ⇒ 'a) ⇒ ('a option ⇒ 'a option)⟩
where
  ⟨opt_lift f ≡ λx. case x of None ⇒ None | Some y ⇒ Some (f y)⟩
```

The set of instants when a clock ticks in a dilated run is the image by the dilation function of the set of instants when it ticks in the subrun.

```
lemma tick_set_sub:
  assumes ⟨dilating f sub r⟩
  shows   ⟨{k. hamlet ((Rep_run r) k c)} = image f {k. hamlet ((Rep_run sub) k c)}⟩
    (is ⟨?R = image f ?S⟩)
proof
  { fix k assume h:⟨k ∈ ?R⟩
    with no_tick_sub[OF assms] have ⟨∃k₀. f k₀ = k⟩ by blast
    from this obtain k₀ where k0prop:⟨f k₀ = k⟩ by blast
    with ticks_sub[OF assms] h have ⟨hamlet ((Rep_run sub) k₀ c)⟩ by blast
    with k0prop have ⟨k ∈ image f ?S⟩ by blast
  }
  thus ⟨?R ⊆ image f ?S⟩ by blast
next
  { fix k assume h:⟨k ∈ image f ?S⟩
    from this obtain k₀ where ⟨f k₀ = k ∧ hamlet ((Rep_run sub) k₀ c)⟩ by blast
```

```
      with assms have ⟨k ∈ ?R⟩ using ticks_sub by blast
  }
  thus ⟨image f ?S ⊆ ?R⟩ by blast
qed
```

Strictly monotonous functions preserve the least element.

```
lemma Least_strict_mono:
  assumes ⟨strict_mono f⟩
  and      ⟨∃x ∈ S. ∀y ∈ S. x ≤ y⟩
  shows    ⟨(LEAST y. y ∈ f ' S) = f (LEAST x. x ∈ S)⟩
using Least_mono[OF strict_mono_mono, OF assms] .
```

A non empty set of `nats` has a least element.

```
lemma Least_nat_ex:
  ⟨(n::nat) ∈ S ⟹ ∃x ∈ S. (∀y ∈ S. x ≤ y)⟩
by (induction n rule: nat_less_induct, insert not_le_imp_less, blast)
```

The first instant when a clock ticks in a dilated run is the image by the dilation function of the first instant when it ticks in the subrun.

```
lemma Least_sub:
  assumes ⟨dilating f sub r⟩
  and      ⟨∃k::nat. hamlet ((Rep_run sub) k c)⟩
  shows    ⟨(LEAST k. k ∈ {t. hamlet ((Rep_run r) t c)})
              = f (LEAST k. k ∈ {t. hamlet ((Rep_run sub) t c)})⟩
          (is ⟨(LEAST k. k ∈ ?R) = f (LEAST k. k ∈ ?S)⟩)
proof -
  from assms(2) have ⟨∃x. x ∈ ?S⟩ by simp
  hence least:⟨∃x ∈ ?S. ∀y ∈ ?S. x ≤ y⟩
    using Least_nat_ex ..
  from assms(1) have ⟨strict_mono f⟩ by (simp add: dilating_def dilating_fun_def)
  from Least_strict_mono[OF this least] have
    ⟨(LEAST y. y ∈ f ' ?S)  = f (LEAST x. x ∈ ?S)⟩ .
  with tick_set_sub[OF assms(1), of ⟨c⟩] show ?thesis by auto
qed
```

If a clock ticks in a run, it ticks in the subrun.

```
lemma ticks_imp_ticks_sub:
  assumes ⟨dilating f sub r⟩
  and      ⟨∃k. hamlet ((Rep_run r) k c)⟩
  shows    ⟨∃k₀. hamlet ((Rep_run sub) k₀ c)⟩
proof -
  from assms(2) obtain k where ⟨hamlet ((Rep_run r) k c)⟩ by blast
  with ticks_image_sub[OF assms(1)] ticks_sub[OF assms(1)] show ?thesis by blast
qed
```

Stronger version: it ticks in the subrun and we know when.

```
lemma ticks_imp_ticks_subk:
  assumes ⟨dilating f sub r⟩
  and      ⟨hamlet ((Rep_run r) k c)⟩
  shows    ⟨∃k₀. f k₀ = k ∧ hamlet ((Rep_run sub) k₀ c)⟩
proof -
  from no_tick_sub[OF assms(1)] assms(2) have ⟨∃k₀. f k₀ = k⟩ by blast
  from this obtain k₀ where ⟨f k₀ = k⟩ by blast
  moreover with ticks_sub[OF assms(1)] assms(2)
    have ⟨hamlet ((Rep_run sub) k₀ c)⟩ by blast
  ultimately show ?thesis by blast
```

qed

A dilating function preserves the tick count on an interval for any clock.

lemma dilated_ticks_strict:
  assumes ⟨dilating f sub r⟩
  shows ⟨{i. f m < i ∧ i < f n ∧ hamlet ((Rep_run r) i c)}
       = image f {i. m < i ∧ i < n ∧ hamlet ((Rep_run sub) i c)}⟩
    (**is** ⟨?RUN = image f ?SUB⟩)
proof
  { **fix** i **assume** h:⟨i ∈ ?SUB⟩
    hence ⟨m < i ∧ i < n⟩ **by** simp
    hence ⟨f m < f i ∧ f i < (f n)⟩ **using** assms
      by (simp add: dilating_def dilating_fun_def strict_monoD strict_mono_less_eq)
    moreover from h **have** ⟨hamlet ((Rep_run sub) i c)⟩ **by** simp
    hence ⟨hamlet ((Rep_run r) (f i) c)⟩ **using** ticks_sub[OF assms] **by** blast
    ultimately have ⟨f i ∈ ?RUN⟩ **by** simp
  } **thus** ⟨image f ?SUB ⊆ ?RUN⟩ **by** blast
next
  { **fix** i **assume** h:⟨i ∈ ?RUN⟩
    hence ⟨hamlet ((Rep_run r) i c)⟩ **by** simp
    from ticks_imp_ticks_subk[OF assms this]
      obtain i_0 **where** i0prop:⟨f i_0 = i ∧ hamlet ((Rep_run sub) i_0 c)⟩ **by** blast
    with h **have** ⟨f m < f i_0 ∧ f i_0 < f n⟩ **by** simp
    moreover have ⟨strict_mono f⟩ **using** assms dilating_def dilating_fun_def **by** blast
    ultimately have ⟨m < i_0 ∧ i_0 < n⟩
      using strict_mono_less strict_mono_less_eq **by** blast
    with i0prop **have** ⟨∃i_0. f i_0 = i ∧ i_0 ∈ ?SUB⟩ **by** blast
  } **thus** ⟨?RUN ⊆ image f ?SUB⟩ **by** blast
qed

lemma dilated_ticks_left:
  assumes ⟨dilating f sub r⟩
  shows ⟨{i. f m ≤ i ∧ i < f n ∧ hamlet ((Rep_run r) i c)}
       = image f {i. m ≤ i ∧ i < n ∧ hamlet ((Rep_run sub) i c)}⟩
    (**is** ⟨?RUN = image f ?SUB⟩)
proof
  { **fix** i **assume** h:⟨i ∈ ?SUB⟩
    hence ⟨m ≤ i ∧ i < n⟩ **by** simp
    hence ⟨f m ≤ f i ∧ f i < (f n)⟩ **using** assms
      by (simp add: dilating_def dilating_fun_def strict_monoD strict_mono_less_eq)
    moreover from h **have** ⟨hamlet ((Rep_run sub) i c)⟩ **by** simp
    hence ⟨hamlet ((Rep_run r) (f i) c)⟩ **using** ticks_sub[OF assms] **by** blast
    ultimately have ⟨f i ∈ ?RUN⟩ **by** simp
  } **thus** ⟨image f ?SUB ⊆ ?RUN⟩ **by** blast
next
  { **fix** i **assume** h:⟨i ∈ ?RUN⟩
    hence ⟨hamlet ((Rep_run r) i c)⟩ **by** simp
    from ticks_imp_ticks_subk[OF assms this]
      obtain i_0 **where** i0prop:⟨f i_0 = i ∧ hamlet ((Rep_run sub) i_0 c)⟩ **by** blast
    with h **have** ⟨f m ≤ f i_0 ∧ f i_0 < f n⟩ **by** simp
    moreover have ⟨strict_mono f⟩ **using** assms dilating_def dilating_fun_def **by** blast
    ultimately have ⟨m ≤ i_0 ∧ i_0 < n⟩
      using strict_mono_less strict_mono_less_eq **by** blast
    with i0prop **have** ⟨∃i_0. f i_0 = i ∧ i_0 ∈ ?SUB⟩ **by** blast
  } **thus** ⟨?RUN ⊆ image f ?SUB⟩ **by** blast
qed

lemma dilated_ticks_right:

```
    assumes ⟨dilating f sub r⟩
    shows    ⟨{i. f m < i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}
              = image f {i. m < i ∧ i ≤ n ∧ hamlet ((Rep_run sub) i c)}⟩
      (is ⟨?RUN = image f ?SUB⟩)
proof
  { fix i   assume h:⟨i ∈ ?SUB⟩
    hence ⟨m < i ∧ i ≤ n⟩ by simp
    hence ⟨f m < f i ∧ f i ≤ (f n)⟩ using assms
      by (simp add: dilating_def dilating_fun_def strict_monoD strict_mono_less_eq)
    moreover from h have ⟨hamlet ((Rep_run sub) i c)⟩ by simp
    hence ⟨hamlet ((Rep_run r) (f i) c)⟩ using ticks_sub[OF assms] by blast
    ultimately have ⟨f i ∈ ?RUN⟩ by simp
  } thus ⟨image f ?SUB ⊆ ?RUN⟩ by blast
next
  { fix i assume h:⟨i ∈ ?RUN⟩
    hence ⟨hamlet ((Rep_run r) i c)⟩ by simp
    from ticks_imp_ticks_subk[OF assms this]
      obtain i₀ where i0prop:⟨f i₀ = i ∧ hamlet ((Rep_run sub) i₀ c)⟩ by blast
    with h have ⟨f m < f i₀ ∧ f i₀ ≤ f n⟩ by simp
    moreover have ⟨strict_mono f⟩ using assms dilating_def dilating_fun_def by blast
    ultimately have ⟨m < i₀ ∧ i₀ ≤ n⟩
      using strict_mono_less strict_mono_less_eq by blast
    with i0prop have ⟨∃ i₀. f i₀ = i ∧ i₀ ∈ ?SUB⟩ by blast
  } thus ⟨?RUN ⊆ image f ?SUB⟩ by blast
qed

lemma dilated_ticks:
  assumes ⟨dilating f sub r⟩
  shows    ⟨{i. f m ≤ i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}
          = image f {i. m ≤ i ∧ i ≤ n ∧ hamlet ((Rep_run sub) i c)}⟩
    (is ⟨?RUN = image f ?SUB⟩)
proof
  { fix i assume h:⟨i ∈ ?SUB⟩
    hence ⟨m ≤ i ∧ i ≤ n⟩ by simp
    hence ⟨f m ≤ f i ∧ f i ≤ (f n)⟩
      using assms by (simp add: dilating_def dilating_fun_def strict_mono_less_eq)
    moreover from h have ⟨hamlet ((Rep_run sub) i c)⟩ by simp
    hence ⟨hamlet ((Rep_run r) (f i) c)⟩ using ticks_sub[OF assms] by blast
    ultimately have ⟨f i ∈?RUN⟩ by simp
  } thus ⟨image f ?SUB ⊆ ?RUN⟩ by blast
next
  { fix i assume h:⟨i ∈ ?RUN⟩
    hence ⟨hamlet ((Rep_run r) i c)⟩ by simp
    from ticks_imp_ticks_subk[OF assms this]
      obtain i₀ where i0prop:⟨f i₀ = i ∧ hamlet ((Rep_run sub) i₀ c)⟩ by blast
    with h have ⟨f m ≤ f i₀ ∧ f i₀ ≤ f n⟩ by simp
    moreover have ⟨strict_mono f⟩ using assms dilating_def dilating_fun_def by blast
    ultimately have ⟨m ≤ i₀ ∧ i₀ ≤ n⟩ using strict_mono_less_eq by blast
    with i0prop have ⟨∃ i₀. f i₀ = i ∧ i₀ ∈ ?SUB⟩ by blast
  } thus ⟨?RUN ⊆ image f ?SUB⟩ by blast
qed
```

No tick can occur in a dilated run before the image of 0 by the dilation function.

```
lemma empty_dilated_prefix:
  assumes ⟨dilating f sub r⟩
  and      ⟨n < f 0⟩
shows    ⟨¬ hamlet ((Rep_run r) n c)⟩
proof -
```

```
    from assms have False by (simp add: dilating_def dilating_fun_def)
    thus ?thesis ..
qed

corollary empty_dilated_prefix':
  assumes ⟨dilating f sub r⟩
  shows    ⟨{i. f 0 ≤ i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}
           = {i. i ≤ f n ∧ hamlet ((Rep_run r) i c)}⟩
proof -
  from assms have ⟨strict_mono f⟩ by (simp add: dilating_def dilating_fun_def)
  hence ⟨f 0 ≤ f n⟩ unfolding strict_mono_def by (simp add: less_mono_imp_le_mono)
  hence ⟨∀i. i ≤ f n = (i < f 0) ∨ (f 0 ≤ i ∧ i ≤ f n)⟩ by auto
  hence ⟨{i. i ≤ f n ∧ hamlet ((Rep_run r) i c)}
         = {i. i < f 0 ∧ hamlet ((Rep_run r) i c)}
         ∪ {i. f 0 ≤ i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}⟩
    by auto
  also have ⟨... = {i. f 0 ≤ i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}⟩
      using empty_dilated_prefix[OF assms] by blast
  finally show ?thesis by simp
qed

corollary dilated_prefix:
  assumes ⟨dilating f sub r⟩
  shows    ⟨{i. i ≤ f n ∧ hamlet ((Rep_run r) i c)}
           = image f {i. i ≤ n ∧ hamlet ((Rep_run sub) i c)}⟩
proof -
  have ⟨{i. 0 ≤ i ∧ i ≤ f n ∧ hamlet ((Rep_run r) i c)}
        = image f {i. 0 ≤ i ∧ i ≤ n ∧ hamlet ((Rep_run sub) i c)}⟩
    using dilated_ticks[OF assms] empty_dilated_prefix'[OF assms] by blast
  thus ?thesis by simp
qed

corollary dilated_strict_prefix:
  assumes ⟨dilating f sub r⟩
  shows    ⟨{i. i < f n ∧ hamlet ((Rep_run r) i c)}
           = image f {i. i < n ∧ hamlet ((Rep_run sub) i c)}⟩
proof -
  from assms have dil:⟨dilating_fun f r⟩ unfolding dilating_def by simp
  from dil have f0:⟨f 0 = 0⟩  using dilating_fun_def by blast
  from dilating_fun_image_left[OF dil, of ⟨0⟩ ⟨n⟩ ⟨c⟩]
  have ⟨{i. f 0 ≤ i ∧ i < f n ∧ hamlet ((Rep_run r) i c)}
        = image f {i. 0 ≤ i ∧ i < n ∧ hamlet ((Rep_run r) (f i) c)}⟩ .
  hence ⟨{i. i < f n ∧ hamlet ((Rep_run r) i c)}
        = image f {i. i < n ∧ hamlet ((Rep_run r) (f i) c)}⟩
    using f0 by simp
  also have ⟨... = image f {i. i < n ∧ hamlet ((Rep_run sub) i c)}⟩
    using assms dilating_def by blast
  finally show ?thesis by simp
qed
```

A singleton of **nat** can be defined with a weaker property.

```
lemma nat_sing_prop:
  ⟨{i::nat. i = k ∧ P(i)} = {i::nat. i = k ∧ P(k)}⟩
by auto
```

The set definition and the function definition of `tick_count` are equivalent.

```
lemma tick_count_is_fun[code]:⟨tick_count r c n = run_tick_count r c n⟩
proof (induction n)
```

```
    case 0
      have ⟨tick_count r c 0 = card {i. i ≤ 0 ∧ hamlet ((Rep_run r) i c)}⟩
        by (simp add: tick_count_def)
      also have ⟨... = card {i::nat. i = 0 ∧ hamlet ((Rep_run r) 0 c)}⟩
        using le_zero_eq nat_sing_prop[of ⟨0⟩ ⟨λi. hamlet ((Rep_run r) i c)⟩] by simp
      also have ⟨... = (if hamlet ((Rep_run r) 0 c) then 1 else 0)⟩ by simp
      also have ⟨... = run_tick_count r c 0⟩ by simp
      finally show ?case .
next
  case (Suc k)
    show ?case
    proof (cases ⟨hamlet ((Rep_run r) (Suc k) c)⟩)
      case True
        hence ⟨{i. i ≤ Suc k ∧ hamlet ((Rep_run r) i c)}
            = insert (Suc k) {i. i ≤ k ∧ hamlet ((Rep_run r) i c)}⟩ by auto
        hence ⟨tick_count r c (Suc k) = Suc (tick_count r c k)⟩
          by (simp add: tick_count_def)
        with Suc.IH have ⟨tick_count r c (Suc k) = Suc (run_tick_count r c k)⟩ by simp
        thus ?thesis by (simp add: True)
      next
        case False
          hence ⟨{i. i ≤ Suc k ∧ hamlet ((Rep_run r) i c)}
              = {i. i ≤ k ∧ hamlet ((Rep_run r) i c)}⟩
            using le_Suc_eq by auto
          hence ⟨tick_count r c (Suc k) = tick_count r c k⟩
            by (simp add: tick_count_def)
          thus ?thesis using Suc.IH by (simp add: False)
    qed
qed
```

To show that the set definition and the function definition of `tick_count_strict` are equivalent, we first show that the *strictness* of `tick_count_strict` can be softened using `Suc`.

```
lemma tick_count_strict_suc:⟨tick_count_strict r c (Suc n) = tick_count r c n⟩
  unfolding tick_count_def tick_count_strict_def using less_Suc_eq_le by auto

lemma tick_count_strict_is_fun[code]:
  ⟨tick_count_strict r c n = run_tick_count_strictly r c n⟩
proof (cases ⟨n = 0⟩)
  case True
    hence ⟨tick_count_strict r c n = 0⟩ unfolding tick_count_strict_def by simp
    also have ⟨... = run_tick_count_strictly r c 0⟩
      using run_tick_count_strictly.simps(1)[symmetric] .
    finally show ?thesis using True by simp
next
  case False
    from not0_implies_Suc[OF this] obtain m where *:⟨n = Suc m⟩ by blast
    hence ⟨tick_count_strict r c n = tick_count r c m⟩
      using tick_count_strict_suc by simp
    also have ⟨... = run_tick_count r c m⟩ using tick_count_is_fun[of ⟨r⟩ ⟨c⟩ ⟨m⟩] .
    also have ⟨... = run_tick_count_strictly r c (Suc m)⟩
      using run_tick_count_strictly.simps(2)[symmetric] .
    finally show ?thesis using * by simp
qed
```

This leads to an alternate definition of the strict precedence relation.

```
lemma strictly_precedes_alt_def1:
  ⟨{ ϱ. ∀n::nat. (run_tick_count ϱ K₂ n) ≤ (run_tick_count_strictly ϱ K₁ n) }
 = { ϱ. ∀n::nat. (run_tick_count_strictly ϱ K₂ (Suc n))
```

$$\leq \text{(run\_tick\_count\_strictly } \varrho \text{ K}_1 \text{ n) })$$
by auto

The strict precedence relation can even be defined using only `run_tick_count`:

lemma zero_gt_all:
  assumes ⟨P (0::nat)⟩
      and ⟨⋀n. n > 0 ⟹ P n⟩
    shows ⟨P n⟩
  using assms neq0_conv **by** blast

lemma strictly_precedes_alt_def2:
  ⟨{ ϱ. ∀n::nat. (run_tick_count ϱ K₂ n) ≤ (run_tick_count_strictly ϱ K₁ n) }
= { ϱ. (¬hamlet ((Rep_run ϱ) 0 K₂))
      ∧ (∀n::nat. (run_tick_count ϱ K₂ (Suc n)) ≤ (run_tick_count ϱ K₁ n)) }⟩
  (**is** ⟨?P = ?P'⟩)
proof
  { **fix** r::⟨'a run⟩
    assume ⟨r ∈ ?P⟩
    hence ⟨∀n::nat. (run_tick_count r K₂ n) ≤ (run_tick_count_strictly r K₁ n)⟩
      by simp
    hence 1:⟨∀n::nat. (tick_count r K₂ n) ≤ (tick_count_strict r K₁ n)⟩
      using tick_count_is_fun[symmetric, of r] tick_count_strict_is_fun[symmetric, of r]
      by simp
    hence ⟨∀n::nat. (tick_count_strict r K₂ (Suc n)) ≤ (tick_count_strict r K₁ n)⟩
      using tick_count_strict_suc[symmetric, of ⟨r⟩ ⟨K₂⟩] **by** simp
    hence ⟨∀n::nat. (tick_count_strict r K₂ (Suc (Suc n))) ≤ (tick_count_strict r K₁ (Suc n))⟩
      by simp
    hence ⟨∀n::nat. (tick_count r K₂ (Suc n)) ≤ (tick_count r K₁ n)⟩
      using tick_count_strict_suc[symmetric, of ⟨r⟩] **by** simp
    hence *:⟨∀n::nat. (run_tick_count r K₂ (Suc n)) ≤ (run_tick_count r K₁ n)⟩
      by (simp add: tick_count_is_fun)
    from 1 **have** ⟨tick_count r K₂ 0 <= tick_count_strict r K₁ 0⟩ **by** simp
    moreover have ⟨tick_count_strict r K₁ 0 = 0⟩ **unfolding** tick_count_strict_def **by** simp
    ultimately have ⟨tick_count r K₂ 0 = 0⟩ **by** simp
    hence ⟨¬hamlet ((Rep_run r) 0 K₂)⟩ **unfolding** tick_count_def **by** auto
    with * **have** ⟨r ∈ ?P'⟩ **by** simp
  } **thus** ⟨?P ⊆ ?P'⟩ ..
  { **fix** r::⟨'a run⟩
    assume h:⟨r ∈ ?P'⟩
    hence ⟨∀n::nat. (run_tick_count r K₂ (Suc n)) ≤ (run_tick_count r K₁ n)⟩ **by** simp
    hence ⟨∀n::nat. (tick_count r K₂ (Suc n)) ≤ (tick_count r K₁ n)⟩
      by (simp add: tick_count_is_fun)
    hence ⟨∀n::nat. (tick_count r K₂ (Suc n)) ≤ (tick_count_strict r K₁ (Suc n))⟩
      using tick_count_strict_suc[symmetric, of ⟨r⟩ ⟨K₁⟩] **by** simp
    hence *:⟨∀n. n > 0 ⟶ (tick_count r K₂ n) ≤ (tick_count_strict r K₁ n)⟩
      using gr0_implies_Suc **by** blast
    have ⟨tick_count_strict r K₁ 0 = 0⟩ **unfolding** tick_count_strict_def **by** simp
    moreover from h **have** ⟨¬hamlet ((Rep_run r) 0 K₂)⟩ **by** simp
    hence ⟨tick_count r K₂ 0 = 0⟩ **unfolding** tick_count_def **by** auto
    ultimately have ⟨tick_count r K₂ 0 ≤ tick_count_strict r K₁ 0⟩ **by** simp
    from zero_gt_all[of ⟨λn. tick_count r K₂ n ≤ tick_count_strict r K₁ n⟩, OF this] *
      have ⟨∀n. (tick_count r K₂ n) ≤ (tick_count_strict r K₁ n)⟩ **by** simp
    hence ⟨∀n. (run_tick_count r K₂ n) ≤ (run_tick_count_strictly r K₁ n)⟩
      by (simp add: tick_count_is_fun tick_count_strict_is_fun)
    hence ⟨r ∈ ?P⟩ ..
  } **thus** ⟨?P' ⊆ ?P⟩ ..
qed

Some properties of `run_tick_count`, `tick_count` and `Suc`:

lemma `run_tick_count_suc`:
  ⟨run_tick_count r c (Suc n) = (if hamlet ((Rep_run r) (Suc n) c)
                                  then Suc (run_tick_count r c n)
                                  else run_tick_count r c n)⟩
by `simp`

corollary `tick_count_suc`:
  ⟨tick_count r c (Suc n) = (if hamlet ((Rep_run r) (Suc n) c)
                              then Suc (tick_count r c n)
                              else tick_count r c n)⟩
by (simp add: tick_count_is_fun)

Some generic properties on the cardinal of sets of nat that we will need later.

lemma `card_suc`:
  ⟨card {i. i ≤ (Suc n) ∧ P i} = card {i. i ≤ n ∧ P i} + card {i. i = (Suc n) ∧ P i}⟩
proof -
  have ⟨{i. i ≤ n ∧ P i} ∩ {i. i = (Suc n) ∧ P i} = {}⟩ **by** auto
  moreover have ⟨{i. i ≤ n ∧ P i} ∪ {i. i = (Suc n) ∧ P i}
              = {i. i ≤ (Suc n) ∧ P i}⟩ **by** auto
  moreover have ⟨finite {i. i ≤ n ∧ P i}⟩ **by** simp
  moreover have ⟨finite {i. i = (Suc n) ∧ P i}⟩ **by** simp
  ultimately show ?thesis
    using card_Un_disjoint[of ⟨{i. i ≤ n ∧ P i}⟩ ⟨{i. i = Suc n ∧ P i}⟩] **by** simp
qed

lemma `card_le_leq`:
  assumes ⟨m < n⟩
    shows ⟨card {i::nat. m < i ∧ i ≤ n ∧ P i}
        = card {i. m < i ∧ i < n ∧ P i} + card {i. i = n ∧ P i}⟩
proof -
  have ⟨{i::nat. m < i ∧ i < n ∧ P i} ∩ {i. i = n ∧ P i} = {}⟩ **by** auto
  moreover with assms **have**
    ⟨{i::nat. m < i ∧ i < n ∧ P i} ∪ {i. i = n ∧ P i} = {i. m < i ∧ i ≤ n ∧ P i}⟩
  by auto
  moreover have ⟨finite {i. m < i ∧ i < n ∧ P i}⟩ **by** simp
  moreover have ⟨finite {i. i = n ∧ P i}⟩ **by** simp
  ultimately show ?thesis
    using card_Un_disjoint[of ⟨{i. m < i ∧ i < n ∧ P i}⟩ ⟨{i. i = n ∧ P i}⟩] **by** simp
qed

lemma `card_le_leq_0`:
  ⟨card {i::nat. i ≤ n ∧ P i} = card {i. i < n ∧ P i} + card {i. i = n ∧ P i}⟩
proof -
  have ⟨{i::nat. i < n ∧ P i} ∩ {i. i = n ∧ P i} = {}⟩ **by** auto
  moreover have ⟨{i. i < n ∧ P i} ∪ {i. i = n ∧ P i} = {i. i ≤ n ∧ P i}⟩ **by** auto
  moreover have ⟨finite {i. i < n ∧ P i}⟩ **by** simp
  moreover have ⟨finite {i. i = n ∧ P i}⟩ **by** simp
  ultimately show ?thesis
    using card_Un_disjoint[of ⟨{i. i < n ∧ P i}⟩ ⟨{i. i = n ∧ P i}⟩] **by** simp
qed

lemma `card_mnm`:
  assumes ⟨m < n⟩
    shows ⟨card {i::nat. i < n ∧ P i}
        = card {i. i ≤ m ∧ P i} + card {i. m < i ∧ i < n ∧ P i}⟩
proof -
  have 1:⟨{i::nat. i ≤ m ∧ P i} ∩ {i. m < i ∧ i < n ∧ P i} = {}⟩ **by** auto
  from assms **have** ⟨∀i::nat. i < n = (i ≤ m) ∨ (m < i ∧ i < n)⟩

```
      using less_trans by auto
    hence 2:
      ⟨{i::nat. i < n ∧ P i} = {i. i ≤ m ∧ P i} ∪ {i. m < i ∧ i < n ∧ P i}⟩ by blast
    have 3:⟨finite {i. i ≤ m ∧ P i}⟩ by simp
    have 4:⟨finite {i. m < i ∧ i < n ∧ P i}⟩ by simp
    from card_Un_disjoint[OF 3 4 1] 2 show ?thesis by simp
qed

lemma card_mnm':
  assumes ⟨m < n⟩
    shows ⟨card {i::nat. i < n ∧ P i}
        = card {i. i < m ∧ P i} + card {i. m ≤ i ∧ i < n ∧ P i}⟩
proof -
  have 1:⟨{i::nat. i < m ∧ P i} ∩ {i. m ≤ i ∧ i < n ∧ P i} = {}⟩ by auto
  from assms have ⟨∀i::nat. i < n = (i < m) ∨ (m ≤ i ∧ i < n)⟩
    using less_trans by auto
  hence 2:
    ⟨{i::nat. i < n ∧ P i} = {i. i < m ∧ P i} ∪ {i. m ≤ i ∧ i < n ∧ P i}⟩ by blast
  have 3:⟨finite {i. i < m ∧ P i}⟩ by simp
  have 4:⟨finite {i. m ≤ i ∧ i < n ∧ P i}⟩ by simp
  from card_Un_disjoint[OF 3 4 1] 2 show ?thesis by simp
qed

lemma nat_interval_union:
  assumes ⟨m ≤ n⟩
    shows ⟨{i::nat. i ≤ n ∧ P i}
        = {i::nat. i ≤ m ∧ P i} ∪ {i::nat. m < i ∧ i ≤ n ∧ P i}⟩
using assms le_cases nat_less_le by auto

lemma card_sing_prop:⟨card {i. i = n ∧ P i} = (if P n then 1 else 0)⟩
proof (cases ⟨P n⟩)
  case True
    hence ⟨{i. i = n ∧ P i} = {n}⟩ by (simp add: Collect_conv_if)
    with ⟨P n⟩ show ?thesis by simp
next
  case False
    hence ⟨{i. i = n ∧ P i} = {}⟩ by (simp add: Collect_conv_if)
    with ⟨¬P n⟩ show ?thesis by simp
qed

lemma card_prop_mono:
  assumes ⟨m ≤ n⟩
    shows ⟨card {i::nat. i ≤ m ∧ P i} ≤ card {i. i ≤ n ∧ P i}⟩
proof -
  from assms have ⟨{i. i ≤ m ∧ P i} ⊆ {i. i ≤ n ∧ P i}⟩ by auto
  moreover have ⟨finite {i. i ≤ n ∧ P i}⟩ by simp
  ultimately show ?thesis by (simp add: card_mono)
qed
```

In a dilated run, no tick occurs strictly between two successive instants that are the images by
`f` of instants of the original run.

```
lemma no_tick_before_suc:
  assumes ⟨dilating f sub r⟩
      and ⟨(f n) < k ∧ k < (f (Suc n))⟩
    shows ⟨¬hamlet ((Rep_run r) k c)⟩
proof -
  from assms(1) have smf:⟨strict_mono f⟩ by (simp add: dilating_def dilating_fun_def)
  { fix k assume h:⟨f n < k ∧ k < f (Suc n) ∧ hamlet ((Rep_run r) k c)⟩
```

      hence $\langle \exists k_0.\ f\ k_0 = k \rangle$ **using** assms(1) dilating_def dilating_fun_def **by** blast
      from this **obtain** k_0 **where** $\langle f\ k_0 = k \rangle$ **by** blast
      with h **have** $\langle f\ n < f\ k_0 \wedge f\ k_0 < f\ (\text{Suc } n) \rangle$ **by** simp
      hence False **using** smf not_less_eq strict_mono_less **by** blast
  } thus ?thesis **using** assms(2) **by** blast
qed

From this, we show that the number of ticks on any clock at `f (Suc n)` depends only on the number of ticks on this clock at `f n` and whether this clock ticks at `f (Suc n)`. All the instants in between are stuttering instants.

lemma tick_count_fsuc:
  assumes $\langle$ dilating f sub r $\rangle$
    shows $\langle$ tick_count r c (f (Suc n))
        = tick_count r c (f n) + card {k. k = f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)} $\rangle$
proof -
  have smf:$\langle$strict_mono f$\rangle$ **using** assms dilating_def dilating_fun_def **by** blast
  moreover have $\langle$finite {k. k $\leq$ f n $\wedge$ hamlet ((Rep_run r) k c)}$\rangle$ **by** simp
  moreover have *:$\langle$finite {k. f n < k $\wedge$ k $\leq$ f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)}$\rangle$ **by** simp
  ultimately have $\langle$ {k. k $\leq$ f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)} =
                {k. k $\leq$ f n $\wedge$ hamlet ((Rep_run r) k c)}
             $\cup$ {k. f n < k $\wedge$ k $\leq$ f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)}$\rangle$
    by (simp add: nat_interval_union strict_mono_less_eq)
  moreover have $\langle$ {k. k $\leq$ f n $\wedge$ hamlet ((Rep_run r) k c)}
           $\cap$ {k. f n < k $\wedge$ k $\leq$ f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)} = {} $\rangle$
    by auto
  ultimately have $\langle$card {k. k $\leq$ f (Suc n) $\wedge$ hamlet (Rep_run r k c)} =
          card {k. k $\leq$ f n $\wedge$ hamlet (Rep_run r k c)}
        + card {k. f n < k $\wedge$ k $\leq$ f (Suc n) $\wedge$ hamlet (Rep_run r k c)}$\rangle$
    by (simp add: * card_Un_disjoint)
  moreover from no_tick_before_suc[OF assms] **have**
    $\langle$ {k. f n < k $\wedge$ k $\leq$ f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)} =
        {k. k = f (Suc n) $\wedge$ hamlet ((Rep_run r) k c)} $\rangle$
    using smf strict_mono_less **by** fastforce
  ultimately show ?thesis **by** (simp add: tick_count_def)
qed

corollary tick_count_f_suc:
  assumes $\langle$ dilating f sub r $\rangle$
    shows $\langle$ tick_count r c (f (Suc n))
        = tick_count r c (f n) + (if hamlet ((Rep_run r) (f (Suc n)) c) then 1 else 0)$\rangle$
using tick_count_fsuc[OF assms]
    card_sing_prop[of $\langle$f (Suc n)$\rangle$ $\langle \lambda$k. hamlet ((Rep_run r) k c)$\rangle$] **by** simp

corollary tick_count_f_suc_suc:
  assumes $\langle$ dilating f sub r $\rangle$
    shows $\langle$ tick_count r c (f (Suc n)) = (if hamlet ((Rep_run r) (f (Suc n)) c)
                        then Suc (tick_count r c (f n))
                        else tick_count r c (f n))$\rangle$
using tick_count_f_suc[OF assms] **by** simp

lemma tick_count_f_suc_sub:
  assumes $\langle$ dilating f sub r $\rangle$
    shows $\langle$ tick_count r c (f (Suc n)) = (if hamlet ((Rep_run sub) (Suc n) c)
                        then Suc (tick_count r c (f n))
                        else tick_count r c (f n))$\rangle$
using tick_count_f_suc_suc[OF assms] assms **by** (simp add: dilating_def)

The number of ticks does not progress during stuttering instants.

```
lemma tick_count_latest:
  assumes ⟨dilating f sub r⟩
      and ⟨f n_p < n ∧ (∀k. f n_p < k ∧ k ≤ n ⟶ (∄k_0. f k_0 = k))⟩
    shows ⟨tick_count r c n = tick_count r c (f n_p)⟩
proof -
  have union:⟨{i. i ≤ n ∧ hamlet ((Rep_run r) i c)} =
        {i. i ≤ f n_p ∧ hamlet ((Rep_run r) i c)}
        ∪ {i. f n_p < i ∧ i ≤ n ∧ hamlet ((Rep_run r) i c)}⟩ using assms(2) by auto
  have partition: ⟨{i. i ≤ f n_p ∧ hamlet ((Rep_run r) i c)}
        ∩ {i. f n_p < i ∧ i ≤ n ∧ hamlet ((Rep_run r) i c)} = {}⟩
    by (simp add: disjoint_iff_not_equal)
  from assms have ⟨{i. f n_p < i ∧ i ≤ n ∧ hamlet ((Rep_run r) i c)} = {}⟩
    using no_tick_sub by fastforce
  with union and partition show ?thesis by (simp add: tick_count_def)
qed
```

We finally show that the number of ticks on any clock is preserved by dilation.

```
lemma tick_count_sub:
  assumes ⟨dilating f sub r⟩
    shows ⟨tick_count sub c n = tick_count r c (f n)⟩
proof -
  have ⟨tick_count sub c n = card {i. i ≤ n ∧ hamlet ((Rep_run sub) i c)}⟩
    using tick_count_def[of ⟨sub⟩ ⟨c⟩ ⟨n⟩] .
  also have ⟨... = card (image f {i. i ≤ n ∧ hamlet ((Rep_run sub) i c)})⟩
    using assms dilating_def dilating_injects[OF assms] by (simp add: card_image)
  also have ⟨... = card {i. i ≤ f n ∧ hamlet ((Rep_run r) i c)}⟩
    using dilated_prefix[OF assms, symmetric, of ⟨n⟩ ⟨c⟩] by simp
  also have ⟨... = tick_count r c (f n)⟩
    using tick_count_def[of ⟨r⟩ ⟨c⟩ ⟨f n⟩] by simp
  finally show ?thesis .
qed
```

```
corollary run_tick_count_sub:
  assumes ⟨dilating f sub r⟩
    shows ⟨run_tick_count sub c n = run_tick_count r c (f n)⟩
proof -
  have ⟨run_tick_count sub c n = tick_count sub c n⟩
    using tick_count_is_fun[of ⟨sub⟩ c n, symmetric] .
  also from tick_count_sub[OF assms] have ⟨... = tick_count r c (f n)⟩ .
  also have ⟨... = #_≤ r c (f n)⟩ using tick_count_is_fun[of r c ⟨f n⟩] .
  finally show ?thesis .
qed
```

The number of ticks occurring strictly before the first instant is null.

```
lemma tick_count_strict_0:
  assumes ⟨dilating f sub r⟩
    shows ⟨tick_count_strict r c (f 0) = 0⟩
proof -
  from assms have ⟨f 0 = 0⟩ by (simp add: dilating_def dilating_fun_def)
  thus ?thesis unfolding tick_count_strict_def by simp
qed
```

The number of ticks strictly before an instant does not progress during stuttering instants.

```
lemma tick_count_strict_stable:
  assumes ⟨dilating f sub r⟩
  assumes ⟨(f n) < k ∧ k < (f (Suc n))⟩
  shows ⟨tick_count_strict r c k = tick_count_strict r c (f (Suc n))⟩
```

proof -
  from assms(1) **have** smf:⟨strict_mono f⟩ **by** (simp add: dilating_def dilating_fun_def)
  from assms(2) **have** ⟨f n < k⟩ **by** simp
  hence ⟨∀i. k ≤ i ⟶ f n < i⟩ **by** simp
  with no_tick_before_suc[OF assms(1)] **have**
    *:⟨∀i. k ≤ i ∧ i < f (Suc n) ⟶ ¬hamlet ((Rep_run r) i c)⟩ **by** blast
  from tick_count_strict_def **have**
    ⟨tick_count_strict r c (f (Suc n)) = card {i. i < f (Suc n) ∧ hamlet ((Rep_run r) i c)}⟩ .
  also have
    ⟨... = card {i. i < k ∧ hamlet ((Rep_run r) i c)}
        + card {i. k ≤ i ∧ i < f (Suc n) ∧ hamlet ((Rep_run r) i c)}⟩
    using card_mnm' assms(2) **by** simp
  also have ⟨... = card {i. i < k ∧ hamlet ((Rep_run r) i c)}⟩ **using** * **by** simp
  finally show ?thesis **by** (simp add: tick_count_strict_def)
qed

Finally, the number of ticks strictly before an instant is preserved by dilation.

lemma tick_count_strict_sub:
  assumes ⟨dilating f sub r⟩
    shows ⟨tick_count_strict sub c n = tick_count_strict r c (f n)⟩
proof -
  have ⟨tick_count_strict sub c n = card {i. i < n ∧ hamlet ((Rep_run sub) i c)}⟩
    using tick_count_strict_def[of ⟨sub⟩ ⟨c⟩ ⟨n⟩] .
  also have ⟨... = card (image f {i. i < n ∧ hamlet ((Rep_run sub) i c)})⟩
    using assms dilating_def dilating_injects[OF assms] **by** (simp add: card_image)
  also have ⟨... = card {i. i < f n ∧ hamlet ((Rep_run r) i c)}⟩
    using dilated_strict_prefix[OF assms, symmetric, of ⟨n⟩ ⟨c⟩] **by** simp
  also have ⟨... = tick_count_strict r c (f n)⟩
    using tick_count_strict_def[of ⟨r⟩ ⟨c⟩ ⟨f n⟩] **by** simp
  finally show ?thesis .
qed

The tick count on any clock can only increase.

lemma mono_tick_count:
  ⟨mono (λ k. tick_count r c k)⟩
proof
  { **fix** x y::nat
    assume ⟨x ≤ y⟩
    from card_prop_mono[OF this] **have** ⟨tick_count r c x ≤ tick_count r c y⟩
      unfolding tick_count_def **by** simp
  } **thus** ⟨⋀x y. x ≤ y ⟹ tick_count r c x ≤ tick_count r c y⟩ .
qed

In a dilated run, for any stuttering instant, there is an instant which is the image of an instant in the original run, and which is the latest one before the stuttering instant.

lemma greatest_prev_image:
  assumes ⟨dilating f sub r⟩
    shows ⟨(∄n_0. f n_0 = n) ⟹ (∃n_p. f n_p < n ∧ (∀k. f n_p < k ∧ k ≤ n ⟶ (∄k_0. f k_0 = k)))⟩
proof (induction n)
  case 0
    with assms **have** ⟨f 0 = 0⟩ **by** (simp add: dilating_def dilating_fun_def)
    thus ?case **using** "0.prems" **by** blast
next
  case (Suc n)
  show ?case
  proof (cases ⟨∃n_0. f n_0 = n⟩)
    case True

```
        from this obtain n₀ where ⟨f n₀ = n⟩ by blast
        hence ⟨f n₀ < (Suc n) ∧ (∀k. f n₀ < k ∧ k ≤ (Suc n) ⟶ (∄k₀. f k₀ = k))⟩
          using Suc.prems Suc_leI le_antisym by blast
        thus ?thesis by blast
    next
      case False
      from Suc.IH[OF this] obtain nₚ
        where ⟨f nₚ < n ∧ (∀k. f nₚ < k ∧ k ≤ n ⟶ (∄k₀. f k₀ = k))⟩ by blast
      hence ⟨f nₚ < Suc n ∧ (∀k. f nₚ < k ∧ k ≤ n ⟶ (∄k₀. f k₀ = k))⟩ by simp
      with Suc(2) have ⟨f nₚ < (Suc n) ∧ (∀k. f nₚ < k ∧ k ≤ (Suc n) ⟶ (∄k₀. f k₀ = k))⟩
        using le_Suc_eq by auto
      thus ?thesis by blast
  qed
qed
```

If a strictly monotonous function on `nat` increases only by one, its argument was increased only by one.

```
lemma strict_mono_suc:
  assumes ⟨strict_mono f⟩
      and ⟨f sn = Suc (f n)⟩
    shows ⟨sn = Suc n⟩
proof -
  from assms(2) have ⟨f sn > f n⟩ by simp
  with strict_mono_less[OF assms(1)] have ⟨sn > n⟩ by simp
  moreover have ⟨sn ≤ Suc n⟩
  proof -
    { assume ⟨sn > Suc n⟩
      from this obtain i where ⟨n < i ∧ i < sn⟩ by blast
      hence ⟨f n < f i ∧ f i < f sn⟩ using assms(1) by (simp add: strict_mono_def)
      with assms(2) have False by simp
    } thus ?thesis using not_less by blast
  qed
  ultimately show ?thesis by (simp add: Suc_leI)
qed
```

Two successive non stuttering instants of a dilated run are the images of two successive instants of the original run.

```
lemma next_non_stuttering:
  assumes ⟨dilating f sub r⟩
      and ⟨f nₚ < n ∧ (∀k. f nₚ < k ∧ k ≤ n ⟶ (∄k₀. f k₀ = k))⟩
      and ⟨f sn₀ = Suc n⟩
    shows ⟨sn₀ = Suc nₚ⟩
proof -
  from assms(1) have smf:⟨strict_mono f⟩ by (simp add: dilating_def dilating_fun_def)
  from assms(2) have *:⟨∀k. f nₚ < k ∧ k < Suc n ⟶ (∄k₀. f k₀ = k)⟩ by simp
  from assms(2) have ⟨f nₚ < n⟩ by simp
  with smf assms(3) have **:⟨sn₀ > nₚ⟩ using strict_mono_less by fastforce
  have ⟨Suc n ≤ f (Suc nₚ)⟩
  proof -
    { assume h:⟨Suc n > f (Suc nₚ)⟩
      hence ⟨Suc nₚ < sn₀⟩ using ** Suc_lessI assms(3) by fastforce
      hence ⟨∃k. k > nₚ ∧ f k < Suc n⟩ using h by blast
      with * have False using smf strict_mono_less by blast
    } thus ?thesis using not_less by blast
  qed
  hence ⟨sn₀ ≤ Suc nₚ⟩ using assms(3) smf using strict_mono_less_eq by fastforce
  with ** show ?thesis by simp
qed
```

The order relation between tick counts on clocks is preserved by dilation.

```
lemma dil_tick_count:
  assumes ⟨sub ≪ r⟩
      and ⟨∀n. run_tick_count sub a n ≤ run_tick_count sub b n⟩
    shows ⟨run_tick_count r a n ≤ run_tick_count r b n⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  show ?thesis
  proof (induction n)
    case 0
      from assms(2) have ⟨run_tick_count sub a 0 ≤ run_tick_count sub b 0⟩ ..
      with run_tick_count_sub[OF *, of _ 0] have
        ⟨run_tick_count r a (f 0) ≤ run_tick_count r b (f 0)⟩ by simp
      moreover from * have ⟨f 0 = 0⟩ by (simp add:dilating_def dilating_fun_def)
      ultimately show ?case by simp
  next
    case (Suc n') thus ?case
    proof (cases ⟨∃n₀. f n₀ = Suc n'⟩)
      case True
        from this obtain n₀ where fn0:⟨f n₀ = Suc n'⟩ by blast
        show ?thesis
        proof (cases ⟨hamlet ((Rep_run sub) n₀ a)⟩)
          case True
            have ⟨run_tick_count r a (f n₀) ≤ run_tick_count r b (f n₀)⟩
              using assms(2) run_tick_count_sub[OF *] by simp
            thus ?thesis by (simp add: fn0)
        next
          case False
            hence ⟨¬ hamlet ((Rep_run r) (Suc n') a)⟩
              using * fn0 ticks_sub by fastforce
            thus ?thesis by (simp add: Suc.IH le_SucI)
        qed
    next
      case False
        thus ?thesis   using * Suc.IH no_tick_sub by fastforce
    qed
  qed
qed
```

Time does not progress during stuttering instants.

```
lemma stutter_no_time:
  assumes ⟨dilating f sub r⟩
      and ⟨⋀k. f n < k ∧ k ≤ m ⟹ (∄k₀. f k₀ = k)⟩
      and ⟨m > f n⟩
    shows ⟨time ((Rep_run r) m c) = time ((Rep_run r) (f n) c)⟩
proof -
  from assms have ⟨∀k. k < m - (f n) ⟶ (∄k₀. f k₀ = Suc ((f n) + k))⟩ by simp
  hence ⟨∀k. k < m - (f n)
            ⟶ time ((Rep_run r) (Suc ((f n) + k)) c) = time ((Rep_run r) ((f n) + k) c)⟩
    using assms(1) by (simp add: dilating_def dilating_fun_def)
  hence *:⟨∀k. k < m - (f n) ⟶ time ((Rep_run r) (Suc ((f n) + k)) c) = time ((Rep_run r) (f n) c)⟩
    using bounded_suc_ind[of ⟨m - (f n)⟩ ⟨λk. time (Rep_run r k c)⟩ ⟨f n⟩] by blast
  from assms(3) obtain m₀ where m0:⟨Suc m₀ = m - (f n)⟩ using Suc_diff_Suc by blast
  with * have ⟨time ((Rep_run r) (Suc ((f n) + m₀)) c) = time ((Rep_run r) (f n) c)⟩ by auto
  moreover from m0 have ⟨Suc ((f n) + m₀) = m⟩ by simp
  ultimately show ?thesis by simp
qed
```

```
lemma time_stuttering:
  assumes ⟨dilating f sub r⟩
      and ⟨time ((Rep_run sub) n c) = τ⟩
      and ⟨⋀k. f n < k ∧ k ≤ m ⟹ (∄k₀. f k₀ = k)⟩
      and ⟨m > f n⟩
    shows ⟨time ((Rep_run r) m c) = τ⟩
proof -
  from assms(3) have ⟨time ((Rep_run r) m c) = time ((Rep_run r) (f n) c)⟩
    using  stutter_no_time[OF assms(1,3,4)] by blast
  also from assms(1,2) have ⟨time ((Rep_run r) (f n) c) = τ⟩ by (simp add: dilating_def)
  finally show ?thesis .
qed
```

The first instant at which a given date is reached on a clock is preserved by dilation.

```
lemma first_time_image:
  assumes ⟨dilating f sub r⟩
    shows ⟨first_time sub c n t = first_time r c (f n) t⟩
proof
  assume ⟨first_time sub c n t⟩
  with before_first_time[OF this]
    have *:⟨time ((Rep_run sub) n c) = t ∧ (∀m < n. time((Rep_run sub) m c) < t)⟩
      by (simp add: first_time_def)
  moreover have ⟨∀n c. time (Rep_run sub n c) = time (Rep_run r (f n) c)⟩
      using assms(1) by (simp add: dilating_def)
  ultimately have **:
    ⟨time ((Rep_run r) (f n) c) = t ∧ (∀m < n. time((Rep_run r) (f m) c) < t)⟩
    by simp
  have ⟨∀m < f n. time ((Rep_run r) m c) < t⟩
  proof -
  { fix m assume hyp:⟨m < f n⟩
    have ⟨time ((Rep_run r) m c) < t⟩
    proof (cases ⟨∃m₀. f m₀ = m⟩)
      case True
        from this obtain m₀ where mm0:⟨m = f m₀⟩ by blast
        with hyp have m0n:⟨m₀ < n⟩ using assms(1)
          by (simp add: dilating_def dilating_fun_def strict_mono_less)
        hence ⟨time ((Rep_run sub) m₀ c) < t⟩ using * by blast
        thus ?thesis by (simp add: mm0 m0n **)
    next
      case False
        hence ⟨∃mₚ. f mₚ < m ∧ (∀k. f mₚ < k ∧ k ≤ m ⟶ (∄k₀. f k₀ = k))⟩
          using greatest_prev_image[OF assms] by simp
        from this obtain mₚ where
          mp:⟨f mₚ < m ∧ (∀k. f mₚ < k ∧ k ≤ m ⟶ (∄k₀. f k₀ = k))⟩ by blast
        hence ⟨time ((Rep_run r) m c) = time ((Rep_run sub) mₚ c)⟩
          using time_stuttering[OF assms] by blast
        also from hyp mp have ⟨f mₚ < f n⟩ by linarith
        hence ⟨mₚ < n⟩ using assms
          by (simp add:dilating_def dilating_fun_def strict_mono_less)
        hence ⟨time ((Rep_run sub) mₚ c) < t⟩ using * by simp
        finally show ?thesis by simp
    qed
  } thus ?thesis by simp
  qed
  with ** show ⟨first_time r c (f n) t⟩ by (simp add: alt_first_time_def)
next
  assume ⟨first_time r c (f n) t⟩
  hence *:⟨time ((Rep_run r) (f n) c) = t ∧ (∀k < f n. time ((Rep_run r) k c) < t)⟩
```

```
      by (simp add: first_time_def before_first_time)
    hence ⟨time ((Rep_run sub) n c) = t⟩ using assms dilating_def by blast
    moreover from * have ⟨(∀k < n. time ((Rep_run sub) k c) < t)⟩
      using assms dilating_def dilating_fun_def strict_monoD by fastforce
    ultimately show ⟨first_time sub c n t⟩ by (simp add: alt_first_time_def)
qed
```

The first instant of a dilated run is necessarily the image of the first instant of the original run.

```
lemma first_dilated_instant:
  assumes ⟨strict_mono f⟩
      and ⟨f (0::nat) = (0::nat)⟩
    shows ⟨Max {i. f i ≤ 0} = 0⟩
proof -
  from assms(2) have ⟨∀n > 0. f n > 0⟩ using strict_monoD[OF assms(1)] by force
  hence ⟨∀n ≠ 0. ¬(f n ≤ 0)⟩ by simp
  with assms(2) have ⟨{i. f i ≤ 0} = {0}⟩ by blast
  thus ?thesis by simp
qed
```

For any instant n of a dilated run, let n_0 be the last instant before n that is the image of an original instant. All instants strictly after n_0 and before n are stuttering instants.

```
lemma not_image_stut:
  assumes ⟨dilating f sub r⟩
      and ⟨n_0 = Max {i. f i ≤ n}⟩
      and ⟨f n_0 < k ∧ k ≤ n⟩
    shows ⟨∄k_0. f k_0 = k⟩
proof -
  from assms(1) have smf:⟨strict_mono f⟩
                  and fxge:⟨∀x. f x ≥ x⟩
    by (auto simp add: dilating_def dilating_fun_def)
  have finite_prefix:⟨finite {i. f i ≤ n}⟩ by (simp add: finite_less_ub fxge)
  from assms(1) have ⟨f 0 ≤ n⟩ by (simp add: dilating_def dilating_fun_def)
  hence ⟨{i. f i ≤ n} ≠ {}⟩ by blast
  from assms(3) fxge have ⟨f n_0 < n⟩ by linarith
  from assms(2) have ⟨∀x > n_0. f x > n⟩ using Max.coboundedI[OF finite_prefix]
    using not_le by auto
  with assms(3) strict_mono_less[OF smf] show ?thesis by auto
qed
```

For any dilating function f, `dil_inverse f` is a contracting function.

```
lemma contracting_inverse:
  assumes ⟨dilating f sub r⟩
    shows ⟨contracting (dil_inverse f) r sub f⟩
proof -
  from assms have smf:⟨strict_mono f⟩
    and no_img_tick:⟨∀k. (∄k_0. f k_0 = k) ⟶ (∀c. ¬(hamlet ((Rep_run r) k c)))⟩
    and no_img_time:⟨⋀n. (∄n_0. f n_0 = (Suc n))
                        ⟶ (∀c. time ((Rep_run r) (Suc n) c) = time ((Rep_run r) n c))⟩
    and fxge:⟨∀x. f x ≥ x⟩ and f0n:⟨⋀n. f 0 ≤ n⟩ and f0:⟨f 0 = 0⟩
    by (auto simp add: dilating_def dilating_fun_def)
  have finite_prefix:⟨⋀n. finite {i. f i ≤ n}⟩ by (auto simp add: finite_less_ub fxge)
  have prefix_not_empty:⟨⋀n. {i. f i ≤ n} ≠ {}⟩ using f0n by blast

  have 1:⟨mono (dil_inverse f)⟩
  proof -
  { fix x::⟨nat⟩ and y::⟨nat⟩ assume hyp:⟨x ≤ y⟩
    hence inc:⟨{i. f i ≤ x} ⊆ {i. f i ≤ y}⟩
```

```
      by (simp add: hyp Collect_mono le_trans)
    from Max_mono[OF inc prefix_not_empty finite_prefix]
      have ⟨(dil_inverse f) x ≤ (dil_inverse f) y⟩ unfolding dil_inverse_def .
  } thus ?thesis unfolding mono_def by simp
  qed

  from first_dilated_instant[OF smf f0] have 2:⟨(dil_inverse f) 0 = 0⟩
    unfolding dil_inverse_def .

  from fxge have ⟨∀n i. f i ≤ n ⟶ i ≤ n⟩ using le_trans by blast
  hence 3:⟨∀n. (dil_inverse f) n ≤ n⟩ using Max_in[OF finite_prefix prefix_not_empty]
    unfolding dil_inverse_def by blast

  from 1 2 3 have *:⟨contracting_fun (dil_inverse f)⟩ by (simp add: contracting_fun_def)

  have ⟨∀n. finite {i. f i ≤ n}⟩ by (simp add: finite_prefix)
  moreover have ⟨∀n. {i. f i ≤ n} ≠ {}⟩ using prefix_not_empty by blast
  ultimately have 4:⟨∀n. f ((dil_inverse f) n) ≤ n⟩
    unfolding dil_inverse_def
    using assms(1) dilating_def dilating_fun_def Max_in by blast

  have 5:⟨∀n c k. f ((dil_inverse f) n) < k ∧ k ≤ n
                              ⟶ ¬ hamlet ((Rep_run r) k c)⟩
    using not_image_stut[OF assms] no_img_tick unfolding dil_inverse_def by blast

  have 6:⟨(∀n c k. f ((dil_inverse f) n) ≤ k ∧ k ≤ n
                    ⟶ time ((Rep_run r) k c) = time ((Rep_run sub) ((dil_inverse f) n) c))⟩
  proof -
    { fix n c k assume h:⟨f ((dil_inverse f) n) ≤ k ∧ k ≤ n⟩
      let ?τ = ⟨time (Rep_run sub ((dil_inverse f) n) c)⟩
      have tau:⟨time (Rep_run sub ((dil_inverse f) n) c) = ?τ⟩ ..
      have gn:⟨(dil_inverse f) n = Max {i. f i ≤ n}⟩ unfolding dil_inverse_def ..
      from time_stuttering[OF assms tau, of k] not_image_stut[OF assms gn]
      have ⟨time ((Rep_run r) k c) = time ((Rep_run sub) ((dil_inverse f) n) c)⟩
      proof (cases ⟨f ((dil_inverse f) n) = k⟩)
        case True
          moreover have ⟨∀n c. time (Rep_run sub n c) = time (Rep_run r (f n) c)⟩
            using assms by (simp add: dilating_def)
          ultimately show ?thesis by simp
      next
        case False
          with h have ⟨f (Max {i. f i ≤ n}) < k ∧ k ≤ n⟩ by (simp add: dil_inverse_def)
          with time_stuttering[OF assms tau, of k] not_image_stut[OF assms gn]
            show ?thesis unfolding dil_inverse_def by auto
      qed
    } thus ?thesis by simp
  qed

  from * 4 5 6 show ?thesis unfolding contracting_def by simp
qed
```

The only possible contracting function toward a dense run (a run with no empty instants) is the inverse of the dilating function as defined by `dil_inverse`.

```
lemma dense_run_dil_inverse_only:
  assumes ⟨dilating f sub r⟩
      and ⟨contracting g r sub f⟩
      and ⟨dense_run sub⟩
    shows ⟨g = (dil_inverse f)⟩
```

proof
  from assms(1) have *:⟨⋀n. finite {i. f i ≤ n}⟩
    using finite_less_ub by (simp add: dilating_def dilating_fun_def)
  from assms(1) have ⟨f 0 = 0⟩ by (simp add: dilating_def dilating_fun_def)
  hence ⟨⋀n. 0 ∈ {i. f i ≤ n}⟩ by simp
  hence **:⟨⋀n. {i. f i ≤ n} ≠ {}⟩ by blast
  { fix n assume h:⟨g n < (dil_inverse f) n⟩
    hence ⟨∃k > g n. f k ≤ n⟩ unfolding dil_inverse_def using Max_in[OF * **] by blast
    from this obtain k where kprop:⟨g n < k ∧ f k ≤ n⟩ by blast
    with assms(3) dense_run_def obtain c where ⟨hamlet ((Rep_run sub) k c)⟩ by blast
    hence ⟨hamlet ((Rep_run r) (f k) c)⟩ using ticks_sub[OF assms(1)] by blast
    moreover from kprop have ⟨f (g n) < f k ∧ f k ≤ n⟩ using assms(1)
      by (simp add: dilating_def dilating_fun_def strict_monoD)
    ultimately have False using assms(2) unfolding contracting_def by blast
  } hence 1:⟨⋀n. ¬(g n < (dil_inverse f) n)⟩ by blast
  { fix n assume h:⟨g n > (dil_inverse f) n⟩
    have ⟨∃k ≤ g n. f k > n⟩
    proof -
      { assume ⟨∀k ≤ g n. f k ≤ n⟩
        with h have False unfolding dil_inverse_def
        using Max_gr_iff[OF * **] by blast
      }
      thus ?thesis using not_less by blast
    qed
    from this obtain k where ⟨k ≤ g n ∧ f k > n⟩ by blast
    hence ⟨f (g n) ≥ f k ∧ f k > n⟩ using assms(1)
      by (simp add: dilating_def dilating_fun_def strict_mono_less_eq)
    hence ⟨f (g n) > n⟩ by simp
    with assms(2) have False unfolding contracting_def by (simp add: leD)
  } hence 2:⟨⋀n. ¬(g n > (dil_inverse f) n)⟩ by blast
  from 1 2 show ⟨⋀n. g n = (dil_inverse f) n⟩ by (simp add: not_less_iff_gr_or_eq)
qed

end

8.1.5 Main Theorems

theory Stuttering
imports StutteringLemmas

begin

Using the lemmas of the previous section about the invariance by stuttering of various properties of TESL specifications, we can now prove that the atomic formulae that compose TESL specifications are invariant by stuttering.

Sporadic specifications are preserved in a dilated run.

lemma sporadic_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦c sporadic τ on c'⟧$_{TESL}$⟩
    shows ⟨r ∈ ⟦c sporadic τ on c'⟧$_{TESL}$⟩
proof -
  from assms(1) is_subrun_def obtain f
    where ⟨dilating f sub r⟩ by blast
  hence ⟨∀n c. time ((Rep_run sub) n c) = time ((Rep_run r) (f n) c)
          ∧ hamlet ((Rep_run sub) n c) = hamlet ((Rep_run r) (f n) c)⟩ by (simp add: dilating_def)
  moreover from assms(2) have
    ⟨sub ∈ {r. ∃ n. hamlet ((Rep_run r) n c) ∧ time ((Rep_run r) n c') = τ}⟩ by simp

```
    from this obtain k where ⟨time ((Rep_run sub) k c') = τ ∧ hamlet ((Rep_run sub) k c)⟩ by auto
    ultimately have ⟨time ((Rep_run r) (f k) c') = τ ∧ hamlet ((Rep_run r) (f k) c)⟩ by simp
    thus ?thesis by auto
qed
```

Implications are preserved in a dilated run.

```
theorem implies_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦c₁ implies c₂⟧_TESL⟩
    shows ⟨r ∈ ⟦c₁ implies c₂⟧_TESL⟩
proof -
  from assms(1) is_subrun_def obtain f where ⟨dilating f sub r⟩ by blast
  moreover from assms(2) have
    ⟨sub ∈ {r. ∀n. hamlet ((Rep_run r) n c₁) ⟶ hamlet ((Rep_run r) n c₂)}⟩ by simp
  hence ⟨∀n. hamlet ((Rep_run sub) n c₁) ⟶ hamlet ((Rep_run sub) n c₂)⟩ by simp
  ultimately have ⟨∀n. hamlet ((Rep_run r) n c₁) ⟶ hamlet ((Rep_run r) n c₂)⟩
    using ticks_imp_ticks_subk ticks_sub by blast
  thus ?thesis by simp
qed
```

```
theorem implies_not_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦c₁ implies not c₂⟧_TESL⟩
    shows ⟨r ∈ ⟦c₁ implies not c₂⟧_TESL⟩
proof -
  from assms(1) is_subrun_def obtain f where ⟨dilating f sub r⟩ by blast
  moreover from assms(2) have
    ⟨sub ∈ {r. ∀n. hamlet ((Rep_run r) n c₁) ⟶ ¬ hamlet ((Rep_run r) n c₂)}⟩ by simp
  hence ⟨∀n. hamlet ((Rep_run sub) n c₁) ⟶ ¬ hamlet ((Rep_run sub) n c₂)⟩ by simp
  ultimately have ⟨∀n. hamlet ((Rep_run r) n c₁) ⟶ ¬ hamlet ((Rep_run r) n c₂)⟩
    using ticks_imp_ticks_subk ticks_sub by blast
  thus ?thesis by simp
qed
```

Precedence relations are preserved in a dilated run.

```
theorem weakly_precedes_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦c₁ weakly precedes c₂⟧_TESL⟩
    shows ⟨r ∈ ⟦c₁ weakly precedes c₂⟧_TESL⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  from assms(2) have
    ⟨sub ∈ {r. ∀n. (run_tick_count r c₂ n) ≤ (run_tick_count r c₁ n)}⟩ by simp
  hence ⟨∀n. (run_tick_count sub c₂ n) ≤ (run_tick_count sub c₁ n)⟩ by simp
  from dil_tick_count[OF assms(1) this]
    have ⟨∀n. (run_tick_count r c₂ n) ≤ (run_tick_count r c₁ n)⟩ by simp
  thus ?thesis by simp
qed
```

```
theorem strictly_precedes_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦c₁ strictly precedes c₂⟧_TESL⟩
    shows ⟨r ∈ ⟦c₁ strictly precedes c₂⟧_TESL⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  from assms(2) have
    ⟨sub ∈ { ϱ. ∀n::nat. (run_tick_count ϱ c₂ n) ≤ (run_tick_count_strictly ϱ c₁ n) }⟩
  by simp
```

with strictly_precedes_alt_def2[of ⟨c_2⟩ ⟨c_1⟩]   **have**
  ⟨sub ∈ { ϱ. (¬hamlet ((Rep_run ϱ) 0 c_2))
∧ ($\forall$n::nat. (run_tick_count ϱ c_2 (Suc n)) ≤ (run_tick_count ϱ c_1 n)) }⟩
by blast
hence ⟨(¬hamlet ((Rep_run sub) 0 c_2))
      ∧ ($\forall$n::nat. (run_tick_count sub c_2 (Suc n)) ≤ (run_tick_count sub c_1 n))⟩
  by simp
hence
  1:⟨(¬hamlet ((Rep_run sub) 0 c_2))
   ∧ ($\forall$n::nat. (tick_count sub c_2 (Suc n)) ≤ (tick_count sub c_1 n))⟩
by (simp add: tick_count_is_fun)
have ⟨$\forall$n::nat. (tick_count r c_2 (Suc n)) ≤ (tick_count r c_1 n)⟩
proof -
  { **fix** n::nat
    have ⟨tick_count r c_2 (Suc n) ≤ tick_count r c_1 n⟩
    proof (cases ⟨$\exists n_0$. f n_0 = n⟩)
      case True — n is in the image of f

        from this **obtain** n_0 **where** fn:⟨f n_0 = n⟩ **by** blast
        show ?thesis
        proof (cases ⟨$\exists sn_0$. f sn_0 = Suc n⟩)
          case True — Suc n is in the image of f

            from this **obtain** sn_0 **where** fsn:⟨f sn_0 = Suc n⟩ **by** blast
            with fn strict_mono_suc * **have** ⟨sn_0 = Suc n_0⟩
              using dilating_def dilating_fun_def **by** blast
            with 1 **have** ⟨tick_count sub c_2 sn_0 ≤ tick_count sub c_1 n_0⟩ **by** simp
            thus ?thesis **using** fn fsn tick_count_sub[OF *] **by** simp
          next
          case False — Suc n is not in the image of f

            hence ⟨¬hamlet ((Rep_run r) (Suc n) c_2)⟩
              using * **by** (simp add: dilating_def dilating_fun_def)
            hence ⟨tick_count r c_2 (Suc n) = tick_count r c_2 n⟩
              by (simp add: tick_count_suc)
            also have ⟨... = tick_count sub c_2 n_0⟩
              using fn tick_count_sub[OF *] **by** simp
            finally have ⟨tick_count r c_2 (Suc n) = tick_count sub c_2 n_0⟩ .
            moreover have ⟨tick_count sub c_2 n_0 ≤ tick_count sub c_2 (Suc n_0)⟩
              by (simp add: tick_count_suc)
            ultimately have
              ⟨tick_count r c_2 (Suc n) ≤ tick_count sub c_2 (Suc n_0)⟩ **by** simp
            moreover have
              ⟨tick_count sub c_2 (Suc n_0) ≤ tick_count sub c_1 n_0⟩ **using** 1 **by** simp
            ultimately have ⟨tick_count r c_2 (Suc n) ≤ tick_count sub c_1 n_0⟩ **by** simp
            thus ?thesis **using** tick_count_sub[OF *] fn **by** simp
        qed
      next
      case False — n is not in the image of f

        from greatest_prev_image[OF * this] **obtain** n_p **where**
          np_prop:⟨f n_p < n ∧ ($\forall$k. f n_p < k ∧ k ≤ n ⟶ ($\nexists k_0$. f k_0 = k))⟩ **by** blast
        from tick_count_latest[OF * this] **have**
          ⟨tick_count r c_1 n = tick_count r c_1 (f n_p)⟩ .
        hence a:⟨tick_count r c_1 n = tick_count sub c_1 n_p⟩
          using tick_count_sub[OF *] **by** simp
        have b: ⟨tick_count sub c_2 (Suc n_p) ≤ tick_count sub c_1 n_p⟩ **using** 1 **by** simp
        show ?thesis
        proof (cases ⟨$\exists sn_0$. f sn_0 = Suc n⟩)
          case True — Suc n is in the image of f

            from this **obtain** sn_0 **where** fsn:⟨f sn_0 = Suc n⟩ **by** blast

```
                    from next_non_stuttering[OF * np_prop this]  have sn_prop:⟨sn₀ = Suc nₚ⟩ .
                    with b have ⟨tick_count sub c₂ sn₀ ≤ tick_count sub c₁ nₚ⟩ by simp
                    thus ?thesis using tick_count_sub[OF *] fsn a by auto
                next
                  case False — Suc n is not in the image of f
                    hence ⟨¬hamlet ((Rep_run r) (Suc n) c₂)⟩
                      using * by (simp add: dilating_def dilating_fun_def)
                    hence ⟨tick_count r c₂ (Suc n) = tick_count r c₂ n⟩
                      by (simp add: tick_count_suc)
                    also have ⟨... = tick_count sub c₂ nₚ⟩ using np_prop tick_count_sub[OF *]
                      by (simp add: tick_count_latest[OF * np_prop])
                    finally have ⟨tick_count r c₂ (Suc n) = tick_count sub c₂ nₚ⟩ .
                    moreover have ⟨tick_count sub c₂ nₚ ≤ tick_count sub c₂ (Suc nₚ)⟩
                      by (simp add: tick_count_suc)
                    ultimately have
                      ⟨tick_count r c₂ (Suc n) ≤ tick_count sub c₂ (Suc nₚ)⟩ by simp
                    moreover have
                      ⟨tick_count sub c₂ (Suc nₚ) ≤ tick_count sub c₁ nₚ⟩ using 1 by simp
                    ultimately have ⟨tick_count r c₂ (Suc n) ≤ tick_count sub c₁ nₚ⟩ by simp
                    thus ?thesis using np_prop mono_tick_count  using a by linarith
                qed
              qed
          } thus ?thesis ..
        qed
        moreover from 1 have ⟨¬hamlet ((Rep_run r) 0 c₂)⟩
          using * empty_dilated_prefix ticks_sub by fastforce
        ultimately show ?thesis by (simp add: tick_count_is_fun strictly_precedes_alt_def2)
      qed
```

Time delayed relations are preserved in a dilated run.

```
theorem time_delayed_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦ a time-delayed by δτ on ms implies b ⟧_TESL⟩
    shows ⟨r ∈ ⟦ a time-delayed by δτ on ms implies b ⟧_TESL⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  from assms(2) have ⟨∀n. hamlet ((Rep_run sub) n a)
                          ⟶ (∀m ≥ n. first_time sub ms m (time ((Rep_run sub) n ms) + δτ)
                                ⟶ hamlet ((Rep_run sub) m b))⟩
    using TESL_interpretation_atomic.simps(5)[of ⟨a⟩ ⟨δτ⟩ ⟨ms⟩ ⟨b⟩] by simp
  hence **:⟨∀n₀. hamlet ((Rep_run r) (f n₀) a)
                  ⟶ (∀m₀ ≥ n₀. first_time r ms (f m₀) (time ((Rep_run r) (f n₀) ms) + δτ)
                              ⟶ hamlet ((Rep_run r) (f m₀) b)) ⟩
    using first_time_image[OF *] dilating_def * by fastforce
  hence ⟨∀n. hamlet ((Rep_run r) n a)
              ⟶ (∀m ≥ n. first_time r ms m (time ((Rep_run r) n ms) + δτ)
                          ⟶ hamlet ((Rep_run r) m b))⟩
  proof -
    { fix n assume assm:⟨hamlet ((Rep_run r) n a)⟩
      from ticks_image_sub[OF * assm] obtain n₀ where nfn0:⟨n = f n₀⟩ by blast
      with ** assm have ft0:
        ⟨(∀m₀ ≥ n₀. first_time r ms (f m₀) (time ((Rep_run r) (f n₀) ms) + δτ)
                  ⟶ hamlet ((Rep_run r) (f m₀) b))⟩ by blast
      have ⟨(∀m ≥ n. first_time r ms m (time ((Rep_run r) n ms) + δτ)
                    ⟶ hamlet ((Rep_run r) m b)) ⟩
      proof -
      { fix m assume hyp:⟨m ≥ n⟩
        have ⟨first_time r ms m (time (Rep_run r n ms) + δτ) ⟶ hamlet (Rep_run r m b)⟩
```

```
        proof (cases ⟨∃m₀. f m₀ = m⟩)
          case True
          from this obtain m₀ where ⟨m = f m₀⟩ by blast
          moreover have ⟨strict_mono f⟩ using * by (simp add: dilating_def dilating_fun_def)
          ultimately show ?thesis using ft0 hyp nfn0 by (simp add: strict_mono_less_eq)
        next
          case False thus ?thesis
          proof (cases ⟨m = 0⟩)
            case True
              hence ⟨m = f 0⟩ using * by (simp add: dilating_def dilating_fun_def)
              then show ?thesis using False by blast
          next
            case False
            hence ⟨∃pm. m = Suc pm⟩ by (simp add: not0_implies_Suc)
            from this obtain pm where mpm:⟨m = Suc pm⟩ by blast
            hence ⟨∄pm₀. f pm₀ = Suc pm⟩ using ⟨∄m₀. f m₀ = m⟩ by simp
            with *  have ⟨time (Rep_run r (Suc pm) ms) = time (Rep_run r pm ms)⟩
              using dilating_def dilating_fun_def by blast
            hence ⟨time (Rep_run r pm ms) = time (Rep_run r m ms)⟩ using mpm by simp
            moreover from mpm have ⟨pm < m⟩ by simp
            ultimately have ⟨∃m' < m. time (Rep_run r m' ms) = time (Rep_run r m ms)⟩ by blast
            hence ⟨¬(first_time r ms m (time (Rep_run r n ms) + δτ))⟩
              by (auto simp add: first_time_def)
            thus ?thesis by simp
          qed
        qed
      } thus ?thesis by simp
      qed
    } thus ?thesis by simp
  qed
  thus ?thesis by simp
qed
```

Time relations are preserved through dilation of a run.

```
lemma tagrel_sub':
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦ time-relation ⌊c₁,c₂⌋ ∈ R ⟧_TESL⟩
    shows ⟨R (time ((Rep_run r) n c₁), time ((Rep_run r) n c₂))⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  moreover from assms(2) TESL_interpretation_atomic.simps(2) have
    ⟨sub ∈ {r. ∀n. R (time ((Rep_run r) n c₁), time ((Rep_run r) n c₂))}⟩ by blast
  hence 1:⟨∀n. R (time ((Rep_run sub) n c₁), time ((Rep_run sub) n c₂))⟩ by simp
  show ?thesis
  proof (induction n)
    case 0
      from 1 have ⟨R (time ((Rep_run sub) 0 c₁), time ((Rep_run sub) 0 c₂))⟩ by simp
      moreover from * have ⟨f 0 = 0⟩ by (simp add: dilating_def dilating_fun_def)
      moreover from * have ⟨∀c. time ((Rep_run sub) 0 c) = time ((Rep_run r) (f 0) c)⟩
        by (simp add: dilating_def)
      ultimately show ?case by simp
  next
    case (Suc n)
    then show ?case
    proof (cases ⟨∄n₀. f n₀ = Suc n⟩)
      case True
      with * have ⟨∀c. time (Rep_run r (Suc n) c) = time (Rep_run r n c)⟩
        by (simp add: dilating_def dilating_fun_def)
```

```
      thus ?thesis using Suc.IH by simp
    next
      case False
      from this obtain n₀ where n₀prop:⟨f n₀ = Suc n⟩ by blast
      from 1 have ⟨R (time ((Rep_run sub) n₀ c₁), time ((Rep_run sub) n₀ c₂))⟩ by simp
      moreover from n₀prop * have ⟨time ((Rep_run sub) n₀ c₁) = time ((Rep_run r) (Suc n) c₁)⟩
        by (simp add: dilating_def)
      moreover from n₀prop * have ⟨time ((Rep_run sub) n₀ c₂) = time ((Rep_run r) (Suc n) c₂)⟩
        by (simp add: dilating_def)
      ultimately show ?thesis by simp
    qed
  qed
qed
```

```
corollary tagrel_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦ time-relation ⌊c₁,c₂⌋ ∈ R ⟧_{TESL}⟩
    shows ⟨r ∈ ⟦ time-relation ⌊c₁,c₂⌋ ∈ R ⟧_{TESL}⟩
using tagrel_sub'[OF assms] unfolding TESL_interpretation_atomic.simps(3) by simp
```

Time relations are also preserved by contraction

```
lemma tagrel_sub_inv:
  assumes ⟨sub ≪ r⟩
      and ⟨r ∈ ⟦ time-relation ⌊c₁, c₂⌋ ∈ R ⟧_{TESL}⟩
    shows ⟨sub ∈ ⟦ time-relation ⌊c₁, c₂⌋ ∈ R ⟧_{TESL}⟩
proof -
  from assms(1) is_subrun_def obtain f where df:⟨dilating f sub r⟩ by blast
  moreover from assms(2) TESL_interpretation_atomic.simps(2) have
    ⟨r ∈ {ϱ. ∀n. R (time ((Rep_run ϱ) n c₁), time ((Rep_run ϱ) n c₂))}⟩ by blast
  hence ⟨∀n. R (time ((Rep_run r) n c₁), time ((Rep_run r) n c₂))⟩ by simp
  hence ⟨∀n. (∃n₀. f n₀ = n) ⟶ R (time ((Rep_run r) n c₁), time ((Rep_run r) n c₂))⟩ by simp
  hence ⟨∀n₀. R (time ((Rep_run r) (f n₀) c₁), time ((Rep_run r) (f n₀) c₂))⟩ by blast
  moreover from dilating_def df have
    ⟨∀n c. time ((Rep_run sub) n c) = time ((Rep_run r) (f n) c)⟩ by blast
  ultimately have ⟨∀n₀. R (time ((Rep_run sub) n₀ c₁), time ((Rep_run sub) n₀ c₂))⟩ by auto
  thus ?thesis by simp
qed
```

Kill relations are preserved in a dilated run.

```
theorem kill_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦ c₁ kills c₂ ⟧_{TESL}⟩
    shows ⟨r ∈ ⟦ c₁ kills c₂ ⟧_{TESL}⟩
proof -
  from assms(1) is_subrun_def obtain f where *:⟨dilating f sub r⟩ by blast
  from assms(2) TESL_interpretation_atomic.simps(8) have
    ⟨∀n. hamlet (Rep_run sub n c₁) ⟶ (∀m≥n. ¬ hamlet (Rep_run sub m c₂))⟩ by simp
  hence 1:⟨∀n. hamlet (Rep_run r (f n) c₁) ⟶ (∀m≥n. ¬ hamlet (Rep_run r (f m) c₂))⟩
    using ticks_sub[OF *] by simp
  hence ⟨∀n. hamlet (Rep_run r (f n) c₁) ⟶ (∀m≥ (f n). ¬ hamlet (Rep_run r m c₂))⟩
  proof -
    { fix n assume ⟨hamlet (Rep_run r (f n) c₁)⟩
      with 1 have 2:⟨∀ m ≥ n. ¬ hamlet (Rep_run r (f m) c₂)⟩ by simp
      have ⟨∀ m≥ (f n). ¬ hamlet (Rep_run r m c₂)⟩
      proof -
        { fix m assume h:⟨m ≥ f n⟩
          have ⟨¬ hamlet (Rep_run r m c₂)⟩
          proof (cases ⟨∃m₀. f m₀ = m⟩)
```

```
                case True
                  from this obtain m₀ where fm0:⟨f m₀ = m⟩ by blast
                  hence ⟨m₀ ≥ n⟩
                    using * dilating_def dilating_fun_def h strict_mono_less_eq by fastforce
                  with 2 show ?thesis using fm0 by blast
              next
                case False
                  thus ?thesis  using ticks_image_sub'[OF *] by blast
            qed
          } thus ?thesis by simp
        qed
      } thus ?thesis by simp
    qed
    hence ⟨∀n. hamlet (Rep_run r n c₁) ⟶ (∀m ≥ n. ¬ hamlet (Rep_run r m c₂))⟩
      using ticks_imp_ticks_subk[OF *] by blast
    thus ?thesis using TESL_interpretation_atomic.simps(8) by blast
qed


lemmas atomic_sub_lemmas = sporadic_sub tagrel_sub implies_sub implies_not_sub
                           time_delayed_sub weakly_precedes_sub
                           strictly_precedes_sub kill_sub
```

We can now prove that all atomic specification formulae are preserved by the dilation of runs.

```
lemma atomic_sub:
  assumes ⟨sub ≪ r⟩
      and ⟨sub ∈ ⟦ φ ⟧_{TESL}⟩
    shows ⟨r ∈ ⟦ φ ⟧_{TESL}⟩
using assms(2) atomic_sub_lemmas[OF assms(1)] by (cases φ, simp_all)
```

Finally, any TESL specification is invariant by stuttering.

```
theorem TESL_stuttering_invariant:
  assumes ⟨sub ≪ r⟩
    shows ⟨sub ∈ ⟦⟦ S ⟧⟧_{TESL} ⟹ r ∈ ⟦⟦ S ⟧⟧_{TESL}⟩
proof (induction S)
  case Nil
    thus ?case by simp
next
  case (Cons a s)
    from Cons.prems have sa:⟨sub ∈ ⟦ a ⟧_{TESL}⟩ and sb:⟨sub ∈ ⟦⟦ s ⟧⟧_{TESL}⟩
      using TESL_interpretation_image by simp+
    from Cons.IH[OF sb] have ⟨r ∈ ⟦⟦ s ⟧⟧_{TESL}⟩ .
    moreover from atomic_sub[OF assms(1) sa] have ⟨r ∈ ⟦ a ⟧_{TESL}⟩ .
    ultimately show ?case using  TESL_interpretation_image by simp
qed


end
```

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