A Formal Framework for High Level Synthesis

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Abstract. In this paper, we propose a new approach to formal synthesis which focuses on the generation of verification-friendly circuits. Starting from a high-level implementation description, which may result from the application of usual scheduling and allocation algorithms, hardware is automatically synthesized. The target architecture is based on *handshake processes*, modules which communicate by a simple synchronizing handshake protocol. The circuits result from the application of only a few basic operations like synchronization, sequential execution or iteration of base handshake processes. Each process is guided by an abstract theorem that is used to derive proof obligations, to be justified after synthesis. Automation has been achieved to the extend that only those “relevant” proof obligations remain to be proven manually, e.g. theorems for data-dependent loops and lemmata about the used data types. The process-oriented implementation language is enriched by loop invariants. If those are given prior to the synthesis process and the underlying data types are only Booleans, i.e. finite-length bitvectors, then the complete synthesis and verification process runs automatically.

1 Introduction

As high-level synthesis [1] has reached the stage of industrial applications, it has turned out that the implicit assumption, that the generated structures just implement the behavioral specification, does not always hold. Software faults, inevitable in complex design tools, hinder the use of synthesized hardware, especially in safety critical applications, and reduce the cost advantages offered by high-level design tools.

Verifying the *design tools* by software verification techniques fails as a potential remedy to this situation due to the complexity of the algorithms to be checked. Automatically verifying the *synthesized hardware* by post verification techniques is possible when using model checking techniques [2]. However, this approach is limited to only small and medium sized circuits. It already fails if a couple of 32 bit registers are used in the data path. More complex circuits may be verified by proof-based approaches [3]. However, these techniques are interactive in general and require a good understanding of mathematical logic and the functioning of the target hardware. Large designs are verifiable if they are hierarchically composed. Obviously, automati-

cally synthesized hardware is hard to tackle using these approaches, since it is synthesized “flat” and its functioning is, especially if optimized, not always understandable to the human hardware verifier.

In this paper, we propose an approach which makes direct use of high-level synthesis algorithms. The high-level implementation description, resulting from scheduling and allocation is mapped onto a target architecture based on modules which communicate by a simple synchronizing handshake protocol, called *handshake processes* [4]. Handshake processes represent basic operations of the flow graph, resulting from the previous synthesis steps. The processes are composed to get a circuit, satisfying the specification. During the composition process the circuit is verified against the high-level specification in order to check the correctness of scheduling and allocation, which have been performed outside the formal framework. The verification process results in proof obligations, which may not be verified automatically. Usually this comprises lemmata describing properties of the used data types. For data-dependent loops, the implementation description language includes loop invariants. Stating these before the synthesis process is started, only data type related proof goals remain to be verified manually. However, this part is also automated if only bitvectors of finite-length are used [5].

This first approach may result in sub-optimal synthesized circuits with regard to area or speed. However, this is not a fundamental drawback of our approach since many of the well-known optimization techniques may be used afterwards. In general, optimization algorithms are easier to verify, e.g. optimizing transformations used in retiming may be checked for their behavior-preserving properties [6]. Moreover, safety critical applications may lead to the acceptance of a certain hardware overhead in favor of correctness, similar to the additional hardware which is accepted for enhanced testability.

The outline of the paper is as follows. In the next section, our approach is compared to related work. After introducing the formal framework, notation and the used logic, the synthesis approach is presented. There, we first present the basic “protocol” of the handshake processes and then show how base and composed processes may be synthesized, using an HDL. The paper ends with experimental results and conclusions.

2 Related Work

In contrast to post-hoc verification, formal synthesis aims at deriving correct implementations from specifications. Most existing approaches are based on refinement techniques, where a formal specification is successively transformed into hardware implementations. The best known approach is based on the use of the LAMBDA system [7]. Hardware is specified in higher-order logic and synthesized by decomposing the specification into smaller pieces, which can be mapped onto a set of connected modules representing implementations. Although supported by a graphical interface, the synthesis has to be performed completely manually as well as the proof that the resulting structure is behaviorally equivalent to the specification. Hence these designs require a thorough understanding of the used logic and the proof rules to be able to perform the necessary interactive theorem proving. Thus, the overall design methodol-

ogy is completely different from classical high-level synthesis and many optimization techniques developed in this area cannot be applied.

The formal synthesis of controllers from temporal logic specifications or timing diagrams has been presented in [8]. Due to the underlying propositional logic, these approaches cannot be extended to data path synthesis.

The approaches aiming at the synthesis of self-timed systems [9] are related to our approach with regard to a similar target structure, namely communicating modules. However, we use a synchronous handshake protocol and use higher-order logics as the underlying formal system instead of process algebras. Moreover, we explicitly provide a framework for coping with data dependent loops.

3 Basics

In the following, we use higher order logic as used in the HOL theorem proving environment [10]. In contrast to classical first-order logic, quantification is possible also over functions and predicates. The logic is based on typed lambda calculus, i.e. every term t has a unique type ty , written as $t:ty$. We use the usual boolean connectives like $\neg$, $\wedge$, $\vee$, or $\rightarrow$ and the symbol λ for lambda abstraction.

The HOL system provides a set of basic types like *ind*, the set of individuals, *bool*, the set of booleans and *num*, the natural numbers. More complex types can be defined using type operators, which take types and produce new ones. Given two types ty_1 and ty_2 , the binary type operator for functions $\rightarrow$ gives the type of all functions from ty_1 to ty_2 , i.e. $ty_1 \rightarrow ty_2$. The pair operator $\#$ forms the cartesian product type of two types $ty_1 \# ty_2$. Another concept, used in the following, is type polymorphism. There are type variables ty_{var} , that can be instantiated with an arbitrary type. In the HOL system, complex types may be defined. Proofs are usually performed interactively in the HOL system. However *tactics* may be defined to automate certain proof tasks. More details can be found in [10]. Proving theorems in the HOL system is usually performed interactively and in “backward” proof style. The goal to be proved is put on top of a goal stack. Repeated rule applications splits the goal into smaller proof goals until axioms are reached and the respective subgoal is removed from the stack. If the goal stack has been completely emptied, the original goal has been proved. Sets of rule applications can be abbreviated as tactics such that partial automation can be achieved.

In the following, modules are represented as predicates and structures of modules as conjunctions of predicates as used in many hardware verification approaches [11]. We use a discrete linear time modelled by natural numbers *num* and wires are functions from time to the respective data type, e.g. $x:num \rightarrow bool$.

Since temporal relationships play an important role for the communication of handshake processes, we use higher-order variants of temporal operators [12, 13, 14].

Specifications of digital circuits can often be described conveniently by the “when” operator [15]. In this paper we use a slightly different semantics and formalization of the when operator which is as follows. The expression $(x \text{ when } f)^{t_0}$ becomes true, if x becomes true for the first time after t_0 , at which f becomes true. In figure 3-1, a timing diagram for x and f is given, which makes $(x \text{ when } f)$ true at time instant t_0 .

Fig. 3-1. Timing diagram of the when operator

The operator is formally defined in equation 3-1.

$$(x \text{ when } f)^{t_0} := \forall \delta. \left(\forall t. (t < \delta) \rightarrow \neg f^{(t_0+t)} \right) \wedge f^{(t_0+\delta)} \rightarrow x^{(t_0+\delta)} \quad (3-1)$$

For the approach, presented in this paper, another definition of the when operator is used (equation 3-2). Intuitively, the when operator can be formalized using a “ready” signal f , a “termination” signal x and an invariant J of a data-dependent loop. The invariant must hold at the beginning of the loop (J^{t_0}). If the loop does not terminate ($\neg f^{(t+t_0)}$) the invariant must also hold at the next loop iteration. Otherwise, the termination signal x must become true in the next time instance. This order of events is visualized by figure 3-2.

$$(x \text{ when } f)^t := \begin{aligned} &\exists J. J^{t_0} \wedge \\ &\left(\forall t. \neg f^{(t_0+t)} \wedge J^{(t_0+t)} \rightarrow J^{(t_0+t+1)} \right) \wedge \\ &\left(\forall \delta. f^{(t_0+\delta)} \wedge J^{(t_0+\delta)} \rightarrow x^{(t_0+\delta)} \right) \end{aligned} \quad (3-2)$$

Fig. 3-2. Visualization of the invariant formalization

Note that the above definitions lead to a “weak when”, i.e. it is not required that the signal f ever becomes true. Using the weak version of the operator for specifications leads to partial correctness results, i.e. the hardware gives the right result at the right time, but only if it terminates. In circuits, whose termination is not obvious, e.g. when using data-dependent loops, then an additional termination condition $\exists t. f^{t+t_0}$ has to be shown.¹ It has been shown previously that, provided that the invariant J is given, proofs of theorems, which contain the temporal operators may be automated [14]. Proof tactics to perform this task are available for the HOL90 theorem proving environment.

4 Handshake Circuits

The main idea underlying this approach is based on the observation that if it is possible to implement modules with a uniform and consistent input/output behavior, then module composition to perform complex computations is almost trivial and the verification of the overall behavior is considerably eased. In most cases the desired correctness theorem, i.e. that the composed structure behaves as specified, may be derived fully automatically.

The interface of a module is as given in figure 4-1. Note that in the following, all modules are described using only one input *inp* and one output *out*. However, *inp* and *out* are of polymorphic type so that bundles of signals may be easily used as type instances.

Fig. 4-1. General handshake circuit

Besides input *inp* and output *out* two further signals are used: the request input *req* indicates that a new input value can be read for the next computation and the finish output *f* denotes the end of a computation cycle. Φ represents the specification of the module function, i.e. the behavior to be eventually verified. More formally, the *module function* is expressed by a formula $\Phi(inp, out, t_1, t_2)$, where the starting time t_1 and finish time t_2 is included. These time instants serve as reference time points for the input and output value and may be also used for formalizing restrictions on the duration of a computation cycle. A typical example is given in equation 4-1 where the sum of inp_1 and inp_2 is computed, needing 3 time units.

$$\Phi(inp_1, inp_2, out, t_1, t_2) = \left(out^{t_2} = inp_1^{t_1} + inp_2^{t_1} \right) \wedge (t_2 - t_1 = 3) \quad (4-1)$$

The *timing behavior of the module* is formalized in terms of the handshake signals *f* and *req* as stated in equation 4-2. The first implication denotes that provided that no computation is active at time t_0 (f^{t_0}), then the outputs are stored until a new task is requested (store mode). The second implication states, that after a request for a computation *req*, the result, computed by Φ , is available at *out* when *f* is true again.

$$\begin{aligned} \text{PROTOCOL}(req, in, f, out, \Phi) := & f^0 \wedge \\ & \forall t_0. \left(f^{t_0} \rightarrow [(\lambda t. (out^t = out^{t_0}) \wedge (f^t = f^{t_0})) \text{ until } req]^{t_0} \right) \wedge \\ & \left(f^{t_0} \rightarrow \left(\left(\lambda t_1. [\lambda t_2. \Phi(inp, out, t_1, t_2) \text{ when } f]^{(t_1+1)} \right) \text{ when } req \right)^{t_0} \right) \end{aligned} \quad (4-2)$$

1. It is easily possible to define a strong when when using the weak version as follows:

$$(x \text{ when } f)^t := (x \text{ when } f)^t \wedge \neg((\lambda t. F) \text{ when } f)^t$$

5 Verifying Handshake Circuits

In this section a high-level implementation description is presented. It is the result of the scheduling and allocation step of high-level synthesis and its semantics is given directly in terms of handshake circuits.

5.1 Notation

The language distinguishes two levels of abstraction. For creating base modules, there are constructs for synchronous RT-level descriptions using a clock. For compound modules, process composition constructs are provided as given in table 5-1.

Level	construct	description
clock level	=	combinational assignment
	$\leftarrow$	synchronous assignment
		clock parallel action
	op	arbitrary (combinational) arithmetic or logic operation
	bop	(combinational) boolean operation resulting in a signal of type bool
	const	arbitrary constants (bits, natural numbers)
proces level	;	sequential composition
	,	parallel composition
	:=	assignment

Table 5-1: Base constructs

Variables in capital letters denote bitvectors, i.e. $\text{Out} = (\text{out}_1, \text{out}_2, \dots, \text{out}_n)$. Sets of registers are abbreviated using an arrow like $\vec{\text{Out}} = (\text{Out}_1, \text{Out}_2, \dots, \text{Out}_q)$.

All processes are defined as follows.

```

process <name> ( $\text{in}_1:\alpha_1, \dots, \text{in}_p:\alpha_p$ ) : ( $\text{out}_1:\beta_1, \dots, \text{out}_q:\beta_q$ ) =
var
   $R_1, \dots, R_k$  . register(n)
   $W_1, \dots, W_l$  . wire(m)
  process <subprocess namei> ...
begin
<body>
end.
```

Each process has a name $\langle \text{name} \rangle$, a set of inputs in_i of type α_i , resulting in q outputs typed β_i . The types α_i and β are bitvectors of finite length. The process may declare local registers R_i of bitwidth n and wires W_i of bit width m . The $\langle \text{body} \rangle$ depends on the type of the process. There are basic processes, which are either sequential loops or combinational circuits, and composed processes. The latter are nested loops, sequences or synchronized parallel processes.

A key point of this approach is its ability to cope with arbitrary hierarchical structures. This is possible by guaranteeing that composed modules have the same input/output behavior as the base modules, i.e. a uniform interface scheme has to be used. In the following base processes, nested loop processes as well as sequential and parallel composition are treated.

5.2 Base Processes

A base process usually consists of a data dependent loop and is defined as follows.

```

init
   $\vec{R} \leftarrow \text{op}_{\text{init}}(\vec{I}, \text{const})^a$ 
while bop() do
   $\vec{R} \leftarrow \text{op}_{\text{loop}}(\vec{R})$ 
end invariant J
output
   $\vec{\text{Out}} = \text{op}_{\text{out}}(\vec{R})$ 
  
```

a. abbreviation for

$$R_1 \leftarrow \text{op}_{\text{init},1}(\vec{I}, \text{const}) \mid \dots \mid$$

$$R_k \leftarrow \text{op}_{\text{init},k}(\vec{I}, \text{const})$$

The invariant J is necessary for the automated verification. Currently it is a statement in higher-order logic¹, using the process signals as arguments. Naturally, a similar construct is also available for REPEAT - UNTIL loops.

The corresponding hardware structure of the module is given in figure 5-1.

Fig. 5-1. Base handshake process

The controller is realized according to the state transition graph (STG) of figure 5-2 and hence is the same for every realization of a while loop.

Fig. 5-2. STG of one_loop_control

A simple combinational module results from the previous case by omitting the while loop, leading to the simplified structure of figure 5-3. The registers are necessary for maintaining the overall handshake behavior and may be omitted if the input signal remains stable during the whole computation.

Fig. 5-3. Combinational base handshake process

The register $\vec{R}$ and the controller one_loop_control of figure 5-3 are necessary to store the results of $\text{op}_{\text{out}}(\text{op}_{\text{init}}(\vec{I}))$ to achieve a behavior which conforms to equation 4-2.

A top level formalization of the circuit structure of figure 5-1 in higher-order logic is shown in equation 5-1.

$$\begin{aligned} \text{circuit}(\text{req}, \vec{I}, \vec{\text{Out}}, f) := \\ \exists \text{init load } f_1. \text{data_path}(\vec{I}, \text{init}, \text{load}, f_1, \vec{\text{Out}}) \wedge \\ \text{one_loop_control}(\text{req}, \text{init}, \text{load}, f_1, f) \end{aligned} \quad (5-1)$$

1. Currently the syntax of the HOL90 theorem proving environment has to be used for invariants.

To verify the module behavior, it has to be shown that the implementation (equation 5-1) implies a behavioral specification (equation 4-2). This comprises the conformance to the handshake protocol and the computing function Φ . Since the handshake circuits have been synthesized verification-friendly, the timing behavior is automatically verified using appropriate theorems [4]. The remaining proof goal is shown in equation 5-2.

$$f^{t_0}, \text{req}^{t_0} \vdash \left[\lambda t_1. \Phi(\vec{I}, \vec{\text{Out}}, t_0, t_1) \text{ when } f \right]^{t_0+1} \quad (5-2)$$

The remaining proof may be further simplified, if the invariant based on the *when* definition of equation 3-2 is used. However, the invariant has to be provided manually either only now or already previously in the implementation description.

In the following, a GCD process is defined to illustrate the definition of base handshake processes. The overall process is written down as follows.

```

process GCD_proc( $I_1$  : num(16),  $I_2$  : num(16)) : ( $\text{Out}$  : num(16)) =
var
   $R_1$ ,  $R_2$  . register(16)
begin
init
   $R_1 \leftarrow I_1$  |
   $R_2 \leftarrow I_2$ 
repeat
  if  $R_1 < R_2$ 
    then  $R_2 \leftarrow R_2 - R_1$ 
    else  $R_1 \leftarrow R_1 - R_2$ 
until ( $R_1 = 0$ )  $\vee$  ( $R_2 = 0$ ) invariant  $J_{\text{GCD}}$ 
output
  if  $R_1 = 0$ 
    then  $\text{Out} \leftarrow R_2$ 
    else  $\text{Out} \leftarrow R_1$ 
end.

```

The specification Φ to be verified is as follows.

$$\Phi([I_1, I_2], \text{Out}, t_1, t_2) := \left(\text{Out}^{t_2} = \text{GCD}\left(I_1^{t_1}, I_2^{t_1}\right) \right) \quad (5-3)$$

Based on a usual definition of the Greatest Common Divisor, GCD , the invariant

J_{GCD} of equation 5-4 is used. Basically it states that the iterative subtraction performed in the registers of the GCD process do not affect the GCD to be computed.

$$\forall t, t > t_0. \left(GCD \left(R_1^{(t+1)}, R_2^{(t+1)} \right) = GCD \left(R_1^t, R_2^t \right) \right) \quad (5-4)$$

5.3 Compound Processes

5.3.1 Nested Loops

A handshake process may be used to construct a nested data dependent loop. It is called “nested”, since most basic handshake processes also contain a data-dependent loop. It thus has a similar function as op_{loop} in figure 5-1 but at a higher level of abstraction.

Given a handshake process₁, which may be defined e.g. as presented in section 5.2.1, nested loops are specified as follows.

```

init
 $\vec{R} \leftarrow op_{init,R}(\vec{I}, const)$ 
 $\vec{W} \leftarrow op_{init,W}(\vec{I}, const)$ 
while  $bop(\vec{R}, \vec{W})$  do
 $\vec{W} \leftarrow process_1(\vec{R}, \vec{W})$ 
end invariant  $J$ 
output
 $\vec{Out} = op_{out}(\vec{R}, \vec{W})$ 

```

The realization of the nested loop using process₁ is given in figure 5-1.

Fig. 5-4. Nested loop handshake process

The STG of the controller `nested_loop_control` is given in figure 5-2. Similar to the controller of figure 5-2, it has a wait state and a computation state. The controller starts in the wait state and reaches after a request signal the computation state. The inner loop is started by signal req_1 . Its termination is signalled to the controller by f_1 and the termination of the outer loop, checked by `bof` is communicated via f_2 .

Fig. 5-5. STG of `nested_loop_control`

As in section 5.2.3, it is sufficient to show, that the following holds.

$$\forall t_0. f^{t_0} \wedge \text{req}^{t_0} \rightarrow \left[\lambda t_1. \Phi \left(\vec{I}, \vec{\text{Out}}, t_0, t_1 \right) \text{ when } f \right]^{t_0+1} \quad (5-5)$$

Having proved equation 5-5, the overall behavior $\text{PROTOCOL}(\text{req}, \vec{I}, \vec{\text{Out}}, f, \Phi)$ may be derived by a preproven lemma [4] if the controller `nested_loop_control` is used. The remaining proof goals are similar to those of section 5.2.3 and omitted here.

5.3.2 Parallel Composition

The parallel composition or *synchronization* of two processes is stated as follows.

$$\begin{aligned} \vec{\text{Out}}_1 &\leftarrow \text{process}_1(\vec{I}_1, \vec{C}_1), \\ \vec{\text{Out}}_2 &\leftarrow \text{process}_2(\vec{I}_2, \vec{C}_2) \end{aligned}$$

The corresponding hardware structure is given in figure 5-6.

Fig. 5-6. Synchronization of two handshake processes

The controller `sync_control` essentially is a simple combinational circuit, where f results from the conjunction of f_1 and f_2 and req_i from the conjunction of req and f .

The verification of the overall behavior is easy, since a preproven lemma [4] is also available here, stating that, provided that both processes work as intended, then both results are available at $\overrightarrow{Out}_1$ and $\overrightarrow{Out}_2$, if f indicates the termination of the composed process.

5.3.3 Sequential Composition

The sequential composition of two processes is stated as follows.

$$\begin{aligned}\overrightarrow{Out}_1 &\leftarrow process_1(\vec{I}_1, \vec{C}_1); \\ \overrightarrow{Out}_2 &\leftarrow process_1(\vec{I}_2, \vec{C}_2)\end{aligned}$$

The corresponding hardware structure is given in figure 5-6.

Fig. 5-7. Sequentialization of two handshake processes

The controller `seq_control` has three states. Its STG is given in figure 5-2. Wait or computation status of both processes are indicated by W and C, i.e. the state CW denotes, that the first process is computing a result and the second waits to be served.

Fig. 5-8. STG of `seq_control`

Also here a preproven lemma [4] is used to prove, that the whole process provides as a result the functional composition of both processes, if it has terminated.

6 Example

In the following, we will verify a synthesized handshake circuit, which realizes the computation of the euclidean metric, defined in equation 6-1.

$$\Phi(I_1, I_2, \text{Out}, t_1, t_2) = \left(\text{Out}^{t_2} = \sqrt{\left(I_1^{t_1}\right)^2 + \left(I_2^{t_1}\right)^2} \right) \quad (6-1)$$

The overall process is as follows, where Mult, Add and Sqrt are previously defined processes. For computing the square root, e.g. Heron's algorithms based on the following iteration may be used.

$$x_{n+1} = \frac{1}{2} \left(\frac{a}{x_n} + x_n \right). \quad (6-2)$$

```

process Euclid_Metric (I1 : num, I2 : num) : (Out : num) =
var
  W1, W2, W3 . wire(16)
begin
  (W1 ← Mult(I1, I1), W2 ← Mult(I2, I2));
  W3 ← Add(W1, W2)
output
  Out ← Sqrt(W3)
end.

```

The corresponding hardware structure is given in figure 6-1. Note that the control signals have been deliberately omitted in the Add module. This optimization step is possible here, since a combinational module is used in a sequential composition and the overall behavior is not changed if the intermediate storage of the combinational results of Add is missing.

The base processes Mult, Add and Sqrt are verified as shown in section 5.2. The verification of the specification Φ of equation 6-1 is performed as shown in section 5.3.2 and section 5.3.3. Hence besides applying the respective simplification lemmata [4], only some internal lines have to be eliminated [16].

7 Experimental Results

Our approach has been successfully tested on several arithmetic circuits. Runtimes can be found in table 7-1. All runtimes have been achieved on a SUN SPARC 10 with 96MB. Finding the loop invariants has turned out to be the main challenge in synthesizing the circuits.

Fig. 6-1. Synthesized structure of the euclid metric

Circuit Name	Time in seconds
VonNeumann 1	7.19
VonNeumann 2	17.33
IncDecAdder 1	6.22
IncDecAdder 2	15.81
Summation	16.77
Signal Generator	44.52
Greatest Common Divisor	27.78
Russian Multiplier	60.14
Divider	73.60
SquareRoot	66.85

Table 7-1: Runtimes of different benchmark circuits

8 Conclusions and Future Work

In this paper, an approach to the formal synthesis of verification-friendly hardware structures has been presented. Having applied standard scheduling and allocation algorithms, known from high-level synthesis, an implementation description in a HDL-like language results. Its semantics is given directly as a composition of handshake circuits based on a synchronous handshake protocol. During the composition of these handshake circuits, a set of correctness theorems is derived which justifies the correctness of the specified circuit. Hence the correctness of scheduling and allocation, performed outside the formal framework, is checked. If during the specification phase, the designer's key ideas are provided via loop invariants, then all correctness proofs are done automatically, provided that a decidable domain like bitvectors have been used.

In case of more complex data types, proof obligations on the data domain are derived automatically, which have then to be justified otherwise, e.g. by manual proofs. The approach is well suited for data driven applications, which are used in safety critical environments. For pure controller circuits, other approaches are better suited, e.g. by performing a post-verification based on model checking.

Using our approach, no time consuming post verification step is necessary to achieve correctness statements on the resulting circuits.

Obviously, the handshake module paradigm leads in some cases to suboptimal hardware solutions. We are currently investigating optimization strategies at higher abstraction levels like operator folding and low level techniques like multilevel logic minimization, FSM minimization and retiming to reduce hardware costs.

9 References

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