

Tyrolean Complexity Tool: Features and Usage*

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Abstract

The *Tyrolean Complexity Tool*, \mathcal{TCT} for short, is an open source complexity analyser for term rewrite systems. Our tool \mathcal{TCT} features a majority of the known techniques for the automated characterisation of polynomial complexity of rewrite systems and can investigate derivational and runtime complexity, for full and innermost rewriting. This system description outlines features and provides a short introduction to the usage of \mathcal{TCT} .

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1 Introduction

In order to measure the complexity of a term rewrite system (TRS for short) it is natural to look at the maximal length of derivation sequences—the *derivation length*—as suggested by Hofbauer and Lautemann in [13]. The resulting notion of complexity is called *derivational complexity*. Hirokawa and the second author introduced in [11] a variation, called *runtime complexity*, that only takes *basic* or *constructor-based* terms as start terms into account. The restriction to basic terms allows one to accurately express the complexity of a program through the runtime complexity of a TRS. An investigation into these notions is of particular interest, as both constitute an *invariant cost model* for rewrite systems [7, 3], in the sense that the actual cost of a reduction on a standard model of computation, viz Turing machines, is bounded by a polynomial in the size of the start term and the length of the reduction. In particular, if the consider TRS defines a function and this TRS admits a polynomial bound on its runtime complexity, then the function is polytime computable.

As first observed in [13], it is by now folklore that termination techniques induce a certain bound on the time complexity of rewrite systems. The seminal paper by Bonfante et. al., [6] gives an early account on taming a termination technique to infer *feasible*, viz *polynomial*, bounds. Since then, a wealth of techniques have been introduced specifically to establish polynomial complexity bounds [2, 11, 17, 18, 20, 21, 19, 15, 1, 12], see [16] for an overview. Motivated not only by these theoretical advances, but also by the *annual international termination competition*¹, which features four dedicated complexity categories since 2008, a vast part of this theoretical body has been implemented in dedicated complexity analysers for rewrite systems. For instance, the termination prover AProVE² features powerful support

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¹ http://www.termination-portal.org/wiki/Termination_Competition/.

² <http://aprove.informatik.rwth-aachen.de/>.



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for analysing the innermost runtime complexity of TRSs. `CaT`³, a variation of the very fast and powerful termination prover `TTT2`⁴, has excellent support to investigate derivational complexity, and also partial support for runtime complexity analysis. The automated complexity analyser `Matchbox/Poly`⁵ verifies polynomially bounded derivational complexity.

Our tool `TCT`, the *Tyrolean Complexity Tool*, is an automated complexity analyser for TRSs in the line of the aforementioned tools. Its distinct feature is that it is currently the only tool that is competitive, and provides dedicated techniques, for both runtime and derivational complexity analysis. `TCT` is *open-source*, released under the *GNU Lesser General Public License (LGPL)* Version 3, and available from

<http://cl-informatik.uibk.ac.at/software/tct/> .

The theoretical framework underlying `TCT`, which allows for this generality and modularity, is documented in separate work [5]. Here we want to outline the practical aspects of `TCT`, version 2.0 to be precise. In Section 2 we provide a brief description of the implementation including accompanying libraries. Section 3, where we discuss features and usage of our tool, constitutes the main part of this work. In Section 4 we indicate future work and conclude.

2 Implementation

Our tool is implemented in the strongly typed, lazy functional programming language `Haskell`⁶ and compiles on the *Glasgow Haskell Compiler on GNU Linux*. The sources consist of about 13,000 lines of code, and additionally 4,000 lines of documentation. Out of the 73 modules, 43 modules are dedicated to the implementation of the various techniques (roughly 56 % of the code), the remaining modules provide the core of `TCT` and utilities. Our tool makes also use of following `Haskell` libraries, separately available from the `TCT` homepage⁷, that have been specifically developed for `TCT`.

- `qlogic` provides facilities for dealing with propositional logic, and consists of approximately 3100 lines of code. Notably it defines an interface to SAT-solvers, including routines to efficiently translate Boolean formulas to conjunctive normal form. Also it features support for theories over natural numbers and integers, implemented by *bit-blasting*.
- `termLib` provides term rewriting functionality, and consists of around 2100 lines of code.
- `parfold` is a small library that provides folding capabilities over lists of concurrently evaluated monad actions, a simple but convenient abstraction to concurrent programming.

3 Features and Usage

The Tyrolean Complexity Tool currently features 23 techniques which are available for runtime and, where applicable, for derivational complexity analysis. Our implementation follows closely the framework provided in [5] which ensures that the techniques are implemented in a modular way. We indicate some characteristic methods implemented in `TCT`:

Matrix Interpretations: Our tool features an implementation of *matrix interpretations* over the naturals [8], as well as *arctic interpretations* [14]. To weaken monotonicity requirements

³ Available from <http://cl-informatik.uibk.ac.at/software/cat/>.

⁴ Available from <http://cl-informatik.uibk.ac.at/software/ttt2/>.

⁵ Available from <http://dfa.imm.htwk-leipzig.de/matchbox/poly/>.

⁶ An open-source product of more than twenty years of cutting-edge research, c.f. <http://haskell.org/>.

⁷ <http://cl-informatik.uibk.ac.at/projects/>.

we have integrated the *usable arguments criterion* [12] and *usable rules w.r.t. argument filterings* [10]. In order to give polynomial bounds on the induced complexity, TCT can employ *triangular matrices* [18], or use the criteria defined in [15, 20]. Moreover, our implementation also integrates the *weight gap principle* [12].

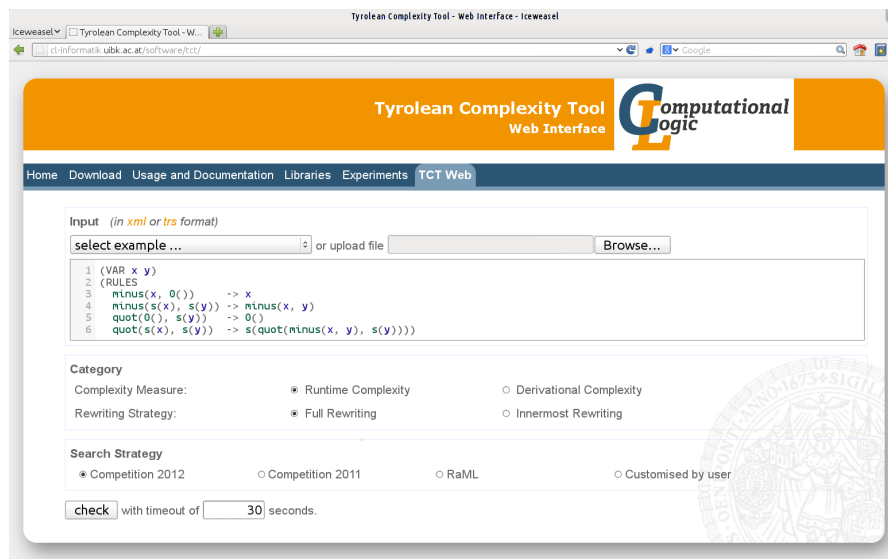
Polynomial Path Orders: Up to our knowledge, TCT is the only tool that features an implementation of *polynomial path orders* [2, 4] as well as the recently introduced *small polynomial path orders* [1]. Both orders constitute a miniaturisation of recursive path orders that induce polynomially bounded innermost runtime complexity. Whereas the former order can only deduce if the innermost runtime complexity is in principle polynomial, its small brother allows a precise control on the complexity certificate obtained.

Match-Bounds: *Match-Bounds* for term rewrite systems [9] is a powerful termination method that induces linear complexity. Our tool supports *match-*, *top-* and *roof-bounds* both for derivational, and its refinement to runtime complexity analysis.

Weak Dependency Pairs and Dependency Tuples: The introduction of *weak dependency pairs* greatly simplifies the task of estimating the runtime complexity of TRSs. Our tool supports this method as well as its refinement to *innermost* rewriting, called *dependency tuples* in [19]. This technique gives rise to advanced techniques specifically designed for the dependency pair setting, notably various *simplifications*, *usable rules*, *path analysis*, (*safe*) *reduction pairs* as well as *dependency graph decomposition*, compare [12, 19, 5].

In the following, we discuss usage of TCT.

3.1 Web Interface



■ **Figure 1** Web Interface of TCT.

Our *web interface*, accessible from the TCT homepage, provides a convenient way to use TCT without the necessity to install the software. The interface is aimed for simplicity, compare Figure 1. For the curious user that wants to play around with TCT, we also provide a wealth of interesting examples. The web interface is configured so that by default an upper bound on the *runtime complexity* of the given rewrite system is estimated. This behaviour can be modified under *category*, where the user can pick from the four different complexity measures TCT currently supports. On success this certificate is presented to the user, together with a proof script that explains in considerable detail how the certificate was obtained.

To find a proof in a reasonable amount of time, the different techniques implemented in TCT need to be combined wisely. This combination depends on the one hand on the input problem, but on the other hand also on the available hardware. In TCT, *proof search* is not hard-wired, instead it is guided by a (*proof*) *search strategy*. The interface allows to specify such a search strategy from a set of pre-defined proof search strategies. Besides the search strategies employed in recent competitions, the web-interface currently offers the search strategy *RaML*, specifically designed for functional programs given as rewrite systems, and a customisable search strategy that allows the explicit inclusion/exclusion of methods.

3.2 Command-Line Interface

The full power of TCT is available through its command-line interface. For installation instructions we refer the reader to the homepage. Here we want to briefly outline usage and customisation, comprehensive documentation can be found online. TCT is run by

```
$ tct [options] [-s <strategy>] <file> ,
```

from the command-line, where [options] specify an optional list of command-line options, <strategy> specifies optionally a proof search strategy, and <file> the *input file*. The input file must adhere either the old *TPDB format*⁸ or the new *XTC Format*⁹.

A list of options can be obtained by typing `tct --help`. In the command-line interface, the proof search strategy is given as an *S-expression* of the form

```
(<name> [[:<argname> <arg>]* [<arg>]*) ,
```

where outermost parentheses can be dropped. Here <name> refers to the name of a proof technique, also called *processor*, the list [[:<argname> <arg>]*] can be used to specify *named optional arguments*, and the list [<arg>]* gives a possibly empty sequence of *positional arguments*. As an example,

```
fastest (timeout 3 (bounds :enrichment match)) (matrix :degree 2) ,
```

provides a valid proof search strategy in TCT. Here `fastest` is used to combine one or more processors in parallel, in this case the `bound` and `matrix` processors, solving the input problem with whichever processor succeeds first. The defined search strategy advises TCT to check for three seconds for *match-boundedness* of the input problem, respectively compatibility with a matrix interpretation that induces a quadratic upper bound. All implemented techniques, including a wealth of *processor combinators* like `fastest` and `timeout`, can be applied directly from the command-line with the option `-s <strategy>`. A complete list of available search strategies, including synopsis and documentation, can be obtained by typing `tct --list`.

Besides basic options given on the command-line, TCT can be configured by modifying the *configuration file*, which resides in `~/tct/tct.hs` by default. This `Haskell` source-file defines the actual binary that is run each time TCT is called. Thus the full expressiveness of `Haskell` is available; as a downside, it requires also a working `Haskell` environment. A minimal configuration is generated automatically on the first run of TCT. This initial configuration consists of a set of convenient imports and the IO action `main` together with a *configuration record* `config`. The configuration record passed in `main` allows one to overwrite various flags of TCT. Most importantly, through the field `strategies` it also allows the modification of the list of proof search strategies that can be employed.

⁸ <http://www.lri.fr/~marche/tpdb/format.html>.

⁹ http://www.termination-portal.org/wiki/XTC_Format_Specification.

```

import Tct (tct)
import Tct.Instances
.....

main :: IO ()
main = tct config

config :: Config
config = defaultConfig { strategies = strategies } where
  strategies = [ matrices :: strategy "matrices" ( optional naturalArg "start" (Nat 1) :+: naturalArg )
              , withDP   :: strategy "withDP" ]

matrices (Nat s :+: Nat n) =
  fastest [ matrix 'withDimension' d 'withBits' bitsForDimension d | d <- [s..s+n] ] where
    bitsForDimension d = if d < 3 then 2 else 1

withDP =
  (timeout 5 dps <> dts)
  >>> try (exhaustively partitionIndependent)
  >>> try cleanTail
  >>> try usableRules where
    dps = dependencyPairs >>> try usableRules >>> wg0nUsable
    dts = dependencyTuples
    wg0nUsable = weightgap 'withDimension' 1 'wg0n' 'Wg0nTrs

```

■ **Figure 2** Configuration defining two new search strategies, called `matrices` and `withDP`.

In Figure 2 we depict a modified configuration that defines two new search strategies, called `matrices` and `withDP`. Strategies are added by overwriting the field `strategies` with a list of declarations of the form

```
<code> :: strategy "<name>" [<parameters-declaration>] .
```

Here `<code>` refers to a definition that evaluates to a processor, and `"<name>"` as well as the optional `<parameters-declaration>` specify how this code is accessible from the command-line. For instance, the first declaration in Figure 2 defines a new search strategy named `matrices`, which is available by supplying the option `-s "matrices [:start <nat>] <nat>"` to the `TCT` executable. Here the parameters to `matrices` are declared by

```
optional naturalArg "start" (Nat 1) :+: naturalArg ,
```

where the infix operator `:+:` is used to specify sequences of parameters. As indicated by the constructor `naturalArg`, the search strategy `matrices` expect two *natural numbers* as arguments. In contrast to the second parameter, the first is optional and defaults to the natural number 1.

In Figure 2, these parameters are provided to the code of `matrices`. Using parameters `s` and `n` as supplied on the command-line, the code evaluates to a processor that searches for `n` compatible matrix interpretations of increasing dimension, in parallel. Both `matrix` and `fastest`, along with other processors, combinators and *modifiers* like `withDimension` and `withBits`, are exported by the module `Tct.Instances`.

The second proof search strategy declared in Figure 2 defines a *transformation* called `withDP`. Transformations are a specific class of processors, that generate from the given input problem a possibly empty set of *sub-problems*, in a complexity-preserving manner.¹⁰ For every transformation `t` and processor `p`, one can use the *processor* `t >>| p` which first applies transformation `t` and then solves the resulting sub-problems using `p`. Search strategy declarations perform such a lifting of transformation implicitly, the declaration of `withDP` for instance results in a search strategy available as `withDP <processor>`. Besides the

¹⁰ Transformations were introduced in Version 1.7 of `TCT`. Although any processor like `matrix` could also be defined as a transformation, the distinction in `TCT` is present mainly for historical reasons.

combinator $\gg|$ and its variation $\gg||$, where the given processor p is applied in parallel on all sub-problems, the module `Tct.Instances` provides a wealth of *transformation combinators*. We briefly discuss here the most important ones. The transformation $t_1 \langle \rangle t_2$ employed in `withDP` first applies transformation t_1 , only if this is unsuccessful it applies transformation t_2 on the input problem instead. A variation of the combinator is given by $t_1 \langle || \rangle t_2$ that applies transformations t_1 and t_2 in parallel, resulting in the sub-problems of whichever transformation succeeds first. The combinator $\langle || \rangle$ thus implements a form of non-deterministic choice. The combinator \gg defines composition of transformations, in the sense that the transformation $t_1 \gg t_2$ first applies transformation t_1 and then transformation t_2 on all resulting sub-problems. We remark that any transformation aborts if it is inapplicable. The combinator `try` overrides this behaviour, in the sense that `try t` behaves exactly like t should t succeed, otherwise it behaves as an identity. Finally, the combinator `exhaustively`, defined by `exhaustively t = t >>> try (exhaustively t)`, applies t in an iterated fashion.

In total, the defined search strategy `withDP` depicted in Figure 2 applies weak dependency pairs (as realised in the definition of `dps`), or dependency tuples (as realised by `dts`) should the former fail. This transformation is followed by a sequence of syntactic simplifications, if applicable. We remark the thoughtful use of `try`. The transformation `dps` fails if the *weight gap principle* cannot be established on all TRS rules, i.e., rules that are not dependency pairs. The latter is implemented by the transformation `wgOnUsable`, and constitutes an implementation of [12, Theorem 6.5]. We finally point out that an extended version of the transformation `withDP` is available in `TCT` as `toDP`.

3.3 Interactive Interface

`TCT` features also an *interactive interface*, `TCT-i` for short. In this section we guide the reader through a small interactive session that outlines the main features, elaborate documentation of this mode is again provided online.

This *semi-automatic* mode is in particular useful when investigating into tight(er) complexity bounds, and to crack hard-to-solve problems. The interactive interface constitutes essentially of a tiny wrapper around `ghci`, the interpreter bundled with the *Glasgow Haskell compiler*. Users familiar with `ghci` will note that all features available in `ghci` are also available in `TCT-i`. The interactive interface is started from the command-line by supplying the option `-i` to the `TCT` executable.

```
$ tct -i
GHCi, version 7.4.1: http://www.haskell.org/ghc/  :? for help
⌘.....
  This is version 2.0 of the Tyrolean Complexity Tool.

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    Georg Moser <georg.moser@uibk.ac.at>, and
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Don't know how to start? Type 'help'.
TCT>
```

The interactive interface maintains a *proof state*, which consists conceptually of a list of *open problems* together with proof information. The command `load "<file>"` is used to populate the proof state by the TRS given as argument.

```
TCT> load "examples/div.trs"

Current Proof State -----
```

```

Selected Open Problems:
-----
Strict Trs:
  { -(x, 0()) -> x
    , -(s(x), s(y)) -> -(x, y)
    , %(0(), s(y)) -> 0()
    , %(s(x), s(y)) -> s(%(-(x, y), s(y))) }
StartTerms: basic terms
Strategy: none
-----

```

The current state can be inspected at any time by typing the command `state`. We note that the rewrite strategy and set of start terms are defined in accordance to the input file. The commands `set [DC|RC|IDC|IRC]` provide short-hands to these accordingly.

The primary means to modify the proof state is the use of the command `apply`. This command takes a single argument, a transformation or processor respectively, which is applied by default on all open problems collected in the current proof state. Both processors and transformations as imported from `Tct.Instances` qualify as arguments to `apply`. Of course one can also use the various combinators that we have seen so far to construct more complex arguments. Notably, since `TCT-i` loads the configuration file of `TCT`, all declarations given in the configuration are available as top-level bindings, and can thus be used in conjunction with `apply`. Recall that our configuration defines a transformation `withDP` that computes weak dependency pairs or dependency tuples respectively, applying various transformations on success. We use this transformation to simplify the input problem.

```

TCT> apply withDP

Problems simplified. Use 'state' to see the current proof state.

```

The output of `apply` is intentionally kept short.¹¹ By typing `state` one can observe that our initially loaded complexity problem has been replaced by the problem obtained by our transformation `withDP`. To see that proof generated so far, one can use the command `proof`. Note that as long as the list of open problems is not empty, this proof is marked as open.

```

TCT> proof

1) dp [OPEN]:
-----
We consider the following problem:
  Strict Trs:
    { -(x, 0()) -> x
      , -(s(x), s(y)) -> -(x, y)
      , %(0(), s(y)) -> 0()
      , %(s(x), s(y)) -> s(%(-(x, y), s(y))) }
  StartTerms: basic terms
  Strategy: none

We add following weak dependency pairs:
⊗.....
1.1) Open Problem [OPEN]:
-----

We consider the following problem:
  Strict DPs:
    { -^#(x, 0()) -> c_1(x)
      , -^#(s(x), s(y)) -> c_2(-^#(x, y))
      , %^#(s(x), s(y)) -> c_4(%^#(-(x, y), s(y))) }
  Weak Trs:
    { -(x, 0()) -> x
      , -(s(x), s(y)) -> -(x, y) }
  StartTerms: basic terms
  Strategy: none

```

¹¹To override this behaviour and see actions performed, one can use the command `setShowProofs`, or alternatively set the field `interactiveShowProofs` to `True` in the configuration record of `TCT`.

Besides `state` and `proof`, following commands allow for further inspection of the current proof state. The command `problems` returns the list of open problems, `wdgs` and `cwdgs` return the corresponding dependency graphs respectively congruence graph and `uargs` returns the usable argument positions. Cf. [12] for an explanation of these attributes. For instance, we can use `cwdgs` to inspect the congruence graph of our open problem as follows.

```
TCT> [cwdg] <- cwdgs
Congruence Graph of Problem 1:
->1:{1,2}
  |
  '->2:{3}

Here dependency-pairs are as follows:

Strict DPs:
{ 1: -^(x, 0()) -> c_1(x)
  , 2: -^(s(x), s(y)) -> c_2(-^(x, y))
  , 3: %^(s(x), s(y)) -> c_4(%^(-^(x, y), s(y))) }
TCT> :module +Tct.Method.DP.DependencyGraph
TCT> isEdgeTo cwdg 1 2
True
```

Once the list of open problem is empty, the complexity of the input problem has been successfully proven. We can do so on our running example using the matrix processor that we have already used before.

```
TCT> apply matrix
Hurray, the problem was solved with certicicate YES(0(1),0(n^2)).
Use 'proof' to show the complete proof.
```

We have found a closed proof that verifies that our initial problem has at most quadratic runtime complexity. We remark that the runtime complexity of the input TRS is even linear. Inspecting the proof we see that the imprecision in the certificate was introduced in the last proof step. Fortunately TCT-i provides a command `undo` that can be used to revert the effect of `apply`. In fact, it reverts any modification on the proof state, except of course the effect of `undo` itself. We refine the proof by restricting the *induced degree* of the constructed interpretation.

```
TCT> undo
Current Proof State -----

Selected Open Problems:
-----
Strict DPs:
{ -^(x, 0()) -> c_1(x)
  , -^(s(x), s(y)) -> c_2(-^(x, y))
  , %^(s(x), s(y)) -> c_4(%^(-^(x, y), s(y))) }
Weak Trs:
{ -(x, 0()) -> x
  , -(s(x), s(y)) -> -(x, y) }
StartTerms: basic terms
Strategy: none
-----

TCT> apply $ matrix 'withDegree' Just 1
Hurray, the problem was solved with certicicate YES(0(1),0(n^1)).
Use 'proof' to show the complete proof.
```

Here the function `withDegree` is used to modify the default parameters as defined in `matrix`.¹² We finally end up with a closed proof that verifies that our loaded TRS has linear runtime complexity. Using the command `writeProof "<file>"` one can write the constructed proof to the given file.

¹²The application operator `$` has low, right-associative binding precedence.

This completes the short tutorial. We remark that for the GNU Emacs¹³ enthusiast, we have also crafted a small major-mode for TCT-i. This mode is available in the source distribution of TCT. The mode can be started by typing `M-x tct` into GNU Emacs. In addition to the features explained above, the major-mode provides a refurbished view on the proof state, compare Figure 3 which shows an example session. The approximated dependency graph depicted in Figure 3 is visualised using the dot tool of the *Graphviz* toolkit.¹⁴

```

emacs@lap40-cl-c703.uibk.ac.at
File Edit Options Buffers Tools TctInteractive Errors Complete In/Out Signals Help

/home/zini/.tct/examples:
total used in directory 52 available 84103440
drwxr-xr-x 6 zini zini 4096 Jan 26 10:44 .
drwxr-xr-x 21 zini zini 4096 Jan 5 23:34 ..
-rw-r--r-- 1 zini zini 346 Jan 26 10:44 egypt.trs
drwxr-xr-x 8 zini zini 4096 Jan 26 11:21 git
drwxr-xr-x 2 zini zini 4096 Jan 26 10:48 misc
drwxr-xr-x 2 zini zini 4096 Jan 26 11:21 raml
-rw-r--r-- 1 zini zini 9683 Jan 24 11:40 raml.tgz
-rwxr-xr-x 1 zini zini 11107 Dec 30 14:41 Rewrite.hs
drwxr-xr-x 2 zini zini 4096 Dec 31 14:44 sorting

* Problem 1:...
* Strict DPs:...
* Weak DPs:...
* Weak Rules:...
* Problem 2:
:PROPERTIES:...

graph TD
    1((1)) --> 1

* Strict DPs:
{ 1: eratos*#(:(x, xs)) -> c_1(eratos*#(filter(x, xs))) }
* Weak Rules:
{ #equal(x, y) -> #eq(x, y)
, #eq(:(x_1, x_2), :(y_1, y_2)) ->
, #and(#eq(x_1, y_1), #eq(x_2, y_2))
, #eq(:(x_1, x_2), nil()) -> #false() }

-U:~%: *Tct-dired* All (5,45) (Dired by name Tct)--11:--:~%: *tcti-state* %{}{115,2} (Org View ARev)--11:27AM 0.10-----

, #divsub(#s(x), #0()) -> #s(x)
, #divsub(#s(x), #s(y)) -> #divsub(x, y)
, #natdiv'(#0(), y) -> #s(#0())
, #natdiv'(#s(x), y) -> #s(#natdiv(#s(x), y))
, #natdiv'(#underflow(), y) -> #0()
, #natadd(#0(), y) -> y
, #natadd(#s(x), y) -> #s(#natadd(x, y)) }
StartTerms: basic terms
Strategy: innermost

Problems simplified. Use 'state' to see the current proof state.

Tct>
-U:~%: *Tct-interactive* Bot (10831,5) (Inf-Haskell:run Tct Compilation)--11:27AM 0.10-----

```

Figure 3 TCT Major Mode for GNU Emacs.

4 Conclusion and Future Work

Our complexity analyser TCT has matured to a state where we can say that it is both versatile and powerful. This is underpinned by the experimental evidence given online¹⁵ which highlights in particular the strength of the underlying combination framework presented in [5].

We of course seek to keep the implementation in line with the active research community. In the upcoming version, we also intend to remove some out-dated design choices, foremost the separation of processors and transformations, which will result in a significantly simplified core. Also, we currently investigate the integration of constrained rewriting. This should leverage the design of complexity preserving reductions from *real world* programs to rewrite systems, in the hope that TCT will act as a powerful backend.

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¹³ GNU Emacs is open-source and available from <http://www.gnu.org/s/emacs/>.

¹⁴ The toolkit is open-source and available from <http://www.graphviz.org/>.

¹⁵ C.f. <http://cl-informatik.uibk.ac.at/software/tct/experiments/tct2/>.

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