SCCharts: Sequentially Constructive Statecharts for Safety-Critical Applications

HW/SW-Synthesis for a Conservative Extension of Synchronous Statecharts

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Abstract

We present a new visual language, *SCCharts*, designed for specifying safety-critical reactive systems. SCCharts use a statechart notation and provide determinate concurrency based on a synchronous model of computation (MoC), without restrictions common to previous synchronous MoCs. Specifically, we lift earlier limitations on sequential accesses to shared variables, by leveraging the sequentially constructive MoC. The semantics and key features of SCCharts are defined by a very small set of elements, the *Core SCCharts*, consisting of state machines plus fork/join concurrency. We also present a compilation chain that allows efficient synthesis of software and hardware.

Categories and Subject Descriptors D.3.3 [*Language Constructs and Features*]: Concurrent programming structures; D.3.4 [*Processors*]: Compilers

Keywords Statecharts, synchronous languages, visual languages, determinacy, concurrency, hw/sw-synthesis, safety-critical systems

1. Introduction

Background. Statecharts, introduced by Harel in the late 1980s [14], have become a popular means for specifying the behavior of embedded, reactive systems. The visual syntax of statecharts is intuitively understandable for application experts from different domains who are not necessarily computer scientists. The statechart concepts of hierarchy and concurrency allow the expression of complex behavior in a much more compact fashion than standard, flat finite state machines. However, defining a suitable semantics for the statechart syntax is by no means trivial, as evinced by the multitude of different statechart interpretations. In the 1990s already, von der Beeck [30] identified a list of 19 different non-trivial semantical issues, and compared 24 different semantics proposals; these did not even include the "official" semantics of the original Harel statecharts (clarified later by Harel [15]) nor the many statechart variants developed since then, such as UML statecharts with its run-to-completion semantics. One of the semantical issues identified early on for statecharts is the question of *determinacy*, which is not surprising as statecharts include concurrency and hence are potentially subject to race conditions. Adopting Milner's distinction of determinacy and determinism [19], we consider a computation as *determinate* if the same sequence of inputs produces the same sequence of outputs, as opposed to *deterministic* computations, which in addition have identical internal behavior/scheduling. In many application areas, including the area of safety-critical applications that has motivated the work presented here, determinacy is a strict requirement. Given a sequence of input stimuli, a safety-critical reactive system must always produce the same sequence of outputs, even if the internal behavior involves concurrency. Many statechart variants do not fulfill this determinacy requirement; e. g., STATEMATE, the original statecharts tool, detected potential non-determinacy at run-time, but not at compile time.

One approach for achieving determinacy, successfully employed by the family of synchronous languages, is to abstract execution time away. This implies unique variable (or *signal*) values throughout an instantaneous reaction chain, or *tick*, which eliminates race conditions. This concept has also been applied to statechart-like visual languages, such as André's SyncCharts [2]. The synchronous model of computation (SMoC) is a sound approach that solves the determinacy issue. However, it is quite restrictive due to the "only one value per reaction" requirement. For example, the classical SMoC cannot directly express something like if $(x < 0)$ x = 0 for some shared variable x. This restriction may seem natural to hardware designers, who are used to the requirement of stable, unique voltage values within a clock cycle and the lack of built-in sequencing in combinational, parallel circuits. However, this limitation often causes bewilderment with programmers used to languages like C or Java, where such sequential variable accesses pose no problem and do not result in compile-time errors. This issue has motivated the *sequentially constructive* (SC) MoC proposed recently [33], which extends the classical synchronous MoC by allowing variables to be read and written in any order as long as sequentiality expressed in the program provides sufficient scheduling information to rule out race conditions.

Contributions and Outline. Concerning programming language design, we here present a new, visual modeling language for reac-

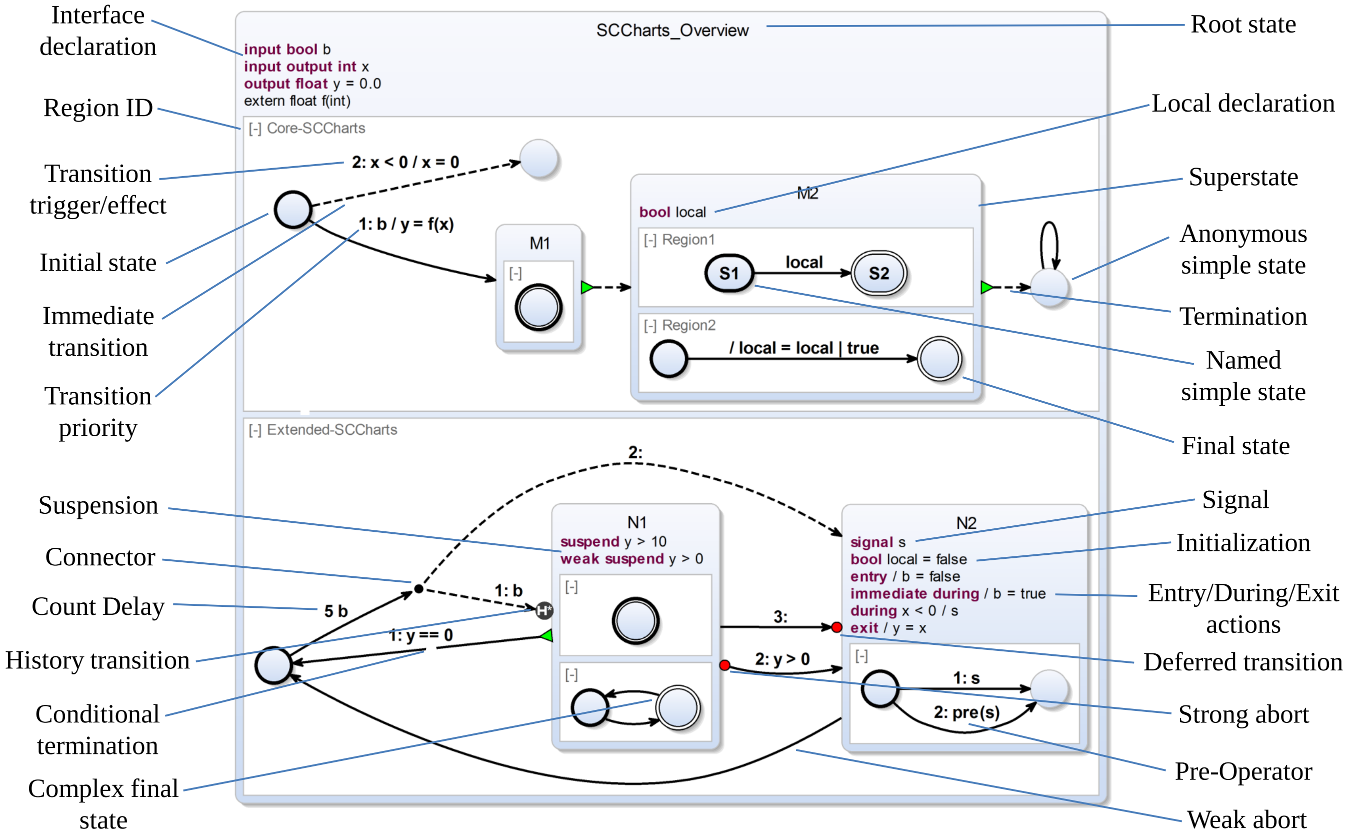


Figure 1. Syntax overview of SCCharts. The upper region contains Core SCCharts elements only, the lower region illustrates Extended SCCharts.

tive systems, called *Sequentially Constructive Statecharts*, or *SCCharts*. SCCharts have been designed with safety-critical applications in mind and aim for easy adaptation. The safety-critical focus is reflected not only in the determinate semantics, but also in the approach to defining the language; the basis of the language is a minimal set of constructs, termed *Core SCCharts*, which facilitate rigorous formal analysis and verification. Building on these core constructs, *Extended SCCharts* add expressiveness with a number of additional constructs (**Sec. 2**). Concerning implementation, we present a complete compilation chain from Extended SCCharts down to software (C) or hardware (VHDL). As a first, *high-level compilation phase*, we discuss a novel approach towards handling aborts and other complex reactive control flow patterns by model-to-model pre-processing transformations into the minimal set of language features provided by Core SCCharts and into an intermediate format called SCG. Each high-level transformation is of limited complexity and open to inspection by the modeler, unlike existing "monolithic" statecharts compilation approaches (**Sec. 3**). Then, building on the SCG, we present two alternative *low-level compilation approaches*. The first, *data-flow* compilation approach is a new, simpler alternative of the established Esterel circuit semantics [20]. Our approach exploits the minimal nature of Core SCCharts, but, unlike the original circuit semantics, also encompasses sequentiality. It is a very direct compilation approach that allows hardware synthesis as well as software synthesis, but is restricted to "acyclic" SCCharts (**Sec. 4**). The second, *priority-based* low-level compilation proposal for SCCharts introduces a new, leaner variant of Synchronous C [31], termed SCL$_P$. This second approach is more permissive in that it also allows control flow cycles, and we expect it to scale better than the data-flow approach, but it does not facilitate hardware synthesis as good as the data-flow approach (**Sec. 5**). We furthermore discuss experimental (**Sec. 6**) and related work (**Sec. 7**) before concluding (**Sec. 8**).

2. The SCCharts Language

Fig. 1 shows an overview of the SCCharts syntax. The upper part illustrates Core SCCharts, which contain the key ingredients of statecharts, namely concurrency and hierarchy. The lower region contains elements from Extended SCCharts.

2.1 Interface Declarations

An SCChart starts at the top with an *interface declaration* that can declare *variables* and *external functions*. Variables can be *inputs*, read from the environment, or *outputs*, written to the environment. Variables can also be *inputoutput* variables, which are both inputs and outputs; these are read from the environment, optionally modified, and written back to the environment. In the following, when we refer to inputs or to outputs, this generally includes inputoutputs as well. The environment initializes inputs at the beginning of the tick (*stimulus*), e. g., according to some sensor data. Outputs are used at the end of a tick (*response*), e. g., to feed some actuators. Output variables that are not also input variables are not initialized by the environment at each tick. During a tick, variables may be incrementally updated by the SCChart through internal computations not observable by the environment.

The interface declaration also allows the declaration of *local variables*, which are neither input nor output. An interface declaration may be attached to states other than the top-level state. This also allows the modularization of SCCharts, at lower levels, using a static macro referencing/expansion mechanism. In this case, the interface declaration serves for compile-time variable binding/renaming. Then the interaction of an SCChart with its environment via input/output variables must not be limited to the beginning and the end of a tick, but can happen arbitrarily, as governed by the SC scheduling rules described later.

Non-input variables are persistent across tick boundaries, even if their scope is left and re-entered, since they are statically allocated. However, they are per default uninitialized, like in C. This means that when a variable v is read and has not been written before, the read value is undefined. We therefore advise to statically (and conservatively) check for such possible uninitialized reads. One way to avoid uninitialized reads is to augment variable declarations with explicit *initializations*, provided by Extended SCCharts.

2.2 States and Transitions

The basic ingredients of SCCharts are *states* and *transitions* that go from a *source state* to a *target state*. When an SCChart is in a certain state, we also say that this state is *active*. Transitions may carry a *transition label*, with a priority p, a trigger t, and an action a, which are all optional, with the syntax "[p:] [t] [/ a]"[1]. The *trigger* is a side-effect-free boolean expression on local and global variables, and the *action* an assignment $x = e$ (or a sequence thereof) of arbitrary data type.

When a transition trigger becomes true and the source state is active, the transition is taken instantaneously, meaning that the source state is left and the target state is entered in the same tick. However, transition triggers are per default *delayed*, or *non-immediate*, meaning that they are disabled in the tick in which the source state just got entered. This convention helps to avoid instantaneous loops, which can potentially result in causality problems. One can override this by making a transition *immediate* (shown as dashed transition). Multiple transitions originating from the same source state are disambiguated with a unique *priority*; first the transition with priority 1 gets tested, if that is not taken, priority 2 gets tested, and so on.

If a state has an immediate outgoing transition that has no trigger condition, we refer to this transition as *default transition*, because it is always enabled, and we say that the state is *transient*, because it will always be left in the same tick as it is entered.

2.3 Hierarchy and Concurrency

A state can be either a *simple state* or it can be refined into a *superstate*, which encloses one or several concurrent *regions* (separated with dashed lines). Conceptually, a region corresponds to a thread. Each region must have exactly one *initial state* (thick border). When a region enters a *final state* (double border), then the region *terminates*.

A superstate may have an outgoing *termination* transition (green triangle), also called *unconditional termination* or, in SyncCharts, *normal termination*, which gets taken when all regions have reached a final state at the end of a tick. Termination transitions are always immediate. They may be labeled with an action, but—in Core SCCharts—do not have an explicit trigger condition. Hence a superstate should have at most one outgoing termination, as in case of multiple terminations only the one with highest priority can ever be taken. In Core SCCharts, superstates cannot be marked final; this is allowed in Extended SCCharts.

2.4 Termination

Region termination, final states and termination transitions may seem like straightforward concepts. However, their precise semantics and the choices we made in SCCharts deserve some further discussion, as different interpretations have emerged in the past.

Region termination here means that a region "does not do anything anymore." Thus in Core SCCharts final states have no outgoing transitions, no refinements, no interface declaration, and no During/Exit actions (introduced in Extended SCCharts) associated with them. Thus final states here have a fairly strong interpretation, i. e., they are quite restricted. This allows a very straightforward implementation, as one can then re-use the information on which regions are active, which is also needed for scheduling purposes. An alternative semantics for final states would be to just say that the surrounding superstate terminates when all its regions have reached a final state. This interpration of final states would be weaker in the sense that it would still allow a region to leave a final state again, and a final state might still perform actions or execute refinements. For Core SCCharts, this choice was rejected, due to the aforementioned efficiency reasons. However, the weaker, more permissive interpretation is included in Extended SCCharts.

Conversely, a region effectively terminates whenever a region has no During action and reaches a state with no outgoing transitions, no refinements, and no associated actions. However, for clarity, we here require that the state must be explicitly marked as final if we want to enable termination of the surrounding superstate. Thus "reaching a final state" is a stronger condition than "region termination," and we link termination of the superstate to all of its regions reaching final states, not to region termination. This implies that a termination transition of a superstate can never be taken if any region enclosed by that superstate does not contain any final state. We therefore suggest to require that a region must contain a final state if its enclosing superstate has an outgoing termination transition. However, unlike suggested for SyncCharts [2], we argue that one should permit final states even if there is no enclosing termination, to clearly indicate termination of a region.

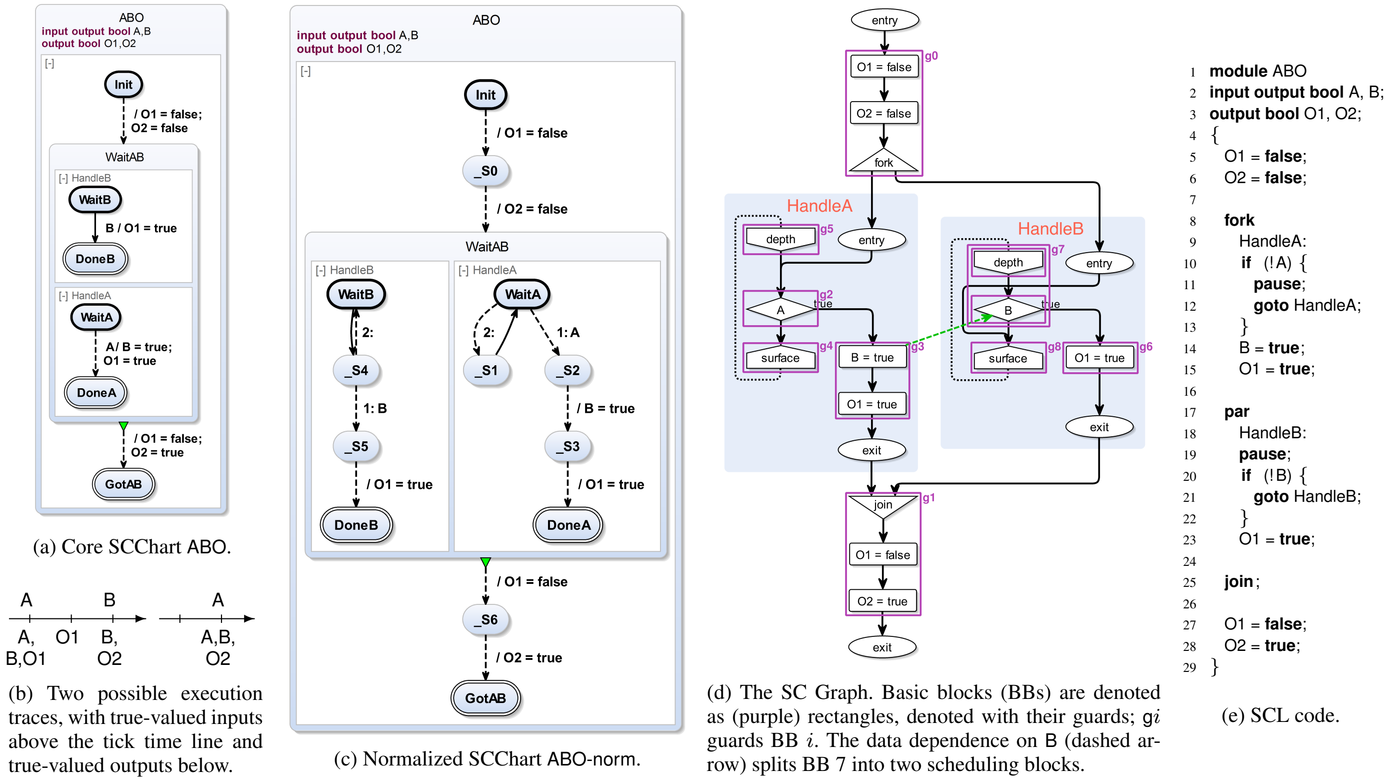
Note that even when all regions of a superstate have reached a final state, and hence have terminated, the enclosing superstate is still considered active until it is left. Thus During actions for the superstate keep getting executed until the state is left.

2.5 The ABO Example

The ABO example shown in Fig. 2a illustrates the concepts of Core SCCharts: ticks, concurrency (with forking and joining), determinate scheduling of shared variable accesses, and sequential overwriting of variables. The interface declaration of ABO states that A and B are Boolean inputs as well as outputs. O1 and O2 are Boolean outputs. Two possible execution traces are shown in Fig. 2b. The first trace begins with A set to true by the environment in the initial tick. This triggers the transition to DoneA and sets both B and O1 to true. As this is the initial tick, the delayed transition from WaitB to DoneB does not get triggered by the B. In the next tick, all inputs are false, no transitions are triggered, and O1 stays at true. In the third and last tick, B triggers the transition to DoneB, which sets O1 to true, but sequentially afterwards, O1 is set to false again as part of the transition to GotAB, which is triggered by the termination of regions HandleA and HandleB. Hence, at the end of this tick, only B and O2 will be true.

The second trace illustrates how A in the second tick triggers the transitions to DoneA as well as to DoneB, hence emission of B and O2 and the termination of the automaton. Note, however, that this behavior is only achieved if the action of the transition to DoneA that writes B is performed *before* the trigger of the transition to DoneB reads B. In other words, there is a race condition on

[1] A syntactic complication, solved by different statechart dialects/tools in different ways, is that the "/" may also indicate division. We here suggest to disambiguate the two interpretations, where necessary, by putting divisions into parentheses. I. e., the leftmost, not parenthesized "/" is interpreted as a trigger/action separator, others are interpreted as division operators.



```
module ABO
input output bool A, B;
output bool O1, O2;
{
  O1 = false;
  O2 = false;

  fork
    HandleA:
      if (!A) {
        pause;
        goto HandleA;
      }
      B = true;
      O1 = true;

  par
    HandleB:
      pause;
      if (!B) {
        goto HandleB;
      }
      O1 = true;

  join;

  O1 = false;
  O2 = true;
}
```

(a) Core SCChart ABO.

(b) Two possible execution traces, with true-valued inputs above the tick time line and true-valued outputs below.

(c) Normalized SCChart ABO-norm.

(d) The SC Graph. Basic blocks (BBs) are denoted as (purple) rectangles, denoted with their guards; gi guards BB i. The data dependence on B (dashed arrow) splits BB 7 into two scheduling blocks.

(e) SCL code.

Figure 2. The ABO example, illustrating the Core SCChart features.

two concurrent accesses to B that could potentially result in non-determinacy, unless we take further measures (see Sec. 2.7).

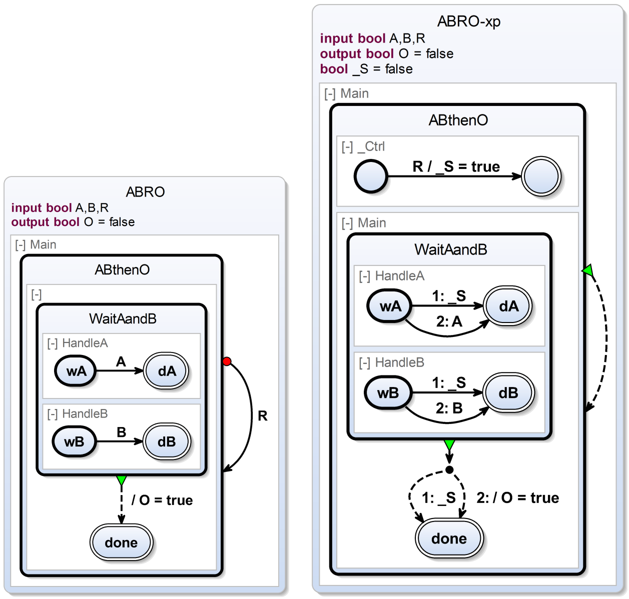
2.6 Extended SCCharts

Extended SCCharts are quite rich and include, for example, all of the language features proposed for SyncCharts [2]. Not all extensions may be of equal use for all applications, and a tool smith might well decide to not support all features in an SCChart modeling tool. E. g., (valued) signals, the pre operator, suspension, and history could all be omitted without affecting the other elements of Extended SCCharts and their transformations.

A report describes Extended SCCharts in full detail [32]. For space considerations, we here merely provide one example of one of the more important extensions, namely aborts. The ABRO SCChart (Fig. 3a), the "hello world" of synchronous programming, compactly illustrates concurrency and preemption. The reset signal R triggers a *strong abort* of the superstate ABthenO, which means that if R is present, ABthenO is instantaneously re-started. The exact semantics of ABRO is expressed by the equivalent ABRO-xp (Fig. 3b), which only uses Core SCCharts features. In ABthenO, a new region _Ctrl sets an internal "strong abort flag" _S in case the abort trigger R becomes true. This flag then prompts a termination of ABthenO, followed by a self transition.

2.7 Sequential Constructiveness

The main goal of the sequentially constructive (SC) MoC is to rule out any race conditions that might induce non-determinacy, without being unnecessarily restrictive. The idea is to enforce a certain protocol on ordering variable accesses, namely the *initialize-update-read (iur) protocol* – but to do so only for variable accesses that are



(a) Original ABRO

(b) After expansion: ABRO-xp

Figure 3. ABRO, illustrating the transformation of a strong abort (triggered by R) into an equivalent SCChart without strong abort.

up to the discretion of a scheduler. I. e., we enforce the iur protocol *only* for concurrent accesses, and *not* for sequential accesses.

DEFINITION 1 (Combination functions). *A function $f(x, y)$ is a* combination function *on x if, for all x, y_1, y_2, $f(f(x, y_1), y_2) = f(f(x, y_2), y_1)$.*

One may construct arbitrarily complicated assignments from which a compiler might try to extract some combination function. However, to facilitate the compiler's job and to make increments also obvious to the human reader of a program, we recommend to use, whenever possible, *augmented assignment* patterns (familiar from C/Java) of the form x f= e, with f being +, *, etc., and e being an expression without side effects and not involving x (e. g., x += 1).

DEFINITION 2 (Initializations, Updates, Reads). *An assignment $x = f(x, e)$ where f is a combination function f and e an expression not referencing x is an* update *for x, of type f. Other assignments $x = e$ are* initializations *of x. A trigger expression e or an assignment $x = e$ is a* read *of every variable y referenced by e, unless x and y are the same variable and the assignment is an update.*

Note that an update $x = f(x, e)$ does not count as a read of x although $f(x, e)$ references x. A transition (trigger and action) can contain several read and write accesses.

We also refer to initializations as *absolute writes* and to updates as *relative writes*. The motivation for distinguishing absolute and relative writes is two-fold. First, the concept of relative writes allows to merge concurrent writes, if they are relative and of the same type, in a determinate fashion. This has been used in the past e. g. for parallelizing computations [25], or also in Esterel, with the *combine operators*, which are a slightly restricted form of our combination functions (Esterel requires commutativity, which we don't—consider, e. g., subtraction). Second, we allow both an initialization and updates to the same shared variable, while maintaining determinacy by ordering the initialization before the update. This allows to emulate Esterel-style signals fairly easily. In a nutshell, we encode signals with booleans, with signal absence encoded by false and signal presence by true; a signal s is initialized to false, and updated to true with s = s or true. The iur protocol assures that signals are initialized before they are emitted (set to true), and that signals are emitted before they are tested for presence. Having explicit access to signal initialization allows, for example, to handle so-called *reincarnated signals* very efficiently, as detailed elsewhere [1].

DEFINITION 3 (Static concurrency). *A pair of variable accesses is* (statically) concurrent*, if they belong to concurrent regions of some superstate S (including arbitrary superstate nesting).*

DEFINITION 4 (iur scheduling relations). *Given two statically concurrent accesses n_1, n_2 on some variable x, we define relations*

- *$n_1 \leftrightarrow_{ww} n_2$ iff n_1 and n_2 both initialize x or both perform updates of different type. We call this a* ww conflict*.*
- *$n_1 \rightarrow_{ir} n_2$ iff n_1 initializes x and n_2 reads x.*
- *$n_1 \rightarrow_{iu} n_2$ iff n_1 initializes x and n_2 updates x.*
- *$n_1 \rightarrow_{ur} n_2$ iff n_1 updates x and n_2 reads x.*
- *$\rightarrow_{iur} =_{\mathrm{def}} \leftrightarrow_{ww} \cup \rightarrow_{ir} \cup \rightarrow_{iu} \cup \rightarrow_{ur}$. This summarizes the constraints induced by concurrent accesses.*

We also refer to these relations as *iur* (*ww*, *ir*, *iu*, *ur*) *order*. This order refines the standard write-before-read requirement of synchronous languages, with the key difference that we here restrict our attention to *concurrent* accesses. Note that these orders must not be acyclic (antisymmetric); for example, due to the symmetry of the ww order, a ww conflict induces an iur cycle.

DEFINITION 5 (Sequential order, instantaneous order). *Given accesses $n_{1,2}$, we define*

- *$n_1 \rightarrow_{seq} n_2$ iff there is an instantaneous sequential control flow path n_1 to n_2 (*sequential order*).*
- *$\rightarrow_{ins} =_{\mathrm{def}} \rightarrow_{seq} \cup \rightarrow_{iur}$ (*instantaneous order*).*

The sequential order becomes apparent in the SCG (Sec. 3.3). For example, it is $n_1 \rightarrow_{seq} n_2$ for accesses $n_{1,2}$ if 1) n_1 is in the trigger and n_2 is in the action of some transition label, or 2) if $n_{1,2}$ belong to two sequentially ordered assignments within one action, or 3) if there is a state S where n_1 is part of a transition that enters S and n_2 is part of a transition with immediate trigger that leaves S. Note that in the presence of immediate self-loops on superstates, accesses may be sequential as well as concurrent to each other.

We also assume that (i) within an assignment, all read accesses are executed before the write, and (ii) each assignment is executed atomically with respect to variable accesses from concurrent regions.

The $\rightarrow_{ins}$ order is a conservative approximation of all scheduling constraints within a tick, which leads to the following conservative approximation of sequential constructiveness.

DEFINITION 6 (Acyclic Sequential Constructiveness (ASC)). *An SCChart is* acyclic sequentially constructive (ASC) *if its $\rightarrow_{ins}$ order is acyclic.*

THEOREM 7. *An ASC program scheduled according to $\rightarrow_{ins}$ produces determinate input/output behavior.*

This can be seen by inspecting the definitions of sequentiality, concurrency and of the iur scheduling relations. For a formal proof see elsewhere [33].

In ABO, only B has concurrent write/read accesses, in the concurrent regions HandleA and HandleB. Clearly, ABO is ASC. The iur protocol requires the write in HandleA to precede the concurrent read in HandleB. This can be achieved by scheduling HandleA before HandleB, and once this is assured, all executions of ABO will produce determinate results.

A distinguishing feature of the SC MOC is that it allows arbitrary sequential variable accesses to shared variables within a tick. In ABO, O1 can be first assigned to true and then to false within the same tick. This is a significant extension of the classical synchronous MoC, which would reject ABO due to the multiple writes to O1 within a tick, and thus would not accept ABO as a valid SyncChart.

2.8 Sequential Constructiveness beyond ASC

Sec. 2.7 introduced (acyclic) SC in a fairly conservative fashion, based solely on structural, static analysis. We recommend this as a "base line," meaning that any SCChart compiler should accept models that are ASC as defined above, and that models should be ASC to ensure portability. However, the SC MoC allows to relax this in several ways without losing determinacy:

1. The $\rightarrow_{iur}$ relation can be reduced to a subset of what results from Def. 4. For example, we can drop $n_1 \rightarrow_{iur} n_2$ if (i) $n_{1,2}$ are *confluent* [33], or (ii) $n_{1,2}$ cannot be *run-time concurrent*, meaning that their activations are always in separate ticks, or in the same tick but in different activations of their common superstate S (due to an instantaneous self-loop on S) and thus sequentially ordered.
2. We can permit $\rightarrow_{ins}$ cycles that solely contain $\rightarrow_{seq}$ edges. Such cycles due to purely sequential control flow do not open any room for scheduler-induced non-determinacy. We refer to such programs (SCCharts) that do not contain any cycles with $\rightarrow_{iur}$ edges as *iur acyclic* programs.

3. Generalizing 2), an $\rightarrow_{ins}$ cycle is problematic only if all its $\rightarrow_{iur}$ edges involve run-time concurrent accesses. This is the case only if for none of its $n_1 \rightarrow_{iur} n_2$ edges the cycle leaves and re-enters a superstate enclosing n_1 and n_2.
4. Similarly, we can replace $\rightarrow_{seq}$ by a weaker $\rightarrow_{df}$ (*data-flow*) order that only orders non-confluent accesses. This is akin to replacing sequential control flow edges by sequential data flow edges, as in a Program Dependence Graph (PDG) [10]. With $\rightarrow_{idf} =_{\text{def}} \rightarrow_{df} \cup \rightarrow_{iur}$ we refer to programs (SCCharts) that do not contain any $\rightarrow_{idf}$ cycles as *data-flow acyclic* programs.
5. Static cycles might be "false" in the sense that it might be possible to respect $\rightarrow_{ins}$ at run-time, due to mutual run-time exclusiveness of parts of the cycle. This could be handled with *dynamic* scheduling, or by conversion into an equivalent, acyclic program [17, 26].

2.9 SCCharts Pragmatics

The SCCharts language has been designed with *modeling pragmatics* in mind [11], i. e., modelers should be able to work productively with complex SCCharts. Specifically, the visual syntax is defined such that it lends itself to fully automatic layout. Automatic layout facilitates a separation of *model* and *view*, which not only frees the designer from the burden of drawing and modifying diagrams manually, but also permits customized, filtered views. Customized views highlight certain model aspects and omit others, with the user/modeling tool acting as *controller* [22]. This "MVC pattern" is well-established in SW engineering, and it is just as useful for visual programming. However, as of today, few modeling languages and tools harness this potential. For example, one might hide transition labels to focus on state relations, or during simulation, one may choose to show the contents of superstates only when they are currently active. This guides the modeler and helps to reconcile model complexity with screen/paper real estate limitations.

Compared to SyncCharts, we chose to express transition priorities not in separate labels, which are difficult to place automatically without overlapping with transitions, but instead made priorities part of the transition labels. Also, we show immediate transitions as dashed lines, rather than hash-prefixes of the transition triggers, to reduce clutter and to facilitate the visual detection of possible instantaneous loops.

In addition to the visual SCCharts syntax presented here, we also developed an SCCharts Textual syntax (SCT), not further detailed here. In our SCCharts modeling prototype, one can create a leading, detailed model description in SCT, while a graphical SCChart with filters set by the modeler is continuously synchronized. This combines advantages of textual entry (speed, ease of revision management, etc.) and graphical view (ease of overview, highlighting of state patterns).

3. High-Level Compilation

SCCharts can be synthesized into hardware and software, and the best compilation approach depends on the characteristics of the execution platform and of the models to be compiled. As SCCharts is a new language, we are still at the beginning of exploring these trade-offs and optimal synthesis strategies. However, we can report on a compilation chain that we have implemented as part of an open-source modeling environment (see Sec. 6). The compilation begins with a *high-level compilation phase*, which consists of the following steps:

1. Expand Extended SCCharts features, resulting in a Core SCChart (Sec. 3.1).
2. Reduce transition complexity, resulting in a normalized Core SCChart (Sec. 3.2).

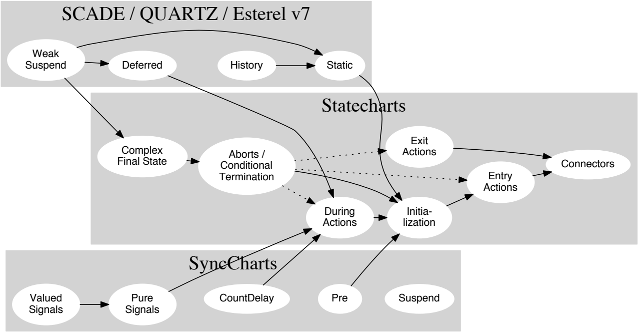


Figure 4. The Extended SCCharts features and their transformation interdependencies.

3. Map into an *SC Graph* (SCG), annotated with scheduling constraints due to concurrent shared variable accesses (Sec. 3.3).

3.1 Step 1: Expand Extended SCCharts

Extended SCCharts provide a set F of *extended features*, listed in Fig. 4, grouped according to their origins. Each feature $f \in F$ is defined in terms of a *transformation rule* T_f that expands an SCChart C that uses f into another, semantically equivalent SCChart C' that does not use f. More precisely, T_f produces an SCChart not containing f but possibly containing features in $\mathit{Prod}_f \subseteq F$. Also, T_f can preserve a certain set of features $\mathit{Handle}_f \subseteq F$. Thus, we must perform the transformations in a certain order, indicated in Fig. 4. Specifically, for $f, g \in F$, we must perform T_f before T_g if (i) $g \in \mathit{Prod}_f$ (solid edges), or (ii) $f \notin \mathit{Handle}_g$ (dotted edges). As can be easily seen, the dependencies form a partial order, i. e., there are no cycles. Thus Extended SCCharts can be compiled into equivalent Core SCCharts in a single pass.

The transformation rules are not only used to *implement* model-to-model (M2M) transformations, but also serve to unambiguously *define* the semantics of the extensions. Each such transformation is of limited complexity, and the results can be inspected by the modeler, or also a certification agency. This is something we see as a main asset of SCCharts for the use of safety-critical systems.

Considering again the aborts extension (Sec. 2.6), the default transformation approach for aborts follows the "write-things-once" (WTO) principle, as illustrated for ABRO in Fig. 3. E. g., the original trigger R appears only once in the transformed model. This transformation adds a constant model increase per original (super-)state and per abort transformation, which makes it a useful default strategy that scales well. For all Extended SCCharts properties, we provide default transformation rules that follow the WTO principle. Thus each extended feature can be transformed away in time linear in model size, and the size of the fully expanded SCChart is linear in the original model size.

As an alternative transformation approach for aborts, one could also replace _S directly by R. This would not require an explicit _Ctrl-thread anymore, which would result in a more compact ABRO-xp. However, this transformation would not be WTO anymore, and in case of multiple, possibly complex trigger conditions, this trigger propagation might lead to a larger model increase than the default transformation.

3.2 Step 2: Normalize SCCharts

To facilitate Step 3, the mapping to the SCG, we *normalize* Core SCCharts such that states have only certain "primitive" outgoing transition patterns as shown in Fig. 5. A *thread* is a set of states connected through transitions with one initial state and an arbitrary

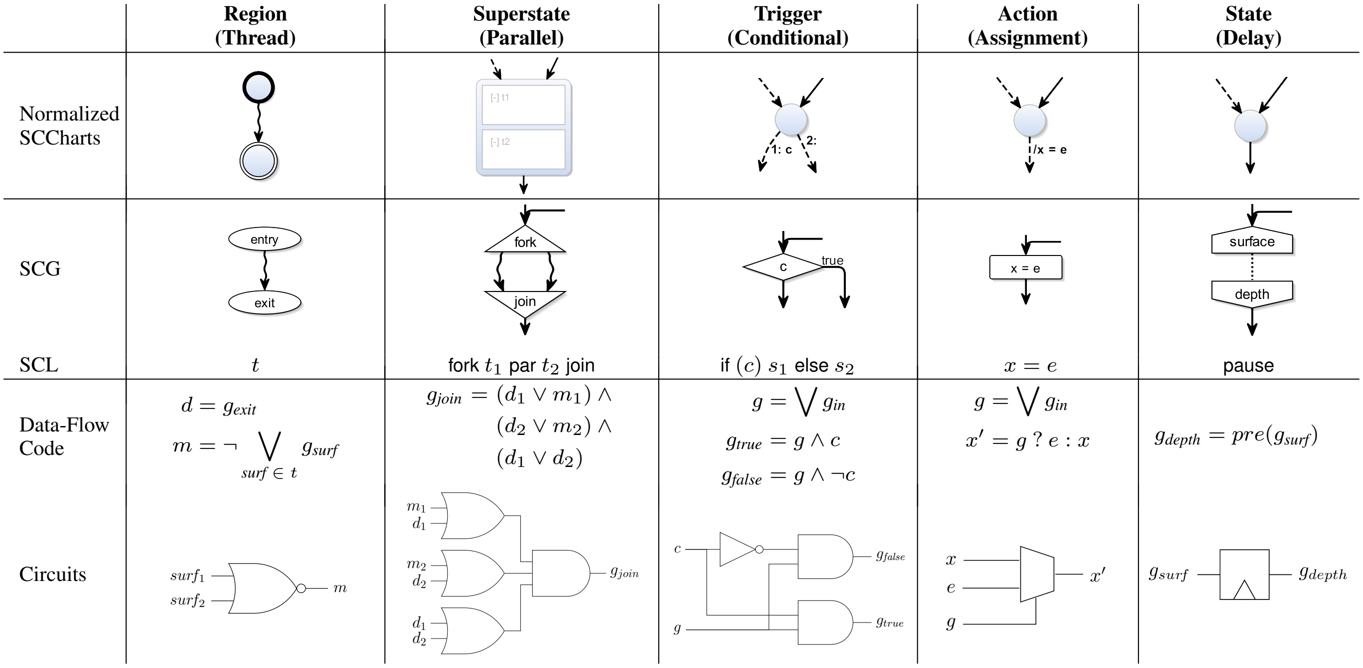
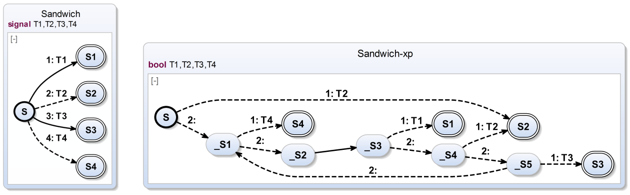


Figure 5. The "synthesis matrix" for SCCharts. The upper part shows the high-level synthesis from normalized SCCharts to the SCG, the lower part shows the data-flow approach for low-level synthesis to software or hardware.



(a) Before (b) After splitting triggers

Figure 6. The normalization of Sandwich requires duplication of an immediate trigger (T2), because there is a delayed trigger of lower priority (T3).

number of final states. A *parallel* is a superstate that contains one or more threads. A *conditional* is a state with two outgoing immediate transitions, one of which has a trigger. An *assignment* is a state with one outgoing immediate transition that has one action. A *delay* is a state with one outgoing delayed transition, without any trigger or action.

If a superstate S does not have an outgoing termination transition, normalization adds a normal termination transition from S to a new, non-final state T. This ensures that join nodes in the SCG have a defined control flow successor. For similar reasons, if a non-final state S does not have any outgoing transitions, we add a delayed self transition. This is equivalent to a halt statement in Esterel.

After these initial steps, normalization transforms states with arbitrary outgoing transition patterns as follows.

1. *Split actions.* For each transition T from some state S_1 to another state S_2, where T has an action A, and T has a trigger or is delayed: remove A from T's transition label, create a new target state $\_S$ for T, and create an immediate transition from $\_S$ to S_2 with action A. If T contains multiple actions, create a sequence of new transitions/states.
2. *Split triggers.* For each state S whose outgoing transitions are not yet in primitive form: create a sequence of conditionals that check the immediate triggers (*surface check*), followed by a delay, followed by another sequence of conditionals that check all triggers (*depth check*) before looping back to the delay.[2] The depth check can reuse triggers from the surface check by looping back not to the delay, but to the first trigger of the surface check for which there exists no delayed trigger with lower priority.

The result of normalizing ABO is shown in Fig. 2c. In ABO, as in most cases, we can construct control flow such that no trigger duplication is necessary when doing the normalization. However, there are counter examples, such as Sandwich (Fig. 6), where the depth check can loop back to (and thus reuse) T4, but not T2. The check of T2 must be duplicated because there is a delayed trigger of lower priority (T3). Thus there must be a surface check (on the path from S to _S2) of T2 that, if not taken, transfers control directly to a test of T4, and a depth check of T2 (on the path from _S2 back to itself) that subsequently tests T3.

3.3 Step 3: Map to SC Graph

Fig. 5 shows the mapping from normalized SCChart components to the SCG. A thread has one *entry node*, corresponding to the initial state, and one *exit node*, which corresponds to all final states of the thread. If a thread has no final states, the exit node is not reachable. A delay consists of *surface* and *depth* nodes that are connected through a *tick edge* (dotted). Other edges of the SCG are *sequential edges* (solid) that correspond to ordinary control flow (see Def. 5). As part of Step 3, the SCG is also annotated with *dependency edges* (dashed, see Fig. 2d), which indicate scheduling constraints

[2] In synchronous programming, the *surface* of a (possibly compound) statement refers to its behavior in the first tick of its execution, and the *depth* refers to its behavior in subsequent ticks.

	Data-Flow	Priority
Accepts all ASC SCCharts	+	+
Accepts all data-flow acyclic SCCharts	+	−
Accepts all iur acyclic SCCharts	−	+
Can synthesize hardware	+	−
Can synthesize software	+	+
Size scales well (linear in size of SCChart)	+	+
Speed scales well (execute only "active" parts)	−	+
Instruction-cache friendly (good locality)	+	−
Pipeline friendly (little/no branching)	+	−
WCRT predictable (simple control flow)	+	+/−
Low execution time jitter (simple/fixed flow)	+	−

Figure 7. Comparison of data-flow vs. priority low-level compilation approaches. The lower part only applies to software. WCRT, the Worst Case Reaction Time, is the maximal execution time per tick.

according to the iur protocol due to shared variable accesses (see Def. 4).

The SCG also has a textual representation, the SC Language (SCL). See Fig. 5 for the abstract SCL syntax and its correspondence to SCG elements. In addition, SCL has a goto statement that jumps to a label l to accommodate the free control flow permitted by state transitions.

4. Data-Flow Low-Level Compilation

Once we have mapped an SCChart to its SCG, there are different options for downstream synthesis. An overview comparison is given in Fig. 7. The *data-flow approach* is suitable if the SCG (including dependency edges, but excluding tick edges) is data-flow acyclic (see Sec. 2.8). The basic idea is to generate a netlist, which can then be realized in hardware, or can be simulated in software. This approach, including the requirement to have an acyclic flow graph, is already well established for compiling SyncCharts or Esterel [20]. We differ from the established circuit translation rules for Esterel in two ways: 1) we have simpler translation rules, mainly because aborts (and suspensions) are already transformed away during high-level synthesis, and 2) the SC MoC permits sequential assignments.

See again Fig. 5 for the mapping from SCG elements to data-flow code and circuits. As we synthesize a netlist where all components are always active, we encode control flow with *guards*. However, instead of creating a guard for every node, we group nodes together into *basic blocks* that consist of nodes with a common control flow entrance and exit node. A guard g is true iff control enters g's basic block in the current tick. For example, the guard for a conditional or an assignment is true iff any of the guards g_{in} of the predecessor nodes (basic blocks) is true. An interesting guard is g_{join}, which indicates whether a set of threads terminates in the current tick. To calculate g_{join}, each thread computes a flag d ("done"), which is true when a thread is done, i. e., the guard of its exit node is true, and a flag m ("empty"), which is true when it has no active delay, i. e., the guards of its surface nodes are all false. For a delay, the guard g_{depth} of the depth node is the registered guard g_{surf} of the surface node.

To permit sequential assignments, we split multiple instances (assignments) of variables apart, akin to SSA [3]. Thus an assignment $x = e$ creates a new instance (wire) x'. The multiplexer that forwards either e or x to x' corresponds to SSA's Φ-nodes. The ordering of the instances must obey the control/dependency ordering induced by the SCG and the iur protocol.

If such an order is not possible, due to a control/dependency cycle, we must **reject** the program and cannot proceed further. As in other hardware compilation approaches (including compilation of synchronous languages), we cannot synthesize loops directly; these would require preprocessing, such as loop unrolling.

```
module ABO−seq
input output bool A, B;
output bool O1, O2;
bool GO, g0, g1, m2, m6, g2,
  g3, g4, g5, g6, g7, g8;
bool g4_pre, g8_pre;
{
  g0 = GO;
  if g0 {
    O1 = false;
    O2 = false; };
  g5 = g4_pre;
  g7 = g8_pre;
  g2 = g0 || g5;
  g3 = g2 && A;
  if g3 {
    B = true;
    O1 = true; };
  g4 = g2 && ! A;
  g6 = g7 && B;
  if g6 {
    O1 = true; };
  g8 = g0 || (g7 && ! B);
  m2 = ! g4;
  m6 = ! g8;
  g1 = (g3 || m2) &&
     (g6 || m6) && (g3 || g6);
  if g1 {
    O1 = false;
    O2 = true; };
  g4_pre = g4;
  g8_pre = g8;
}
```

(a) SCL code, permitting multiple assignments per variable.

```
−− Main logic
g0 <= GO;
O1 <= false WHEN g0 ELSE O1_pre;
O2 <= false WHEN g0 ELSE O2_pre;
g5 <= g4_pre;
g7 <= g8_pre;
g2 <= g0 or g5;
g3 <= g2 and A_in;
B <= true WHEN g3 ELSE B_in;
O1_2 <= true WHEN g3 ELSE O1;
g4 <= g2 and not A_in;
g6 <= g7 and B;
O1_3 <= true WHEN g6 ELSE O1_2;
g8 <= g0 or (g7 and not B);
m2 <= not (g4);
m6 <= not (g8);
g1 <= (g3 or m2) and
         (g6 or m6) and
         (g3 or g6);
O1_4 <= false WHEN g1 ELSE O1_3;
O2_2 <= true WHEN g1 ELSE O2;

−− Assign outputs
A_out <= A_in;
B_out <= B;
O1 <= O1_4;
O2 <= O2_2;
```

(b) VHDL code (behavioral part), with single assignments per variable/wire. Variable name suffixes "_in/_out" denote inputs/outputs, "x_pre" indicates registered value of x, and "x_i" denotes instance i of x.

Figure 8. Illustration of the data-flow low level synthesis approach with ABO.

Recall that non-input variables are persistent, and that we do not make any guarantees about uninitialized variables. Thus, if a non-input variable x is possibly read in a tick before it is written, it must be initialized from a register that stores the last value of x from the previous tick, or, if this is the initial tick for entering the scope of x, some arbitrary constant.

For hardware synthesis, the resulting netlist requires no further considerations. For software synthesis, we must ensure that the data-flow equations are computed in an order compliant with the SCG control/dependency edges. For that purpose, we subdivide basic blocks at each incoming or outgoing dependency edge into *scheduling blocks* that can be scheduled atomically.

For ABO, Fig. 8a shows the SCL code after sequentialization and guard introduction. This still assumes persistent variables (outputs and pause registers) and allows multiple variable assignments, as would be suitable for software synthesis. This SCL code could be mapped directly to a *tick function* in C, with state externalized into the surface guards (g4_pre/g6_pre). A tick function computes a single reaction and is typically embedded in some while loop that iterates in regular intervals. Fig. 8b shows the corresponding VHDL code, after SSA-transformation and explicit registering.

From the initial SCChart to the VHDL (or C), all transformation steps are model-to-model transformations, where we successively replace complex constructs with equivalent, simpler constructs, but stay on the same semantical foundation; the SCG/SCL/C/VHDL artefacts are just different graphical/textual serializations.

```
// Boolean type
typedef int bool;
#define false 0
#define true  1

// Enable/disable threads with prioID p
#define _u2b(u)             (1 << u)
#define _enable(p)          _enabled |= _u2b(p);  \
                            active |= _u2b(p)
#define _isEnabled(p)       ((_enabled & _u2b(p)) != 0)
#define _disable(p)         _enabled &= ˜_u2b(p)

// Set current thread continuation
#define _setPC(p, label)  _pc[p] = &&label

// Pause, resume at <label>
#define _pause(label)       _setPC(_cid, label); \
                            goto _L_PAUSE

// Pause, resume at pause
#define _concat_helper(a, b)   a ## b
#define _concat(a, b)       _concat_helper(a, b)
#define _label_             _concat(_L, __LINE__)
#define pause               _pause(_label_); _label_ :

// Fork/join sibling thread with prioID p
#define fork1(label, p)   _setPC(p, label); _enable(p);
#define join1(p)            _label_ : if (_isEnabled(p)) \
                            { _pause(_label_); }

// Terminate thread at ”par”
#define par                 goto _L_TERM;
```

(a) Selected SCL$_P$ macros. The address of label is obtained with &&label. The concatenation operator ## prevents macro expansion of its arguments, hence we need _concat_helper. __LINE__ expands to the current line number.

```
int tick ()
{
  tickstart(2);
  O1 = false;
  O2 = false;

  fork1(HandleB, 1) {
    HandleA:
    if (!A) {
      pause;
      goto HandleA;
    }
    B = true;
    O1 = true;

  } par {

    HandleB:
    pause;
    if (!B) {
      goto HandleB;
    }
    O1 = true;
  } join1(2);

  O1 = false;
  O2 = true;
  tickreturn;
}
```

(b) ABO SCL$_P$ tick function

```
int tick ()
{
  if ( _notInitial ) { active = enabled; goto _L_DISPATCH; } else {
          _pc[0] = &&_L_TICKEND; enabled = (1 << 0); active =
          enabled; _cid = 2; ; enabled |= (1 << _cid); active |= (1
          << _cid); _notInitial = 1; } ;
  O1 = 0;
  O2 = 0;

  _pc[1] = &&HandleB; enabled |= (1 << 1); active |= (1 << 1); {
    HandleA:
    if (!A) {
      _pc[_cid] = &&_L94; goto _L_PAUSE; _L94:;
      goto HandleA;
    }
    B = 1;
    O1 = 1;

  } goto _L_TERM; {

    HandleB:
    _pc[_cid] = &&_L103; goto _L_PAUSE; _L103:;
    if (!B) {
      goto HandleB;
    }
    O1 = 1;
  } _L108: if (((enabled & (1 << 2)) != 0)) { _pc[_cid] = &&_L108;
          goto _L_PAUSE; };

  O1 = 0;
  O2 = 1;
  goto _L_TERM; _L_TICKEND: return (enabled != (1 << 0));
          _L_TERM: enabled &= ˜(1 << _cid); _L_PAUSE: active &=
          ˜(1 << _cid); _L_DISPATCH: __asm volatile(”bsrl␣%1,%0\n
          ” : ”=r” (_cid) : ”r” (active) ); goto *_pc[_cid];
}
```

(c) ABO SCL$_P$ tick function after macro expansion. The flag _notInitial is initially 0, indicating the initial tick.

Figure 9. The tick function synthesized for the ABO example (Fig. 2) with the priority approach. In the initial tick, the tickstart(p) macro initializes the root thread (prioID 0) and sets the prioID of the current thread to p; in subsequent ticks, it only activates the enabled threads. The tickreturn does some bookkeeping: at the _L_TICKEND label, the return value indicates whether any threads other than the root thread are still enabled; at _L_TERM, we disable the current thread; at _L_PAUSE, we deactivate the current thread, retrieve in _cid the active thread with highest prioID (on the x86 and with gcc, we can embed the "Bit Scan Reverse" assembler instruction), and jump to its continuation.

5. Priority-Based Low-Level Compilation

While the reaction time of software produced with the data-flow approach (Sec. 4) is proportional to the size of the SCChart, the reaction time of the more software-like *priority approach* presented now depends only on the components that are active within a tick. Thus the priority approach can scale better to very large models. Furthermore, the priority approach targets only software and thus, unlike the data-flow approach, has no trouble accepting control flow cycles, i. e., it accepts all iur acyclic programs (see Sec. 2.8). However, it rejects some programs that the data-flow approach accepts, because the data-flow approach considers sequential control flow only if it is relevant for the flow of data.

The priority approach extends SCL with prioIDs (Sec. 5.1), which are used at run time to schedule concurrent threads. The resulting language, termed *SCL$_P$*, consists of the sequential core of C, plus a set of predefined C macros that emulate reactive control flow (Fig. 9a). Control is not realized with guards for each basic block, as was the case in the data-flow approach, but instead with continuation points for each thread. In gcc, this is done with computed gotos; if computed gotos are not available, as in ANSI C, this can be emulated with switch-case logic. Hence SCL$_P$ can be compiled with any ordinary C compiler.

5.1 Thread segment IDs, Node Priorities, prioIDs

Each thread consists of a set of *thread segments*, which are delineated by fork/join nodes in the SCG and have a *thread segment ID* (*tsID*). Furthermore, each SCG node has a *priority*. SCL$_P$ dispatches threads based on a *prioID*, which combines the node priority with the tsID in a lexicographic fashion. For an SCL$_P$ program with tsIDs in $\mathbb{N}_{<n}$ for some n, prioIDs are computed as *priority* × *n* + *tsID*. This induces an ordering dominated by priorities, identical priorities are resolved by tsIDs. Encoding both thread IDs and priorities into a single scalar permits efficient thread book keeping. For example, in the implementation of the SCL$_P$ operators the prioID indexes an array that stores for each thread its continuation, and also indexes bit vectors that keep track of which threads are currently active. The chosen encoding permits on the one hand dynamic priority changes of a thread, and thus instantaneous back-and-forth communication between concurrent threads, and on the other hand still allows a fast dispatching based solely on which thread has the highest prioID.

The priorities and tsIDs must be assigned such that the resulting prioIDs induce a scheduling order that respects the scheduling constraints induced by the SC MoC. This is achieved, e. g., with the priority assignment algorithm [33] that runs in linear time and requires that the program is iur acyclic (see Sec. 2.8). There is also a _TickEnd thread, with priority 0 and tsID 0, which is always running and manages the return from the tick function.

In ABO, the concurrent access to shared variable B induces one dependence, which can be handled by assigning priority 1 to the nodes in HandleA and in the initial thread segment of the root thread (up to the fork), and priority 0 to the other nodes. The *root thread* corresponds to the SCChart's root state and gets started when the program gets started; when the root thread terminates, the whole program terminates. In ABO there are no concurrent threads of same priority, hence the assignment of tsIDs does not influence any scheduling decisions; we can thus arbitrarily assign tsID 2 to HandleA and tsID 1 to HandleB. However, we can avoid unnecessary jumps and run-time prioID changes by 1) ordering HandleA before HandleB in the fork/join, so that the thread with lowest prioID comes last and gets to execute the join, 2) propagating HandleA's tsID 2 up to the initial segment of the root thread, and 3) propagating HandleB's tsID 1 down to the final segment of the root thread (from the join onwards). Thus, there are $n = 3$ tsIDs in use, and the resulting prioIDs are $1 \times 3 + 2 = 5$ (HandleB/root), $0 \times 3 + 1 = 1$ (HandleA/root), and $0 \times 0 + 0 = 0$ (_TickEnd).

To minimize storage requirements and to maximize the number threads/priorities that can be encoded with only scalar bit vectors, we compress the range of prioIDs by skipping unused prioIDs. For ABO, shown in Fig. 9b, this results in shifting prioID 5 to prioID 2.

5.2 The SCL$_P$ Operators

The SCL$_P$ macros are tickstart(p), which starts the root thread with prioID p; tickreturn, which contains some pausing/dispatching logic and returns 1 or 0 depending on whether the root thread is still running or not; pause, which pauses a thread until the next tick starts; fork$n(l_1, p_1, \ldots, l_n, p_n)$, which forks off n sibling threads with start labels l_i and prioIDs p_i; par, which acts as a thread barrier by terminating a thread; and join$n(p_1, \ldots, p_n)$, which joins sibling threads with n different prioIDs p_i. Note that the join$n$ is not performed by the parent thread, but by one of its child threads; the parent thread does not get started again until its children have terminated. To catch the termination of sibling threads instantaneously, the thread executing the join$n$ must run at a prioID that is lower than that of these siblings. In case a sibling thread to be joined may perform a priority change, it must be considered with all prioIDs that it may take on. A further operator, not required in ABO, is prio(p), which allows to change the prioID of a thread.

When a parent thread forks off child threads, the child thread that is started immediately after the fork gets to reuse the tsID of the parent thread. Similarly, after the join, the resuming parent thread reuses the tsID of the child thread performing the join. This implies that the forking of a single thread requires neither an extra tsID nor the associated bookkeeping information (resumption address etc.), which is one of the aspects where SCL$_P$ is more efficient than the original Synchronous C [31].

Fig. 9 shows the SCL$_P$ version of ABO, along with selected SCL$_P$ macro definitions and the result of macro-expanding ABO (gcc -E). The continuation point for the thread with prioID p is stored in _pc[p]. The prioID of the currently running thread is _cid. The threads that still have work to do in the current tick are represented in a bit-vector active, similarly enabled indicates threads that have not terminated yet. Thus the enabled bits are the inverse of the m ("empty") flags computed in the data-flow approach. The macros presented here represent the bit vectors with scalars, thus the word size limits the maximum prioID; we have also developed alternative macros that use arrays instead and thus do not have that limitation.

6. Implementation and Experiments

As this paper is about a new modeling language, there are only limited quantitative comparison points. However, there are some questions to ask that warrant practical experimentation. To answer these, we have implemented the compilation stacks just described as part of the KIELER Eclipse-based open-source modeling environment[3]. All phases, from Extended SCCharts to C/VHDL, are implemented as model-to-model transformations written in Xtend[4]. SCCharts and intermediate SCChart/SCG models are visualized with KLighD [23], with fully automatic layout; this includes all SCChart figures in this paper.

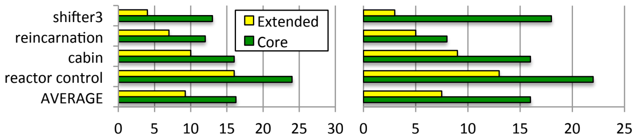


Figure 10. Number of states (left) and transitions (right), Extended SCCharts vs. equivalent Core SCCharts.

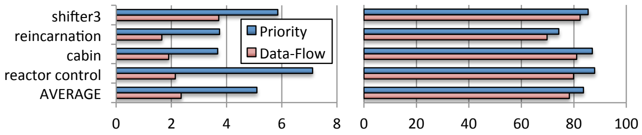


Figure 11. Clock cycles per tick (left) and executable size in KBytes (right), priority vs. data-flow low-level compilation.

First of all, there is the question of correctness. As stated in Sec. 7, SCCharts are a conservative extension of SyncCharts. Thus valid SyncCharts should also be valid SCCharts, with the same behavior. To that end, we have collected >100 validation benchmarks with input and output traces during the course of developing SCCharts and the transformations presented here, and we have validated that the SCCharts compiler does produce the same result as both another SyncChart-to-Synchronous C compiler [29] and, where traces were available, Esterel Studio.

Another question to ask is how much Extended SCChart models increase when transforming them to Core SCCharts. In Fig. 10 we compare the number of nodes and transitions for some benchmarks suggested by Traulsen et al. [29]. On average, the Extended SCCharts model has 42% fewer states and 53% fewer transitions than the equivalent expanded Core SCCharts model. Thus, the expansion leads to a model size increase, which is not surprising as the main motivation for the SCChart extensions is to express complex behavior in a more compact, abstract manner than is possible with Core SCCharts only. However, the expansions do not cause model size explosion either, which confirms that the Core SCChart operations capture the essence of the MoC. It also suggests that the generic transformations are reasonably efficient, although an expert modeler might in certain cases produce even more compact Core SCCharts.

For the same set of benchmarks, Fig. 11 compares for low-level synthesis the priority synthesis approach with the data-flow approach. The measurements were made on an Intel Core 2 Duo P8700 (2.53GHz) architecture. At least for these small-to-medium size benchmarks, the data-flow approach is faster; it has to compute more than the priority approach, as it always simulates the whole program, but its very linear control flow structure allows very fast execution. E. g., branching can be implemented with conditional

[3] http://www.informatik.uni-kiel.de/rtsys/kieler/

[4] http://www.eclipse.org/xtend/

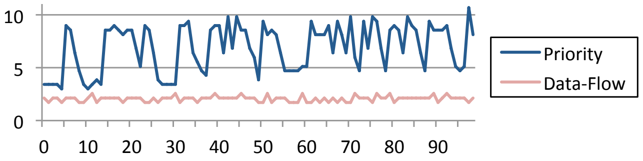


Figure 12. Jitter comparison (in *msec*) of low-level synthesis approaches, for cabin running 100 ticks.

moves rather than conditional jumps, which avoids branch misprediction penalties and thus helps modern, deeply pipelined architectures. The size differences are less significant.

Fig. 12 illustrates for one of the benchmarks the execution times per reaction for a sequence of reactions. Not surprisingly, the execution times of the priority approach show a significant variance, i. e., a high jitter. The data-flow approach has a much steadier response time (and is faster on average), as there is basically no internal control flow that depends on the inputs and the internal state.

7. Related Work

The proper handling of concurrency has a long tradition in computer science, yet, as argued succinctly by Hansen [13] or Lee [16], still has not found its way into mainstream programming languages such as Java. Synchronous languages were largely motivated by the desire to bring determinacy to reactive control flow, which covers concurrency and preemption [4]. Syntax and semantics of SCCharts have taken much inspiration from André's SyncCharts [2], introduced as Safe State Machines (SSMs) in Esterel Studio, and its predecessor Argos [18]. SyncCharts combines a statechart syntax with a semantics very close to the synchronous, textual language Esterel [5]. Colaço et al. [7, 8] have presented a SyncCharts/SSM variant, now implemented in the *Safety Critical Application Development Environment* (SCADE), whose semantics is an extension of the synchronous data-flow semantics of Lustre [12]. They use an elegant construct that basically refines boolean clocks into "state clocks." The functional synchronous Lucid Synchrone [8] allows the definition of local names, which can be used to encode sequential orderings, as in let x = . . . in x = x + 1; the same effect can be achieved by converting a program into static single assignment (SSA) form [3]. In Lucid Synchrone, this is motivated also by the desire to sequentialize external function calls with side effects, such as "print." Caspi et al. [6] have extended Lustre with a shared memory model. However, they adhere to the current synchronous model of execution in that they forbid multiple writes even when they are sequentially ordered. Unlike these SyncCharts/Lustre variants, SCCharts presented here are not restricted to constructiveness in Berry's sense [5], but relax this requirement to sequential constructiveness (SC). Thus SCCharts are a conservative extension of SyncCharts, in the sense that Berry-constructive SyncCharts are also valid SCCharts, but there is a large class of valid SCCharts that are perfectly determinate under SC scheduling but would be rejected by a SyncCharts compiler. In a nutshell, like Harel has [14] stated "statecharts = state-diagrams + depth + orthogonality + broadcast communication," one may say "SyncCharts = statecharts syntax + Esterel semantics" and "SCCharts = SyncCharts + sequential constructiveness + extensions," where the extensions are mostly drawn from SCADE (e. g., deferred transitions) and Quartz [24]/Esterel v7 (e. g., weak suspend).

Edwards [9] and Potop-Butucaru et al. [20] provide good overviews of compilation challenges and approaches for concurrent languages, including synchronous languages. We present an alternative compilation approach that handles most constructs that are challenging for a synchronous languages compiler by a sequence of model-to-model transformations, until only a small set of Core SCChart constructs remains. This applies in particular to aborts in combination with concurrency, which we, as part of the high-level compilation phase, reduce to (normal) terminations. Compared to existing approaches, this significantly simplifies down-stream compilation.

More specifically, the problem of compiling SCCharts is closely related to the compilation of Esterel, modulo the additional liberty provided by sequential constructiveness and some specific language constructs that are not common to both languages. For example, state transitions correspond to gotos, which are not present in Esterel, but which have been proposed as extensions there, in fact largely motivated by the desire to compile state machines directly into Esterel [27]. Conversely, Esterel has traps that are not present in SCCharts, but that can be encoded with aborts [21]. Our SCG, which results from the high-level compilation phase, is closely related to the concurrent control-flow graph (CCFG) used by the Columbia Esterel Compiler (CEC) as intermediate representation [9], the main difference being that we permit arbitrary control flow including loops and that we have more refined types of data dependencies. The SCG is also related to the GRaph Code (GRC) [20] that, like the CCFG, has a separate structure to keep state across tick boundaries ("reconstruction tree"). In comparison, the SCG has a rather simple means to express state, namely registers that correspond to the non-transient SCChart states. This corresponds to a one-hot encoding of the possible continuation points of each thread. In the priority-based low-level synthesis approach, this one-hot encoding is condensed into one program counter per active thread. In summary, there are numerous ways to compile the SCG to hardware or software, and we expect that much of the earlier work on Esterel compilation could also be applied, with some modifications, to the SCG; the two low-level synthesis paths presented here present rather straightforward options, with little compile-time partial evaluation.

8. Wrap-Up

SCCharts combine the intuitive nature of statecharts with the sequentially constructive model of computation, which naturally extends the sound basis of synchronous concurrency with sequential variable accesses. The core of SCCharts is defined by a very small set of operations, primarily state machines plus hierarchy, where superstates can be left with a join-like termination of their sub-states. Based on these core operations, we derive a number of high-level constructs, notably different types of aborts, through simple model-to-model transformations that largely preserve the write-things-once principle and thus keep the SCCharts compact.

The flexible yet determinate semantics of SCCharts makes them particularly suitable for safety-critical applications. This is augmented by direct synthesis paths to both software and hardware, which run in linear time, scale well, and where all intermediate steps are open to inspection. We have presented two alternatives for the low-level transformation that map from the SCG to C/VHDL: 1) the data-flow approach, which directly maps SCChart elements to data-flow elements or code and which is a sensible default strategy in most cases, and 2) the priority approach, which produces software only, but accepts a larger class of programs and for very large programs has asymptotically better performance. One characteristic of the SCG-based, step-wise synthesis proposed here is that there are no conceptual breaks between SCCharts and the low-level implementation. This drastically facilitates, for example, the handling of signals and the signal reincarnation problem, which we can handle at the SCChart/SCG level with linear overhead [1], whereas handling signal reincarnation at the Esterel level has potentially quadratic overhead [28]. Many further details, including detailed descriptions of the Extended SCChart features and of the synthesis approaches, were omitted here for space constraints but are found elsewhere [32].

Future work includes further exploration of model-to-model optimizations, applying our synthesis approach to Esterel-like languages, optimized tsID/priority assignments, experimentation with industry-scaled applications, and further improvements to the automatic layout of SCCharts and SCGs.

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