Bar-Hillel Theorem Mechanization in Coq

Closure of Context-Free Languages Under Intersection With Regular Languages

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Abstract

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1 Introduction

Formal language theory has deep connection with different areas such as ststic code analysis [?], graph database querying [? ?], formal verification [?], and others. One of the most friquent scenarion is formulate problem in terms of languages intersection. For example in verification one can use one languge as a model of program and another language for undesirable behaviors (for example from program specification). In case when intersection of these two languags is not empty one can conclude that program is incorrect, so we are interested in languages intersection emptiness problem desidability. But in some case we want to build constructive representation of intersection. For example, when we use languages intersection as a model for qury execution: language which prodused by intersection is a qury result and we want to have ability to process it.

Thus emptiness of intersection and constructive representation of intersection are useful for different applications. The simplest case is linear—regular and we have a big number of works on sertified regular expressions [?]. Regular—regular and regualr queryies in Coq [?]. Next and one on wost comprehansive cases with desidable problem of emptyness problem: regular—context-free. It is actual for parsing, program analysis, graph analysis [?]. Constructive result is important: paths, etc

It is the well-known fact tat context-free languages are closed under intersection with regular languages. Theoretical result is Bar-Hillel theorem [?] which provides construction for resulting language description.

Some of these aplications require sertifications. For verification is evident. For databases, for example, it may be necessary to reason on sequrity aspects and, thus, we should create certified solutions for query executing. So, mechanization of BH theorem may be ysefull step for... On the other hand, mechanization (formalization) is important and many work done on formal languages theory mechanization. Parsing algorithms and reasoning about other problems on languages intersection.

Short overview of current results. Many different parts of formal languages are mechanized. Smolka. Algorithms and basic results.

Our work is a first step: mechanization of theoretical results. The main contribution of this paper may be summarized as follows.

- We provide constructive proof of the Bar-Hillel theorem in Coq.
- We generalize Smolka's CFL results: terminals is abstract types....
- All code are publised on GitHub: https://github.com/YaccConstructor/YC_in_Coq.

This work is organized as follows. First of all, we formulate theorem to proof and !!! Describe our solution. This description is splitted into steps. Smolka's results generalization, trivial cases handling, general case. Summarization. Related works Discussion and conclusion.

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2 Bar-Hillel Theorem

Original Bar-Hillel theorem and proof which we use as base. We work with the next formulation of the theorem.

Lemma 2.1. *If L is a context free language and $\varepsilon \notin L$ then there is grammar in Chomsky Normal Form that generates L.*

Lemma 2.2. *If $L \neq \emptyset$ and L is regular then L is the union of regular language $A_1, \dots, A_n$ where each A_i is accepted by a DFA with exactly one final state.*

Theorem 2.3. *If L_1 is a context free language and L_2 is a regular language then $L_1 \cap L_2$ is context free.*

Sketch of the proof:

1. By lemma 2.1 we can assume that there is a context-free grammar G_{CNF} in Chomsky normal form, such that $L(G_{CNF}) = L_1$
2. By lemma 2.2 we can assume that there is a set of regular languages $\{A_1 \dots A_n\}$ where each A_i is recognized by a DFA with exactly one final state and $L_2 = A_1 \cup \dots \cup A_n$
3. For each A_i we can explicitly define a (?) grammar of the intersection: $L(G_{CNF}) \cap A_i$
4. Finally, we join them together with the (?) operation of union

3 The Chomsky Normal Form

One of important part of our proof is the fact that any context-free language can be described with grammar in Chomsky Normal Form (CNF) or, equally, any context-free grammar can be converted in grammar in CNF which specifies the same language. Let us remind the definition of CNF and main steps of algorithm for CFG to CNF conversion.

Definition 3.1 (Chomsky Normal Form)**.** Let define that context-free grammar is in CNF if:

- start nonterminal is not occurs in right side of rules,
- all rules have one of the next form: $N_i \rightarrow t_i$, $N_i \rightarrow N_j N_k$ or $S \rightarrow \varepsilon$ where N_i, N_j, N_k are nonterminals, t_i is terminal and S is start nonterminal.

Steps of transformation.

1. Eliminate the start symbol from right-hand sides of rules.
2. Eliminate rules with nonsolary terminals
3. Eliminate rules which right-hand side contains more than two nonterminals
4. Delete ε-rules.
5. Eliminate unit rules.

As far as Bar-Hillel theorem operates with arbitrary context-free languages but proof requires grammar CNF, it is necessary to create certified algorithm for arbitrary CFG to CNF conversion. We want to reuse existing proof of conversion of arbitrary context-free grammar to CNF. We choose Smolka's version which contains proof for conversion to CNF in the next form.

```
CNF!!!
```

Listing 1. TODO

4 B-H in Coq

In this section we describe in detail all the fundamental parts of the proof. Also in this section, we briefly describe motivation to use the chosen definitions. In addition, we discuss the advantages and disadvantages of using of third-party proofs.

Overall goal of this section is to provide step-by-step algorithm of constructing the CNF grammar of the intersection of two languages. Final formulation of the obtained theorem can be found in the last subsection.

All code are published on GitHub [1].

4.1 Smolka's code generalization

In this section, we describe the exact steps taken to use the proof of TODO:Smolka's theorem in the proof of this article's theorem.

A substantial part of this proof relies on the work of TODO:Smolka. From this work(,?) many definitions and theorems were taken. Namely, the definition of a grammar, definitions of a derivation in grammar, some auxiliary lemmas about the decidability of properties of grammar/derivation, we also use the theorem that states that there always exists the transformation from context-free grammar to grammar in Chomsky Normal Form (CNF).

However, this proof had one major flaw that we needed to fix.

One could define a terminal symbol as in inductive type over natural numbers[TODO].

```
Inductive ter : Type := | T : nat -> ter.
```

Listing 2. TODO

That is how it was done in Smolka (???). However for purposes of our proof, we need to consider nonterminals over the alphabet of triples. Therefore, it was decided to add polymorphism over the target alphabet. Namely, let Tt and Vt be types with decidable relation of equality, then we can define the types of terminal and nonterminal over alphabets Tt and Vt respectively as follows (???):

[1] https://github.com/YaccConstructor/YC_in_Coq

```
Inductive ter : Type := | T : Tt -> ter.
Inductive var : Type := | V : Vt -> var.
```

Listing 3. TODO

The proof of Smolka has a clear structure, therefore only part of the proof where the use of natural numbers was essential has become incorrect. One of the grammar transformations (namely deletion of long rules) requires the creation of many new non-terminals. In the original proof for this purpose, the maximum over non-terminals included in the grammar was used. However, it is impossible for an arbitrary type.

To tackle this problem we introduce an additional assumption on alphabet types for terminals and nonterminals. We require an existence of the bijection between natural numbers and alphabet of terminals as well as nonterminals.

```
Lemma language_normalform G A u :
  Vs A el dom G ->
  u <> [] ->
  (language G A u <->
     language (normalize G) A u).
```

Listing 4. TODO

4.2 Part ..: derivation and so on

Symbol is either a terminal or a nonterminal.

```
Inductive symbol : Type :=
| Ts : ter -> symbol
| Vs : var -> symbol.
```

Listing 5. TODO

Next we define word and phrase as lists of terminals and symbols respectively.

```
Definition word := list ter.
Definition phrase := list symbol.
```

Listing 6. TODO

TODO: add def of "terminal"

We have two different definitions because the notion of nonterminal doesn't make sense for DFA, but in order to construct derivation in grammar we need to use nonterminal in intermediate states.

Further we prove that if phrase consists only of terminals there exists save conversion between word and phrase.

We inheriting our definition of CFG from [] paper. Rule is pair of nonterminal and list of symbols. Grammar is a list of rules.

```
Inductive rule : Type :=
| R : var -> phrase -> rule.

Definition grammar := list rule.
```

Listing 7. TODO

An important step towards the definition of a language (?) governed (formed?)(?!) by a grammar is the definition of derivability. Having $der(G, A, p)$ — means that phrase p is derivable in grammar G starting from(?) nonterminal A.

```
Inductive der (G : grammar)
          (A : var) : phrase -> Prop :=
| vDer : der G A [Vs A]
| rDer l : (R A l) el G -> der G A l
| replN B u w v :
der G A (u ++ [Vs B] ++ w) ->
    der G B v -> der G A (u ++ v ++ w).
```

Listing 8. TODO

Our proof requires grammar to be in CNF. We used statement that every grammar in convertible into CNF from Minka(?) work.

4.3 General scheme of proof

General scheme of our proof is based on constructive proof presented by [?]. In the following subsections, the main steps of the proof will be presented. Overall, we will adhere to the following plan.

1. First we consider trivial cases, like DFA with no states or empty languages
2. Every CF language can be converted to CNF
3. Every DFA can be presented as an union of DFAs with single final state
4. Intersecting grammar in CNF with DFA with one final state
5. Proving than union of CF languages is CF language

4.4 Part one: trivial cases

Cases when one or both of the initial languages are empty we call trivial. Since in this case, the intersection language is also empty it is easy to construct the corresponding grammar.

We do the case analysis.

TODO: add some text

4.5 Part two: regular language and automata

In this section we describe definitions of DFA and DFA with exactly one final state, we also present function that converts any DFA to a set of DFA with one final state and lemma that states this split is well-defined(?).

A list of terminals we call word.

We assume that regular language by definition described by DFA. As the definition of an DFA, we have chosen a general definition, which does not impose any restrictions on the type of input symbols and the number of states. Thus, in our case, the DFA is a 5-tuple, (1) a state type, (2) a type of input symbols, (3) a start state, (4) a transition function, and (5) a list of final states.

```
Context {State T: Type}.
Record dfa: Type :=
  mkDfa {
    start: State;
    final: list State;
    next: State -> (@ter T) -> State;
  }.
```

Listing 9. TODO

Next we define a function that would evaluate in what state the automaton will end up if it starts from state s and receives a word w.

```
Fixpoint final_state
           (next_d: dfa_rule)
           (s: State)
           (w: word): State :=
  match w with
  | nil => s
  | h :: t => final_state next_d (next_d s h) t
  end.
```

Listing 10. TODO

We say that the automaton accepts a word w being in state s if the function [$final\_state\_sw$] ends in one of the final states. Finally, we say that an automaton accepts a word w, if when(?) the DFA starts from the initial state, it ends in one of the final states.

In order to define the DFA with exactly one final state, it is necessary to replace the list of final states by one final state in the definition of an(?) ordinary DFA. The definitions of "accepts" and "dfa_language" vary slightly.

Alternative: In the proof we need a subset (subtype?) of all automata. Namely, automata with one finite state. We can define them as follows. We say that dfa is a single-final-state-automata, if and only if the predicate "is final state?" can be represented as "is equal to the state fin?"

```
Record s_dfa : Type :=
  s_mkDfa {
    s_start: State;
    s_final: State;
    s_next: State -> (@ter T) -> State;
  }.
```

Listing 11. TODO

TODO?: add code

Similarly, we can define functions $s\_accepts$ and $s\_dfa\_language$ for sDFA. Since in this case, there is only one final state, to define function $s\_accepts$ it is enough to check the state in which the automaton stopped with the finite state. The function $s\_dfa\_language$ repeats the function $dfa\_language$, except that the function must now use $s\_accepts$ instead of accepts.

Now it is easy to define a function that converts an ordinary DFA into a sequence (set?) of DFAs (?) with one final state.

```
Fixpoint split_dfa_list
    (st_d : State)
    (next_d : dfa_rule)
    (f_list : list State): list (s_dfa) :=
  match f_list with
  | nil => nil
  | h :: t => (s_mkDfa st_d h next_d)
               :: split_dfa_list st_d next_d t
  end.

Definition split_dfa (d: dfa) :=
   split_dfa_list (start d) (next d) (final d).
```

Listing 12. TODO

Correctness of "split":

```
Lemma correct_split:
  forall dfa w,
    dfa_language dfa w <->
    exists sdfa,
       In sdfa (split_dfa dfa) /\
       s_dfa_language sdfa w.
```

Listing 13. TODO

Theorem 4.1.

Proof.
TODO: add proof
bla-bla-bla

4.6 Part ..: Chomsky induction

TODO: add some text

Naturally many statements about properties of language's words can be proved by induction over derivation structure. Unfortunately, grammar can derive phrase us an intermediate step, but DFA supposed to work only with words, so we cant simply apply induction over derivation structure. To tackle this problem we create custom induction-principle for grammars in CNF.

The main point is that if we have a grammar in CNF, we can always divide the word into two parts, each of which is derived only from one nonterminal. Note that if we naively take a step back, we can get nonterminal in the middle of the word. Such a situation will not make any sense for DFA.

With induction we always work with subtrees that describes some part of word. Here is a picture of subtree describing intuition behind Chomsky induction.

TODO: add picture

TODO: add Lemma derivability_backward_step.

More formally: Let G be a grammar in CNF. Consider arbitrary nonterminal $N \in G$ and phrase which consists only on terminals w. If w is derivable from N and $|w| \geq 2$, then there exists nonterminals N_1, N_2 and subphrases of w — w_1, w_2 such that: $N \to N_1 N_2 \in G$, $der(N_1, w_1)$, $der(N_2, w_2)$, $|w_1| \geq 1$, $|w_2| \geq 1$ and $w_1 + +w_2 = w$.

Proof.

The next step is to prove the following statement:

Let G be a grammar in CNF. And P be a predicate on nonterminals and phrases (i.e. $P : var \to phrase \to Prop$). Let us also assume that the following two hypotheses are satisfied: (1) for every terminal production (i.e. in the form $N \to a$) of grammar G, $P(r, [Tsr])$ and (2) for every $N, N_1, N_2 \in G$ and two phrases which consist only of terminals w_1, w_2, if $P(N_1, w_1)$, $P(N_2, w_2)$, $der(G, N_1, w_1)$ and $der(G, N_2, w_2)$ then $P(N, w_1{+}{+}w_2)$. Then for any nonterminal N and any phrase consisting only of terminals w, the fact that w is derivable from N implies $P(N, w)$.

Basically, this principle says that if some P holds for two basic situations, then P hold for any derivable word.

Proof?. There is a constant n such that $|w| \leq n$. We prove the statement by induction on n.

Base: $n = 0$,

Induction step:

TODO: add some text

As one might notice, TODO

4.7 Part ..: intersection

Since bla-bla-bla, we can assume that we have (1) DFA with exactly one final state — dfa and (2) grammar in CNF — G.

Let G_{INT} be the grammar of intersection. In G_{INT} nonterminals presented as triples $(from \times var \times to)$ where $from$ and to are states of dfa, and var is a nonterminal of(in?) G.

4.7.1 Function

Next we present adaptation of the algorithm given in [].

Since G is a grammar in CNF, it has only two type of productions: (1) $N \to a$ and (2) $N \to N_1 N_2$, where N, N_1, N_2 are nonterminals and a is a terminal.

For every production $N \to N_1 N_2$ in G we generate a set of productions of the form $(from, N, to) \to (from, N_1, m)(m, N_2, to)$ where: $from$, m, to — goes through all dfa states.

```
Definition convert_nonterm_rule_2
  (r r1 r2: _)
  (state1 state2 : _) :=
  map (fun s3 => R (V (s1, r, s3))
                   [Vs (V (s1, r1, s2));
                    Vs (V (s2, r2, s3))])
    list_of_states.

Definition convert_nonterm_rule_1
             (r r1 r2: _)
             (s1 : _) :=
  flat_map (convert_nonterm_rule_2 r r1 r2 s1)
           list_of_states.

Definition convert_nonterm_rule (r r1 r2: _) :=
  flat_map (convert_nonterm_rule_1 r r1 r2)
           list_of_states.
```

Listing 14. TODO

For every production of the form $N \to a$ we add a set of productions $(from, N, (dfa\_step(from, a))) \to a$ where: $from$ — goes through all dfa states and $dfa\_step(from, a)$ is the state in which the dfa appears after receiving terminal a in state $from$.

```
Definition convert_terminal_rule
            (next: _)
            (r: _)
            (t: _): list TripleRule :=
  map (fun s1 => R (V (s1, r, next s1 t)) [Ts t])
      list_of_states.
```

Listing 15. TODO

TODO: add some text

Next we join the functions above to get a generic function which works for both types of productions.

```
Definition convert_rule (next: _) (r: _ ) :=
  match r with
  | R r [Vs r1; Vs r2] =>
      convert_nonterm_rule r r1 r2
  | R r [Ts t] =>
      convert_terminal_rule next r t
  | _  => []   (* Never called *)
  end.

Definition convert_rules
  (rules: list rule) (next: _): list rule :=
  flat_map (convert_rule next) rules.

(* Maps grammar and s_dfa to grammar over triples *)
Definition convert_grammar grammar s_dfa :=
  convert_rules grammar (s_next s_dfa).
```

Listing 16. TODO

Note that since the grammar is in CNF,(?) the third alternative is never called.

Note that at this point we do not have any manipulations with starting rules. Nevertheless(?), the hypothesis of the uniqueness of the final state of the DFA, will help us unambiguously introduce the starting nonterminal of the grammar of intersection.

4.7.2 Correctness

TODO: add some text

In the interest of clarity of exposition, we skip some auxiliary lemmas, such as "we can get the initial grammar from the grammar of intersection by projecting the triples back to terminals/nonterminals ". Also note that the grammar after the conversion remains in CFN. Since the transformation of rules does not change the structure of the rules, but only replaces one(??!!) terminals and nonterminals with others.

Next we prove the two main lemmas. Namely, the derivability in the initial grammar and the *s_dfa* implies the derivability in the grammar of intersection. And the other way around, the derivability in the grammar of intersection implies the derivability in the initial grammar and the *s_dfa*.

Let G be a grammar in CNF. In order to use Chomsky Induction we also assume that syntactic analysis is possible.

Theorem 4.2. *Let s_dfa be an arbitrary DFA, let r be a nonterminal of grammar G, let from and to be two states of the DFA. We also pick an arbitrary word — w. If in grammar G it is possible to derive w out of r and starting from the state from when w is received, the s_dfa ends up in state to, then word w is also derivable in grammar (convert_rules G next) from the nonterminal (V (from, r, to)).*

Proof. TODO. In another case, it would be logical to use induction on the derivation structure in G. But as it was discussed earlier, this is not the case, otherwise we will get a phrase (list of terminals and nonterminals) instead of a word. Let's apply chomsky induction principle with $P := funrphr => \forall(next : dfa\_rule)(fromto : DfaState), final\_statenextfrom(to_wordphr) = to- > der(convert\_rulesGnext)(V(from, r, to))phr$. We will get the bla-bla, bla-bla, bla-bla-bla

Since a language is just a bla-bla-bla, we use the lemma above to prove bla-bla-bla

4.8 Part ..: union

After the previous step, we have a list of grammars of CF languages, in this section, we provide a function by which we construct a grammar of the union of languages.

For this, we need nonterminals from every language to be from different nonintersecting sets. To achieve this we add labels to nonterminals. Thus, each grammar of the union would have its own unique ID number, all nonterminals within one grammar will have the same ID which coincides with the ID of a grammar. In addition, it is necessary to introduce a new starting nonterminal of the union.

```
Inductive labeled_Vt : Type :=
| start : labeled_Vt
| lV : nat -> Vt -> labeled_Vt.

Definition label_var (label: nat)
                     (v: @var Vt): @var
                     labeled_Vt :=
  V (lV label v).
```

Listing 17. TODO

Construction of new grammar is quite simple. The function that constructs the union grammar takes a list of grammars, then, it (1) splits the list into head [*h*] and tail [*tl*], (2) labels [*length tl*] to *h*, (3) adds a new rule from the start nonterminal of the union to the start nonterminal of the grammar [*h*], finally (4) the function is recursively called on the tail [*tl*] of the list.

4.8.1 Equivalence proof

In this section, we prove that function *grammar_union* constructs a correct grammar of union language indeed. Namely, we prove the following theorem.

Theorem 4.3. *Let grammars be a sequence of pairs of starting nonterminals and grammars. Then for any word w, the fact that w belongs to language of union*

```
Definition label_grammar label grammar := ...

Definition label_grammar_and_add_start_rule
             label
             grammar :=
  let '(st, gr) := grammar in
  (R (V start) [Vs (V (lV label st))])
     :: label_grammar label gr.

Fixpoint grammar_union
   (grammars : seq (@var Vt * (@grammar Tt Vt)))
     : @grammar
   Tt
   labeled_Vt :=
  match grammars with
  |  [] => []
  |  (g::t) =>
       label_grammar_and_add_start_rule
         (length t)
         g ++ (grammar_union t)
  end.
```

Listing 18. TODO

is equivalent to the fact that there exists a grammar $(st, gr) \in grammars$ *such that* w *belongs to language generated by* (st, gr).

```
Variable grammars: seq (var * grammar).

Theorem correct_union:
  forall word,
    language (grammar_union grammars)
      (V (start Vt)) (to_phrase word) <->
    exists s_l,
      language (snd s_l) (fst s_l)
        (to_phrase word) /\
      In s_l grammars.
```

Listing 19. TODO

Proof of theorem 4.3. Since the statement is formulated as an equivalence, we divide the proof into two parts:
1. If w belongs to the union language, then w belongs to one of the initial language.
2. If w belongs to one of the initial language, then w belongs to the union language.
The fact that $(st, grammar) \in grammars$ implies that there exist $gr1$ and $gr2$ such that: $gr1{+}{+}(st, grammar) :: gr2 = grammars$.

Proof. This proved through induction over l. assume l = h :: t, then either word accepted by h or tail. If word accepted by h If word accepted by l. We just proving that adding one more language to union preserves word derivability. Which is equivalent to proving that adding new rules to grammar preserves word derivability

2. If we have derivation for some word in new grammar lanager we can provide derivate in for some language from union.

Proof. Here we converting derivability procedure for language union into derivability procedure of one of language. Then we proving that in derivation we can use rules from only one language at time. Finally we converting derivation by simple relabelling back all nonterminals.

4.9 Part N: taking all parts together

TODO: add some text

Theorem 4.4. *For any two decidable types Terminal and Nonterminal for type of terminals and nonterminals correspondingly. If there exists bijection from Nonterminal to* $\mathbb{N}$ *and syntactic analysis in the sense of definition TODO is possible, then for any DFA dfa which accepts Terminal and any grammar* G*, there exists the grammar of intersection* $L(DFA)$ *and* G.

Proof.

5 Related Works

There is a big number of works in mechanization of different parts of formal languages theory and certified implementations of parsing algorithms and algorithms for graph data base querying. These works use different tools, such s Coq, Agda, Isabelle/HOL, and aimed to different problems such as theory mechanisation or executable algorithm certification.

Huge work was done by Ruy de Queiroz who formalize diferent parts of formal langue theory, such as puping lemma [?], context-free grammar simplification [?] and closure properties [?] in Coq. All these results are summarized in [?].

Anoter part of formal languages formalization in Coq by Gert Smolka et.al. [? ?].

Also exist som works by Denis Firsov who implement in Agda many parts of formal language theory and parsing algorithms: CYK [?], Chomsky Normal Form [?], etc [?].

Certified parsers parser generators.

In HOL4.

Certified prolog querying in Coq [?]

6 Conclusion

We present mechanized proof of Bar-Hillel theorem on closure of context-free languages under intersection with regular one. Also we generalize results of Smolka and !!!

: generalized terminal alphabet. It makes More flexible and ease for reusing. All results are published at GitHub.

One of direction of future research is mechanization of practical algorithms which are just implementation of Bar-Hillel theorem. For example, context-free path querying algorithm, based on CYK [**?** **?**] or even on GLL [**?**] parsing algorithm [**?**]. Final target here is certified CFPQ alike Regular by Vardi

Yet another direction is mechanization of other problems on language intersection which can be useful for applications. For example, intersection of two context-free grammars one of which describes finite language [**?** **?**]. It may be useful for compressed data processing.

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