The **irace** Package: User Guide

Manuel López-Ibáñez, Leslie Pérez Cáceres, Jérémie Dubois-Lacoste,
Thomas Stützle and Mauro Birattari
IRIDIA, CoDE, Université Libre de Bruxelles, Brussels, Belgium

June 1, 2016

Contents

1 General information

1.1 Background

The **irace** package implements the *iterated racing* procedure, which is an extension of Iterated F-race (I/F-Race). The main use of **irace** is the automatic configuration of optimization algorithms, that is, finding the most appropriate settings of an optimization algorithm given a set of instances of an optimization problem. It builds upon the **race** package by Birattari and it is implemented in R. The **irace** package is available from CRAN. More information about **irace** is available at `http://iridia.ulb.ac.be/irace`.

1.2 Version

The current version of the **irace** package is version 2.0. Previous versions of the package can be found in the **irace** package CRAN website.

`https://cran.r-project.org/web/packages/irace/`

Previous versions of **irace** *might not be compatible with the file formats detailed in this document.*

1.3 License

2 Before starting

[MANUEL: I think this could be a bit more detailed by defining what is a parameter, a configuration, an instance, etc. but ok for now.]

The **irace** package provides an automatic configuration tool for tuning optimization algorithms. The **irace** tool automatically finds good configurations for the parameters values of a (target) algorithm saving the effort that normally requires manual tuning.

Figure 1 gives a general scheme of how **irace** works. **irace** receives as input a `parameter space definition` corresponding to the parameters of the target algorithm that will be tuned, a set of `instances` for which the parameters must be tuned for and a set of `options` for **irace**.

irace moves through the parameter search space in search of good performing algorithm configurations, for doing so **irace** executes the target algorithm on

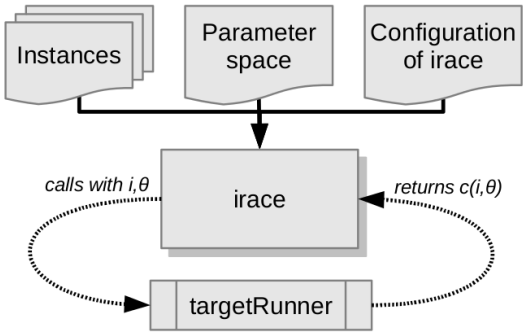


Figure 1: Scheme of **irace** flow of information.

different instances and with different parameter configurations. To execute the target algorithm with a specific parameter configuration (θ) and instance (i) a `targetRunner` must be provided. The `targetRunner` acts as an interface between the execution of the target algorithm and **irace**, it receives the instance and configuration as argument and must return the evaluation of the execution of the target algorithm.

The following user guide contains a guidelines to use **irace** and define the needed components to execute **irace** to automatically configure an optimization algorithm.

3 Installation

3.1 System requirements

- R (version $\geq$ 2.14.0) is required for running irace, but you don't need to know the R language to use it. R is freely available and you can download it from the R project website:

  http://www.r-project.org

  See Section A for a quick installation guide of R.

- If you wish to use the command-line scripts `irace` and `parallel-irace`, they require GNU Bash.

3.2 irace installation

The **irace** package can be installed automatically within R or by manual download and installation. We advise to use the automatic installation unless particular circumstances do not allow it. The instructions to install **irace** with the two mentioned methods are the following:

1. **Install automatically within R**:
   In the R console execute the following line to install the package :

```
> install.packages("irace")
```

Select a mirror close to your location, and test the installation in the R console with:

```
> library("irace")
> CTRL+d
```

If your run OS X you can use the `Packages and data -> Package installer` menu in the R console and on Windows you can use the `Packages` menu, follow the given instructions for installing the **irace** package.

2. **Manual download and installation**:
   Go to the **irace** package CRAN website:

   http://cran.r-project.org/package=irace

   Download one of the three versions available depending of your operating system:

   - `irace_2.0.tar.gz` (Unix/BSD/GNU/Linux)
   - `irace_2.0.tgz` (OSX)
   - `irace_2.0.zip` (Windows)

   To install the package on GNU/Linux and OSX, you must execute the following command at the command-line:

   ```
   # Replace <package> with the path of the downloaded file.
   R CMD INSTALL <package>
   ```

   To install the package on Windows open R and execute the following line on the R console:

   ```
   > # Replace <package> with the path of the downloaded file.
   > install.packages("<package>", repos = NULL)
   ```

Once **irace** has been installed, load the package and test that the installation was successful by opening an R console and executing:

```
> # Load the package
> library("irace")
> # Obtain the installation path
> system.file(package="irace")
```

The last command must print out the path of the library where **irace** is installed. In the following of this document the variable `$IRACE_HOME` is used in replacement of this path. When executing any provided command that includes the `$IRACE_HOME` variable do not forget replace this variable with the installation path of **irace**. If you are using GNU/Linux or OSx you can create the `$IRACE_HOME` variable and add the path to your `.bash_profile`, `.bashrc` or `.profile` by executing the commands:

```
# Replace <installation path> with the irace installation path
export IRACE_HOME=<installation path>
export PATH=${IRACE_HOME}/bin/:$PATH
```

After adding this and opening a new terminal, you should be able to launch **irace** as follows:

```
irace --help
```

Unfortunately, this is not possible in Windows given that the command-line wrapper is not supported. To launch **irace**, you need to open the R console and execute:

```
> library("irace")
> irace.cmdline("--help")
```

3.2.1 Local installation

If the previous installation instructions fail to install the package because of insufficient permissions, you need to force a local installation. If you run GNU/Linux or OSx, execute the following commands to install the package in a local directory:

```
# Create a directory for the installation
mkdir ~/R
# Replace <package> with the path of the downloaded file.
R CMD INSTALL --library=~/R <package>
export R_LIBS=~/R:${R_LIBS}
```

If you use Windows, you can install the package in a local directory by executing the following lines in the R console:

```
> # Replace <package> with the path of the downloaded file.
> # Replace <installation path>' with the path used for
> # installation in the previous step.
> install.packages("<package>",
+                  repos = NULL,
+                  lib="<installation path>")
> # Set the local library, this must be executed
> # for every new session.
> .libPaths(c("<installation path>", .libPaths()))
```

Note that in both cases the directory where **irace** will be installed **must** exist before attempting the installation. Since the **irace** package is installed in a local library, you **must** provide to R the path to this library when loading the package.

Once installed, load the package and test the correct installation by opening an R console and executing:

```
> # Replace <installation path>' with the path used for
> # installation in the previous step.
> library("irace", lib.loc="<installation path>" )
> system.file(package="irace")
```

The last line must show the installation path of **irace**. In the following of this document the variable `$IRACE_HOME` is used in replacement of this path. When executing any provided command that includes the `$IRACE_HOME` variable do not forget replace this variable with the installation path of **irace**. If you are running GNU/Linux or OSx you can create the `$IRACE_HOME` variable and add permanently the local library path to your `.bash_profile`, `.bashrc` or `.profile` by executing the following commands:

```
# Replace <installation path> with the path used for
# installation in the previous step.
export IRACE_HOME=<installation path>
export PATH=${IRACE_HOME}/bin/:$PATH
# Use the following line only if local installation was forced
export R_LIBS=~/R:${R_LIBS}
```

4 Executing irace

Before performing the tuning of your algorithm it is necessary to define an **irace** tuning scenario that will give **irace** all the necessary information to optimize the parameters of the algorithm. The tuning scenario is composed of the following elements:

1. Target algorithm parameter description (see Section 5.1).
2. Target algorithm runner (see Section 5.2).
3. Training instances list (see Section 5.4)
4. Irace options (see Section 11).
5. *Optional:* Initial configurations (see Section 5.5).
6. *Optional:* Forbidden configurations (see Section 5.6).
7. *Optional:* Target algorithm evaluator (see Section 5.3).

These scenario elements can be provided as plain text files or as R objects. This user guide provides examples of both modalities, but we advise the use of plain text files which we consider the simpler option.

For a step by step guide to create the scenario elements for your target algorithm continue to Section 4.1. For an example execution of **irace** using the **ACOTSP** scenario go to Section 4.2.

Once all the scenario elements are prepared you can execute **irace**. **irace** can be executed using the command-line wrappers provided by the package (only available for GNU/Linux and OS X) or directly from the R console:

1. On GNU/Linux and OSx execute **irace** by doing:

```
# $IRACE_HOME is the installation directory of irace.
$IRACE_HOME/bin/irace --scenario scenario.txt
```

   For this example we assume that the needed scenario files have been set properly in the `scenario.txt` file using the options described in Section 11. Most **irace** options can be specified in the command line or directly in the `scenario.txt` file.

2. On any operating system you can execute **irace** from the R console by executing:

```
> library("irace")
> parameters <- readParameters("parameters.txt")
> scenario <- readScenario(filename="scenario.txt",
+                          scenario=defaultScenario())
> irace(scenario=scenario, parameters=parameters)
```

irace provides a check tool to test that the scenario elements are correctly defined. We recommend to perform a check every time you create a new scenario. When performing the check, **irace** will control that the scenario and parameter definition are correct and will test the execution of the target algorithm. To check your scenario execute the following commands:

1. On GNU/Linux and OSx execute from the command-line:

```
# $IRACE_HOME is the installation directory of irace.
$IRACE_HOME/bin/irace --scenario scenario.txt --check
```

2. On any operating system execute from the R console the following lines:

```
> library("irace")
> scenario <- readScenario(filename="scenario.txt",
+                          scenario=defaultScenario())
> checkIraceScenario(scenario=scenario)
```

4.1 Step by step setup guide

This section provides a guide to setup a basic execution of **irace**. The template files provided in the package (`$IRACE_HOME/templates`) will be used as base for creating your new scenario. Please follow carefully the indications provided in each step and in the template files used, if you have doubts check the the sections that describe each scenario element in detail.

1. Create a directory (e.g. `~/tuning/`) for the scenario setup, this directory will contain all the files that describe the scenario.

```
mkdir ~/tuning
cd ~/tuning
```

To set the working directory in R use the following lines in the R console:

```
> set.wd("~/tuning")
```

2. Copy all the template files in the to the `$IRACE_HOME/templates/` directory to the scenario directory.

```
# $IRACE_HOME is the installation directory of irace.
cp $IRACE_HOME/templates/*.tmpl  ~/tuning/
```

Remember that `$IRACE_HOME` is the path to the installation directory of **irace**. It can be obtained in the R console with:

```
> library("irace")
> system.file(package="irace")
```

3. For each template in your tuning directory, remove the `.tmpl` suffix, and modify them following the next steps.

4. Define the target algorithm parameters to be tuned, follow the instructions in `parameters.txt`. Available parameter types and other guidelines can be found in Section 5.1.

5. *Optional*: Define forbidden parameter values combinations, that is, configurations that **irace** must not consider in the tuning. Follow the instructions in `forbidden.txt`. More information about forbidden configurations in Section 5.6. **Important**: If you do not need to define forbidden configurations remove this file from the directory.

6. *Optional*: Define the initial parameter configuration(s) of your algorithm, this option allows you to provide good starting configurations (if you know some) for the tuning. Follow the instructions in `configurations.txt`. More information in Section 5.5. **Important**: If you do not need to define initial configurations remove this file from the directory.

7. Put the instances you would like to use for the tuning of your algorithm in the folder `~/tuning/Instances/`. In addition, you can create a file (e.g. `instances-list.tmpl`) that specifies which instances from that directory should be run and which instance-specific parameters to use. If you will be using the instance list file, set in the `scenario.txt` file as:

```
trainInstancesFile = "instances-list.txt"
```

See Section 5.4 for guidelines.

8. Uncomment and assign in `scenario.txt` only the options for which you need a value different than the default. The names of the template files match the default names of the scenario options. Some common parameters that you might want to adjust are:

   - `execDir` (`--exec-dir`): set a directory in which **irace** will execute the target algorithm, the default value is the current directory.
   - `logFile` (`--log-file`): set the name of the results R data file that produces **irace**.
   - `maxExperiments` (`--max-experiments`): set the maximum number of executions of the target algorithm that **irace** is allowed. The default is 1000.

   For more information of **irace** options and their default values see Section 11.

9. Modify the `target-runner` script to run your algorithm, this script must execute your algorithm with the parameters and instances specified by **irace** and return **only** one number corresponding to the evaluation of the execution. The template we use in this guide is in bash, that means it can only be used in GNU/Linux and OSx systems, for other systems you can use any other scripting language, we provide a python template in the `$IRACE_HOME/examples/python` package directory. Follow this instructions to adjust the `target-runner` to your algorithm:

   (a) Set the `EXE` variable with the path to the executable of the target algorithm.

   (b) Set the `FIXED_PARAMS` if you need extra arguments in the execution line of your algorithm, an example could be the time that your algorithm is required to run (`FIXED_PARAMS="--time 60"`) or the number of evaluations required (`FIXED_PARAMS="--evaluations 10000"`).

   (c) The line provided in template:

   ```
   $EXE ${FIXED_PARAMS} -i ${INSTANCE} --seed ${SEED}
                        ${CAND_PARAMS}
   ```

   Will execute the executable described in the EXE variable. You must change this line according to the way your algorithm is executed. In this example, the algorithm receives the instance to solve with the flag `-i` and the seed with the flag `--seed`. The variable `CAND_PARAMS` adds to the command line the parameters that **irace** has give for the execution. You are free to set the command line execution as needed, for example the instance might not need a flag and might need to be only the first argument:

   ```
   $EXE ${INSTANCE} ${FIXED_PARAMS} --seed ${SEED}
                    ${CAND_PARAMS}
   ```

   The output of your algorithm is redirected to the file defined in the `$STDOUT` variable when there is an error in the execution the output of it will be in `$STDERR`. The line:

```
if [ -s "$STDOUT" ]; then
```

checks if the file where the output of your algorithm was redirected exists. The example provided in the template assumes that your algorithm prints in the last output line the best result found (only a number). The line:

```
COST=$(cat ${STDOUT} | grep -e '^[[:space:]]*[+-]
    ?[0-9]' | cut -f1)
```

parses the output of your algorithm to obtain the result from the last line. The `target-runner` script must return **only** one number. In the template example the result is returned with `echo "$COST"` and the used files are deleted.

The `target-runner` *script must be executable.*

You can test the target runner from the R console by performing an scenario check:

```
> library("irace")
> scenario <- readScenario(filename="scenario.txt",
+                          scenario=defaultScenario())
> checkIraceScenario(scenario=scenario)
```

If you are using GNU/Linux you can also execute the check from the command-line:

```
# $IRACE_HOME is the installation directory of irace.
$IRACE_HOME/bin/irace --scenario scenario.txt --check
```

If you have problems related to the `target-runner` script when executing **irace** see Section B for a check list to find the problems. For more information about the `targetRunner` please see Section 5.2,

10. *Optional*: Modify the `target-evaluator` file. You can follow the guidelines provided for defining the `targetEvaluator` in Section 5.3.

Once the files have been prepared you can execute **irace** using the command-line or directly from the R console:

- **On the console**: call the command:

```
cd ~/tuning/
$IRACE_HOME/bin/irace
```

- **On the R console**: create the R objects `scenario` and `parameters`, go to the created directory (`cd tuning`), open an R console and execute:

```
> library("irace")
> parameters <- readParameters("parameters.txt")
> scenario <- readScenario(filename="scenario.txt",
+                          scenario=defaultScenario())
> irace(scenario=scenario, parameters=parameters)
```

This will perform one run of **irace**. See the output of `irace --help` in the command-line or `irace.usage()` in R for quick information on additional **irace** parameters, for more information about **irace** options see Section 11.

Command-line parameters override the scenario setup specified in the scenario.txt file.

4.2 Set-up example for ACOTSP

The **ACOTSP** tuning example can be found in the package installation:

`$IRACE_HOME/examples/acotsp`

Additionally, a number of example scenarios can be found in the `examples` folder. More examples of tuning scenarios can be found in the Algorithm Configuration Library (AClib):

http://www.aclib.net/

In this section we describe how to execute the **ACOTSP** scenario, if you wish to start setting up your own scenario continue in the next section. For the example we assume a GNU/Linux system but making the necessary changes in the commands and `targetRunner`, it can be executed in any system that has a `C` compiler. To execute this scenario follow the steps described in the following:

1. Create a directory for the tuning (e.g. `~/tuning/`) and copy the example scenario files located in the `examples` folder to the created directory:

```
mkdir ~/tuning
cd ~/tuning
# $IRACE_HOME is the installation directory of irace.
cp $IRACE_HOME/examples/acotsp/* ~/tuning/
```

2. Download the training instances from http://iridia.ulb.ac.be/irace/ to the `~/tuning/` directory.

3. Create the instance directory (e.g. `~/tuning/Instances`) and decompress the instance files in on it.

```
mkdir ~/tuning/Instances/
cd ~/tuning/
tar -xvf tsp-instances-training.tar.bz2 Instances/
```

4. Download the **ACOTSP** software from http://www.aco-metaheuristic.org/aco-code/ to the `~/tuning/` directory and compile it.

```
cd ~/tuning/
tar -xvf ACOTSP-1.03.tgz
cd ~/tuning/ACOTSP-1.03
make
```

5. Create a directory for the executable and copy it:

```
mkdir ~/bin/
cp ~/tuning/ACOTSP-1.03/acotsp ~/bin/
```

6. Create a directory for executing the experiments and execute **irace**:

```
mkdir ~/tuning/acotsp-arena/
cd ~/tuning/
# $IRACE_HOME is the installation directory of irace.
$IRACE_HOME/bin/irace
```

7. You can also execute **irace** from the R console using:

```
> library("irace")
> set.wd("~/tuning/")
> parameters <- readParameters("parameters-acotsp.txt")
> scenario <- readScenario(filename="scenario.txt",
+                          scenario=defaultScenario())
> irace(scenario=scenario, parameters=parameters)
```

5 irace scenario

5.1 Target algorithm parameters

The target parameters are defined by a parameter file as described in Section 5.1.4. Optionally, when executing **irace** from the R console, the parameters can be specified directly as an R object (see Section 5.1.5). For defining your parameters follow the guidelines provided in the following sections.

5.1.1 Parameter types

In **irace** each target parameter has an associated type which defines the possible values it can take and the way **irace** handles them internally. Understanding the nature of the domains of the target parameters is important to select appropriate types. The four basic types supported by **irace** are the following:

- *Real* parameters are numerical parameters that can take any floating-point values within a given range. The range is specified as an interval '`(<lower bound>,<upper bound>)`'. This interval is closed, that is, the parameter value may eventually be one of the bounds. The possible values are rounded to a number of *decimal places* specified by option `digits`. For example, given the default number of digits of 4, the values 0.12345 and 0.12341 are both rounded to 0.1234.
- *Integer* parameters are numerical parameters that can take only integer values within the given range. The range is specified as for real parameters.

- *Categorical* parameters are defined by a set of possible values specified as '`(<value 1>, ..., <value n>)`'. The values are quoted or unquoted character strings. Empty strings and strings containing commas or spaces must be quoted.
- *Ordinal* parameters are defined by an *ordered* set of possible values in the same format as for categorical parameters. They are handled internally as integer parameters, where the integers correspond to the indexes of the values.

5.1.2 Parameter values

For each target parameter an interval or a set of values must be defined. There is no limit for the size of the set or the length of the interval, but keep in mind that larger domains could increase the difficulty of the tuning task. Choose always values that you consider relevant for the tuning. All intervals are considered as closed intervals.

It is possible to define parameters that will have always the same value. Such "fixed" parameters will not be tuned but their values are used when executing the target algorithm and they are affected by constraints defined on them. All fixed parameters must be defined as categorical parameters and have a one element set.

5.1.3 Conditional parameters

Conditional parameters are active only when others have certain values, this dependencies define a hierarchical relation between parameters. For example, if the target algorithm can select to use or not a tabu search, then only if a tabu search is chosen as local search the, the parameter that controls the length of the tabu list needs to be set.

5.1.4 Parameter file format

For simplicity, the description of the parameters space is given as a table. Each line of the table defines a configurable parameter:

```
<name> <label> <type> <range> [ | <condition>]
```

where each field is defined as follows:

`<name>`	The name of the parameter as an unquoted alphanumeric string, for instance: '`ants`'.
`<label>`	A *label* for this parameter. This is a string that will be passed together with the parameter to `targetRunner`. In the default `targetRunner` provided with the package (Section 5.2), this is the command-line switch used to pass the value of this parameter, for instance '`"--ants "`'.
`<type>`	The type of the parameter, either *integer*, *real*, *ordinal* or *categorical*, given as a single letter: '`i`', '`r`', '`o`' or '`c`'.
`<range>`	The range or set of values of the parameter delimited by simple parethesis. e.g. `(0,1)` or `(a,b,c,d)`.
`<condition>`	An optional *condition* that determines whether the parameter is enabled or disabled, thus making the parameter subordinate. If the condition evaluates to false, then no value is assigned to this parameter, and neither the parameter value nor the corresponding label are passed to `targetRunner`. The condition must be a valid R logical expression[1]. The condition may contain the name of other parameters as long as the dependency graph does not contain any cycle. Otherwise, **irace** will detect the cycle and stop with an error.

Figure 2 gives as example the parameters file of the ACOTSP scenario:

```
# name      switch           type values    [| conditions (using R syntax)]
algorithm   "--"             c    (as,mmas,eas,ras,acs)
localsearch "--localsearch " c    (0, 1, 2, 3)
alpha       "--alpha "       r    (0.01, 5.00)
beta        "--beta "        r    (0.01, 10.00)
rho         "--rho  "        r    (0.00, 1.00)
ants        "--ants "        i    (5, 100)
nnls        "--nnls "        i    (5, 50)    | localsearch %in% c(1, 2, 3)
q0          "--q0 "          r    (0.0, 1.0) | algorithm %in% c("acs")
dlb         "--dlb "         c    (0, 1)     | localsearch %in% c(1,2,3)
rasrank     "--rasranks "    i    (1, 100)   | algorithm %in% c("ras")
elitistants "--elitistants " i    (1, 750)   | algorithm %in% c("eas")
```

Figure 2: Parameter file (`parameters.txt`) for tuning **ACOTSP**.

5.1.5 Parameters R format

The target parameters are stored in an R `list` you can obtain from the R console using the following command:

```
> parameters <- readParameters(file="parameters.txt")
```

See the help of the `readParameters` function (`?readParameters`) for more information. The structure of the parameter list that is created is as follows:

[1] For a quick list of R operators see: https://stat.ethz.ch/R-manual/R-devel/library/base/html/Syntax.html

`names`	Vector that contains the names of the parameters.
`types`	Vector that contains the type of each parameter 'i', 'c', 'r', 'o'.
`switches`	Vector that contains the switches to be used for the parameters on the command line.
`domain`	List of vectors, where each vector may contain two values (minimum, maximum) for real and integer parameters, or a set of values for categorical and ordinal parameters.
`conditions`	List of R logical expressions, with variables corresponding to parameter names.
`isFixed`	Logical vectors that specifies which parameter is fixed and, thus, it does not need to be tuned.
`nbParameters`	An integer, the total number of parameters.
`nbFixed`	An integer, the number of parameters with a fixed value.
`nbVariable`	Number of variable (to be tuned) parameters.

The following example shows the structure of the `parameters` R object for the `algorithm`, `ants` and `q0` parameters of the **ACOTSP** scenario:

```
> print(parameters)

# $names
# [1] "algorithm" "ants"      "q0"
#
# $types
# algorithm      ants        q0
#       "c"       "i"       "r"
#
# $switches
# algorithm      ants        q0
#      "--" "--ants "   "--q0 "
#
# $domain
# $domain$algorithm
# [1] "as"   "mmas" "eas"  "ras"  "acs"
#
# $domain$ants
# [1]   5 100
#
# $domain$q0
# [1] 0 1
#
#
# $conditions
# $conditions$algorithm
# expression(TRUE)
#
# $conditions$ants
```

```
# expression(TRUE)
#
# $conditions$q0
# expression(algorithm %in% c("acs"))
#
#
# $isFixed
# algorithm       ants         q0
#     FALSE     FALSE     FALSE
#
# $nbParameters
# [1] 3
#
# $nbFixed
# [1] 0
#
# $nbVariable
# [1] 3
```

5.2 Target algorithm runner

The execution of a candidate configuration on a single instance is done by means of a user-given auxiliary program or, alternatively, a user-given R function. The function (or program name) is specified by the option `targetRunner`. The `targetRunner` must return the evaluation of the execution unless a post-execution evaluation (e.g.multi objective evaluation) is required, see Section 5.3 for details.

The objective of **irace** *is to minimize the obtained evaluations. If you wish to maximize you can multiply the evaluations by* `-1` *before returning them.*

5.2.1 Target runner executable program

When `targetRunner` is an auxiliary executable program, it is invoked for each candidate configuration, passing as arguments:

```
<configuration_id> <instance_id> <seed> <instance> [<extra_instance_params>] <command_line>
```

1. `configuration id` : The numeric identifier uniquely identifies a configuration.
2. `instance id`: The numeric identifier uniquely identifies a pair `<instance, seed>`.
3. `seed`: Seed to be used for the execution.
4. `instance`: Instance to be used for the execution.

5. `extra instance parameters`: User-defined value associated to the instance.

6. `command line`: Candidate configuration command line.

The experiment list shown in Section 5.2.2, would result in the following execution line:

```
./targetRunner 1 113 734718556 \
 /home/user/instances/tsp/2000-533.tsp --eas --localsearch 0 \
 --alpha 2.92 --beta 3.06 --rho 0.6 --ants 80
```

The command line is constructed by appending to each parameter label (switch), *without separator*, the value of the parameter, following the order given in the parameter table. The program `targetRunner` must print (only) a real number, which corresponds to the cost measure of the candidate configuration for the given instance. The working directory of `targetRunner` is set to the execution directory specified by the option `execDir`. This allows the user to execute several runs of **irace** in parallel without the runs interfering with each other.

5.2.2 Target runner R function

When `targetRunner` is an R function, then it is invoked for each candidate configuration as:

```
> targetRunner(experiment, scenario)
```

where `experiment` is a list that contains the information of candidate and instance to execute one experiment and `scenario` is the scenario list. The structure of the `experiment` list is as follows:

`id.configuration`	The numeric identifier uniquely identifies a configuration.
`id.instance`	The numeric identifier uniquely identifies a pair `<instance, seed>`.
`seed`	Seed to be used for the execution.
`configuration`	Data frame with a column per parameter name.
`instance`	Instance to be used for the execution.
`extra.params`	User-defined value associated to the instance.
`switches`	Parameter switches in the order of parameters used in `configuration`.

The following is an example of an experiment list for the **ACOTSP** scenario:

```
> print(experiment)

# $id.configuration
# [1] 1
```

```
#
# $id.instance
# [1] 113
#
# $seed
# [1] 734718556
#
# $configuration
#   algorithm localsearch alpha beta rho ants nnls q0  dlb
# 1       eas           0  2.92 3.06 0.6   80   NA NA <NA>
#   rasrank elitistants
# 1      NA         588
#
# $instance
# [1] "/home/user/instances/tsp/2000-533.tsp"
#
# $extra.params
# NULL
#
# $switches
#        algorithm      localsearch            alpha
#             "--" "--localsearch "       "--alpha "
#             beta               rho             ants
#        "--beta "        "--rho  "        "--ants "
#             nnls               q0              dlb
#        "--nnls "          "--q0 "         "--dlb "
#          rasrank      elitistants
#    "--rasranks " "--elitistants "
```

The function `targetRunner` must return a numerical value corresponding to the evaluation of the candidate configuration on the given instance.

5.3 Target evaluator

The evaluation of the execution of a candidate configuration on an instance must be returned when finalizing the `targetRunner` execution (See Section 5.2). Nevertheless there are cases when the evaluation of the candidate configurations must be delayed until all candidate configurations in a race have been executed on a instance.

irace provides the option to postpone the evaluations of the candidate configurations by the use of a user-defined evaluation by setting the `targetEvaluator` parameter as either an R function or an auxiliary program. The `targetEvaluator` evaluations are executed when all alive candidate configurations have been executed on an instance.

When targetEvaluator is in use targetRunner must not return the evaluation of the configuration.

As an example, `targetEvaluator` may be used to dynamically find nor-

malization bounds for the output returned by an algorithm for each individual instances. In this case, `targetRunner` will save the output of the algorithm, then the first call to `targetEvaluator` will examine the output produced by all calls to `targetRunner` for the same instance, update the normalization bounds and return the normalized output. Subsequent calls to `targetEvaluator` for the same instance will simply return the normalized output.

A similar need arises when using quality measures for multi-objective optimization algorithms, such as the hypervolume [], which typically require specifying reference points or sets. By using `targetEvaluator`, it is possible to dynamically compute the reference points or sets while **irace** is running. Examples are provided at `examples/hypervolume`. See also Section 10.1 for more information on how to tune multi-objective algorithms.

5.3.1 Target evaluator R function

When `targetEvaluator` is an R function, then it is invoked for each candidate configuration as:

```
> targetEvaluator(experiment, num.configurations, all.conf.id,
+ scenario, target.runner.call)
```

, where `experiment` is a list that contains the information of one experiment (See Section 5.2.2), `num.configurations` is the number of configurations alive on the race, `all.conf.id` is the list of the alive candidates configurations ids, `scenario` is the scenario list and `target.tunner.call` is the string of the `targetRunner` execution line.

The function `targetEvaluator` must return a numerical value corresponding to the cost measure of the candidate configuration on the given instance.

5.3.2 Target evaluator executable program

When `targetEvaluator` is an auxiliary executable program, then it is invoked for each candidate configuration once all the alive candidates have been executed in an instance. The executable receives the following arguments:

1. `configuration id`: The numeric identifier uniquely identifies a configuration.
2. `instance id`: The numeric identifier uniquely identifies a pair `<instance, seed>`.
3. `seed`: Seed to be used for the execution.
4. `instance`: Instance to be used for the execution.
5. `total candidates`: Number of alive candidates.
6. `alive candidates ids`: Alive candidates ids.

The `targetEvaluator` executable must print a numerical value corresponding to the cost measure of the candidate configuration on the given instance.

5.4 Training instances

The training instances can be specified using the options `trainInstancesDir` and `trainInstancesFile`. The default training instance directory is *./Instances*, you can modify this directory using the `trainInstancesDir` option (e.g. `--train-instances-dir ~/my-instances/`). A file containing a list of instances can be specified using the `trainInstancesFile` option (e.g. `--train-instances-file ./instances-list.txt`).

The format of the file is one instance per line, the first value of each line corresponds to the instance filename. If `trainInstancesDir` is provided the instance filename is considered relative to the directory specified. The following values in each line correspond to extra parameters to be used with the specific instance. The following example shows a training instance file for the **ACOTSP** scenario:

```
#Example training instances file
100/100-1_100-2.tsp --time 1
100/100-1_100-3.tsp --time 2
100/100-1_100-4.tsp --time 3
```

Figure 3: Training instances file for tuning **ACOTSP**.

If `./my-instances/` is provided as `trainInstancesDir`, **irace** will assume instances are located in this directory, for example the first instance would be passed to `targetRunner` as `./my-instances/100/100-1_100-2.tsp`. Disable the use of a directory by setting it as empty. Extra parameters are always passed to `targetRunner` together with the candidate configuration parameters values.

When having instances that are not files, for example descriptive types (e.g. functions), use the name and extra instance parameters to define the instance. For example:

```
#Example training instances file
rosenbrock --nvar 20
rosenbrock --nvar 30
rastrigin --nvar 20
rastrigin --nvar 30
```

Figure 4: Training instances file example with no instance files.

Optionally when executing **irace** from the R console you can use directly the `scenario$instances` variable. To create an instance list for the previous example use:

```
> scenario$instances <-
+  c("rosenbrock", "rosenbrock", "rastrigin", "rastrigin")
> scenario$instances.extra.params <-
+  c("--nvar 20", "--nvar 30", "--nvar 20", "--nvar 30")
```

The `deterministic` option activates the deterministic algorithm mode. Each instance will be used at most once per race. Use this mode for algorithms that

do not have an stochastic behavior and therefore executing instances several times with different seeds does not make sense.

If `deterministic` *is active and the number of training instances provided to* **irace** *is less than* `firstTest` *(default: 5), no statistical test will be performed on the race.*

When `deterministic` is disabled **irace** assigns each instance a seed once all the `<instance,seed>` pairs are used new pairs are generated with different seeds.

The option `sampleInstances` enables the sampling of the instances, disable this option (`--sample-instances 0`) if you know the order provided in the instance file is adequate for the tuning.

We advise to always sample instances in order to prevent biasing the tuning due to the instance order.

5.5 Initial candidates

The scenario option `configurationsFile` allows to specify a set of configurations to start the execution of **irace**. If the number of initial configurations supplied is less than the number of configurations required by **irace** in the first iteration, extra candidate configurations will be sampled uniformly.

The format of the configurations file is one configuration per line, and one parameter value per column. The first line must give the parameter name corresponding to each column (names must match those given in the parameters file). Each configuration must satisfy the parameter conditions (`NA` should be used for those parameters that are not enabled for a given configuration) and, if given, the constraints described by forbidden configurations (Section 5.6).

Figure 5 gives an example file that corresponds to the **ACOTSP** scenario:

```
## Initial candidate configuration for irace
algorithm localsearch alpha beta rho  ants nnls dlb q0 rasrank elitistants
as        0           1.0   1.0  0.95 10   NA   NA  0  NA      NA
```

Figure 5: Initial configuration file (`default.txt`) for tuning **ACOTSP**.

We advise to use this feature when a default configuration of the target algorithm exists or when different sets of good target parameters values are known. This will allow **irace** to start the search from those parameter values and attempt to improve their performance.

5.6 Forbidden configurations

The scenario option `forbiddenFile` allows to specify a file containing parameter value combinations that should not be generated during the tuning. This option can be useful when some known combination of values could cause the target algorithm to crash or when it is know that some parameter combinations do no produce satisfactory results.

The format of the forbidden configurations file is one constraint per line. Each constraint is a logical expression (in R syntax), for a quick list of R logical operators see:

https://stat.ethz.ch/R-manual/R-devel/library/base/html/Syntax.html

The parameters are called by the parameter name set in the `parameterFile` described in Section 5.1.

If a parameter configuration is generated that makes the logical expression evaluate to `TRUE`, then the configuration is considered forbidden and is discarded. Figure 6 shows an example file that corresponds to the **ACOTSP** scenario:

```
## Examples of valid logical operators are:
## ==  !=  >=  <=  >  <  &  |  !  %in%
(alpha == 0.0) & (beta == 0.0)
```

Figure 6: Forbidden configurations file (`forbidden.txt`) for tuning **ACOTSP**.

Note that if initial configuration are provided (Section 5.5), they must also comply with the constraints defined in `forbiddenFile`.

6 Parallelization

A single run of **irace** can be done much faster by executing the calls to `targetRunner` (the runs of the target algorithm) in parallel. There are three ways to parallelize a single run of **irace**:

- **Parallel processes**: The option `parallel` allows executing in parallel, within a single computer, the calls to `targetRunner`, by means of the **parallel** R package. For example, adding `--parallel N` to the command line of **irace** will launch in parallel up to N calls of the target algorithm.

- **MPI**: By enabling the option `mpi`, calls to `targetRunner` will be executed in parallel by using the message passing interface (MPI) protocol (requires the **Rmpi** R package). In this case, the option `parallel` controls the number of slave nodes used by **irace**. For example, adding `--mpi 1 --parallel N` to the command-line will create N slaves + 1 master, and execute up to N calls of `targetRunner` in parallel.

  The user is responsible for setting up the required MPI environment. MPI is commonly available in computing clusters and requires launching **irace** in some particular way. An example script for using MPI mode in an SGE cluster is given at `$IRACE_HOME/examples/mpi/`.

- **SGE cluster**: This mode uses the commands `qsub` and `qstat` often found in Sun Grid Engine (SGE) and compatible clusters. The command `qsub` must return a message that contains the string: `Your job JOBID`, where

JOBID is a unique identifier for the job submitted. The command qstat -j JOBID must return nonzero if JOBID has finished its execution, and zero otherwise.

Enabling the option sgeCluster (--sge-cluster 1) will launch as many calls of targetRunner as possible and use qstat to wait for cluster jobs. The user must call qsub from targetRunner with the appropriate settings for their cluster, otherwise targetRunner will not submit jobs to the cluster. In this mode, **irace** must run in the submission node, and hence, qsub should not be used to invoke **irace** itself. Moreover, the use of a separate targetEvaluator script is required to parse the results of targetRunner and return them to **irace**. See the examples in $IRACE_HOME/examples/sge-cluster/.

- targetRunnerParallel: This option allows users to fully control the parallelization of targetRunner. Its value must be an R function that will be invoked by **irace** as follows:

```
targetRunnerParallel(experiments, targetRunner, scenario)
```

  where experiments is a list that contains elements with the information of configurations and instances to be executed (see Section 5.2 for a description), targetRunner is the targetRunner script or function and scenario is the scenario list. The targetRunnerParallel function must execute the targetRunner using the given experiments and scenario provided, and return a list of the same length as experiments containing the output of each call to targetRunner.

7 Testing of configurations

Once the tuning process is finished **irace** commonly returns a set of configurations, out of which one is the best regarding the mean. These configurations have been found to be not statistically different and therefore they all could be appropriate to use. To further investigate the quality of this configurations **irace** offers the possibility of executing the testing of these configurations on a test instance set at the end of the execution. Even more, the testing can also be performed including the best configuration of each iteration.

The options testNbElites and testIterationElites allow to set a testing of the best configurations found after the **irace** execution has been completed. The test instance set can be specified by the options testInstancesDir and testInstancesFile if using a directory or text file, or by setting the variable scenario$testInstances directly from the R console. For the testing each instance is assigned a different seed in the same way that is done for the tuning. To set the testing instances follow the same guidelines as for the training instances (see Section 5.4).

There are two types of testing:

- **Final elite configurations testing**: testNbElites indicates the number of elite configurations to be tested, if the number of elite configurations

is less than the value provided for `testNbElites`, then the number of elite configurations is used as `testNbElites`.

- **Iteration elite configurations testing**: `testIterationElites` enables the testing of the best configuration found at each iteration.

If the the testing options are specified when launching **irace** the, testing will be performed immediately after the tuning. The testing can be executed later using the following R command:

```
> testing.main(logFile="~/tuning/irace.Rdata")
```

This line will load the **irace** results found in the generated `logFile` file to perform the testing. The testing results will be saved in the **irace** log file specified in `scenario$logFile` in the `iraceResults$testing` R object. The structure of the object is described in Section 9.2 for examples on how to analyse the data or the testing and the **irace** data see Section 9.3.

8 Recovering irace runs

Problems like power cuts, hardware malfunction or the need to use computational power for other tasks may occur during the execution of the **irace** causing that the tuning is not executed completely. **irace** saves at the end of each iteration an R data file that not only contains the information of the tuning progress (See Section 9.2) but also internal information that allows to recover an incomplete execution.

To recover an **irace** execution use the `recoveryFile` option and specify the R data log file to be used. **irace** will continue the execution from the last saved iteration. The state of the random generator is saved and loaded, therefore, as long as the execution is continued in the same machine, the obtained results will be exactly as executing **irace** in one go. You can specify the `recoveryFile` from the command-line or from the scenario file, and execute **irace** as described in Section 4. For example from the command-line use:

```
irace --recovery-file "./irace-backup.Rdata"
```

When an execution is recovered, the **irace** log will be saved on the file specified with the `logFile` option.

You must define a different location for the `logFile` *and the* `recoveryFile`*. Before executing the recovery please change the name of the saved R data file.*

When recovery is done you can modify some **irace** options from the command-line or from the scenario file.

- `execDir`
- `logFile`

- `debugLevel`
- `parallel`
- `loadBalancing`
- `mpi`
- `sgeCluster`

It is not possible (and in most cases not correct) to change the scenario options , given that the previous results can become invalid. However there are some cases in which this options must be changed, for example, if you have instances that are files, it might be the case that the instances are not available in the same location. To change the location of them you should modify directly the R data file, please be careful not to change the order of the instances, because this would make the results obtained by **irace** invalid. To change the instances path open the R console and use:

```
> load ("~/tuning/irace.Rdata")
> new.path <- "~/experiments/tuning/instances/"
> iraceResults$scenario$instances <-
+    paste (new.path,
+           basename(iraceResults$scenario$instances),
+           sep="")
> save (iraceResults, file="~/tuning/irace.Rdata")
```

This example can also can be applied to the target execution files `targetRunner` and `targetEvaluator`.

Before changing any other option directly in the R data log, please consider carefully the effect the change will cause in the tuning. For questions contact us in the **irace** *group (Section13).*

9 Output and results

During the execution of **irace** a text output with the progress of the tuning will be shown in the standard output. Additionally, after each iteration an R data file is produced (`logFile` option), this file contains the partial results of the **irace** execution.

9.1 Text output

Figure 7 shows the output of **irace** until the first iteration. This is an execution of the elitist **irace** version using the **ACOTSP** benchmark with 1000 evaluations as budget.

Note that **irace** gives a warning because has found a file with the default scenario file name, this is just a notice. Initially, general information about the selected **irace** options is printed:

- `nbIterations` indicates the minimum number of iterations **irace** has calculated for the scenario. Depending on the development of the tuning the final iterations that are executed can be more.
- `minNbSurvival` indicates the minimum number of alive configurations that are required to continue a race. When less configurations are alive the race is stopped and a new iteration begins.
- `nbParameters` is the number of parameters of the scenario.
- `seed` is the number that was used to initialize the random number generator in **irace**.
- `confidence level` is the confidence level of the statistical test.
- `budget` is the total number of evaluations available for the tuning.
- `mu` is a value used for calculating the minimum number of iterations.
- `deterministic` indicates if the target algorithm has been marked as deterministic.

In each iteration information about the progress of the execution printed as follows:

- `experimentsUsedSoFar` is the number of experiments from the total budget has been used until the actual iteration.
- `remainingBudget` is the number of evaluations that have not been used yet.
- `currentBudget` is the number of evaluations **irace** has allocated to the current iteration.
- `nbConfigurations` is the number of configurations **irace** will use in the current iteration. On the first iteration this number of configurations include the initial configurations provided and in later iterations includes the elite candidates of the previous iterations.

After the iteration information a table is shows the progress of the iteration execution. Each row of the table gives information about the execution of an instance in the race. The first column contains a symbol that describes the results or non application of the statistical test:

In each iteration is initially printed information about the progress of the execution:

- `|x|` : No statistical test was performed for this instance. To adjust in which instances of a race statistical tests are performed see **irace** options `firstTest` and `eachTest` in Section 11.
- `|-|` : Statistical test performed and configurations have been discarded, to know how many configurations have been discarded see the table column `Alive`.

```
*****************************************************************************
Warning: A default scenario file './scenario.txt' has been found and will be read
# 2016-05-02 19:24:50 CEST: Elitist race
# Elitist instances: 1
# Elitist limit: 2

# 2016-05-02 19:24:50 CEST: Initialization
# nbIterations: 5
# minNbSurvival: 5
# nbParameters: 11
# seed: 1234
# confidence level: 0.95
# budget: 1000
# mu: 5
# deterministic: FALSE

# 2016-05-02 19:24:50 CEST: Iteration 1 of 5
# experimentsUsedSoFar: 0
# remainingBudget: 1000
# currentBudget: 200
# nbConfigurations: 33
  Markers:
     x No test is performed.
     - The test is performed and some configurations are discarded.
     = The test is performed but no configuration is discarded.
     ! The test is performed and configurations could be discarded but elite
       configurations are preserved.

+-+---------+------+-----+------------+-----------+--------+-----+----+------+
| | Instance| Alive| Best|   Mean best| Exp so far|  W time|  rho|KenW|  Qvar|
+-+---------+------+-----+------------+-----------+--------+-----+----+------+
|x|        1|    33|   15| 23268924.00|         33|00:01:55|   NA|  NA|    NA|
|x|        2|    33|    8| 23185736.50|         66|00:01:53|+0.97|0.99|0.0025|
|x|        3|    33|    8| 23239054.33|         99|00:01:56|+0.96|0.97|0.0030|
|x|        4|    33|    8| 23168442.50|        132|00:01:55|+0.96|0.97|0.0027|
|-|        5|     3|    8| 23222299.80|        165|00:01:56|-0.05|0.16|0.7109|
+-+---------+------+-----+------------+-----------+--------+-----+----+------+
Best configuration:           8    mean value:     23222299.80
Description of the best configuration:
  .ID. algorithm localsearch  alpha   beta    rho ants nnls     q0 dlb rasrank
8    8       acs           1 3.8157 8.5915 0.4141   59   10 0.5812   1      NA
  elitistants .PARENT.
           NA       NA

# 2016-05-02 19:34:27 CEST: Elite configurations:
   algorithm localsearch  alpha   beta    rho ants nnls     q0 dlb rasrank elitistants
8        acs           1 3.8157 8.5915 0.4141   59   10 0.5812   1      NA          NA
18      mmas           2 3.1134 7.3864 0.4623   60   32     NA   1      NA          NA
15       ras           3 2.5838 6.5086 0.5082   42    6     NA   0      90          NA
```

Figure 7: Sample text output of **irace**.

- `|=|` : Statistical test performed and no configurations have veen discarded. This means **irace** needs more information to identify the best configurations.
- `|!|`: This indicator exists only for the elitist version of **irace**, indicates that the statistical test was performed and some elite configurations show bad performance and could be discarded but they are kept given the elitist

irace discarding rules. See **irace** option `elitist` in Section 11 for more information.

The `instance` column gives the number of `<instance, seed>` pair executed, this number corresponds to the index of the list found in `scenario$instancesList`, see Section 9.2 for more information.

The `Alive` column gives the number of configurations that have not been discarded after the statistical test was performed. The column `Best` gives the id of the best configuration according to the experiments performed so far in the race (includes previous instances). The `Mean best` column gives the mean of the best configuration across all the instances executed so far in the race. The `Exp so far` gives the number of evaluations performed so far. The `W time` column gives the waiting time to execute all the configurations in the current instance.

The columns `rho` and `KenW` give the values of the Spearman's rho and the Kendall concordance coefficient of the configurations across the instances executed so far. The `Qvar` gives the variance measure across the instances. Use `rho`, `KenW` and `Qvar` to analyze how consistent is the performance of the configurations across the instances. Note that this values are only valid for the instances that were already executed in the iteration. Values close to 1 for `rho` and `KenW` and values close to 0 for the `Qvar` indicate that the performance is consistent and therefore the scenario is homogeneous. For heterogeneous we provide advice in Section 10.3.

Finally **irace** outputs the best configuration found and a list of the elite configurations. The elite configurations are configurations that did not show statistical difference during the race, they are printed according to their mean performance on the executed instances.

9.2 Data file output

The R data file created by **irace** (`logFile`) contains an object called `iraceResults`, you can load this data in the R console by:

```
> load("irace-output.Rdata")
```

The `iraceResults` object is a list, the elements of a list can be accessed in R by using the `$` or `[[]]` operators:

```
> iraceResults$irace.version

# [1] "2.0.1397M"

> iraceResults[["irace.version"]]

# [1] "2.0.1397M"
```

The `iraceResults` list contains the following elements:

- `scenario`: The scenario R object containing the **irace** options used for the execution. See Section 11 and the help of the **irace** package, open an R console and type: `?defaultScenario`. See Section 11 for more information.

- `parameters`: The parameters R object containing the description of the target algorithm parameters. See Section 5.1.

- `allConfigurations`: The target algorithm configurations generated by **irace**. This object is a `data frame`, each row is a candidate configuration, the first column (`.ID.`) indicates the internal identifier of the configuration, the following columns correspond to the parameter values, each column named as the parameter name specified in the parameter object. The final column (`.PARENT.`) is the identifier of the configuration from which model the actual configuration was sampled.

```
> head(iraceResults$allConfigurations)

#   .ID. algorithm localsearch  alpha   beta    rho ants nnls
# 1    1        as           2 2.9953 0.6188 0.7023   75    6
# 2    2      mmas           0 4.6876 8.2611 0.1948   44   NA
# 3    3      mmas           1 3.6487 6.7212 0.2986   91   44
# 4    4        as           0 4.5230 3.3080 0.3026   58   NA
# 5    5        as           2 2.6748 3.2815 0.4874    5   25
# 6    6      mmas           0 3.0051 5.1321 0.5918   24   NA
#   q0  dlb rasrank elitistants .PARENT.
# 1 NA    1      NA          NA       NA
# 2 NA <NA>      NA          NA       NA
# 3 NA    1      NA          NA       NA
# 4 NA <NA>      NA          NA       NA
# 5 NA    0      NA          NA       NA
# 6 NA <NA>      NA          NA       NA
```

- `allElites`: A list that contains one element per iteration, each element contains the internal identifier of the elite candidate configurations of the corresponding iteration (identifiers correspond to `allConfigurations$.ID.`).

```
> print(iraceResults$allElites)

# [[1]]
# [1]  8 18 15
#
# [[2]]
# [1] 47
#
# [[3]]
# [1] 47 67 70 69
#
# [[4]]
# [1]  47 118  70  96  95
#
# [[5]]
# [1] 118 154  47 119  95
#
```

```
# [[6]]
# [1] 118  47  95 164 156
#
# [[7]]
# [1]  95  47 164 156 118
```

The configuration are ordered by mean performance, that is, the id of the best configuration corresponds to the first id. To obtain the values of the parameters of all elite configuration found by **irace** use:

```
> getFinalElites(irace.logFile="irace-output.Rdata", n=0)

#   .ID. algorithm localsearch  alpha   beta    rho ants nnls
# 1   95       acs           3 2.1078 3.5827  0.399   44   30
# 2   47       acs           3 1.5946 2.6973 0.7878   37   31
# 3  164       acs           3 2.0925 3.7981 0.9098   18   34
# 4  156       acs           3 1.4171 5.3167 0.5322   23   31
# 5  118       acs           3 1.5666 5.7256 0.6368   27   43
#       q0 dlb rasrank elitistants .PARENT.
# 1 0.3813   1      NA          NA       47
# 2 0.2983   1      NA          NA       15
# 3 0.2981   1      NA          NA       47
# 4 0.3379   1      NA          NA      118
# 5 0.1491   1      NA          NA       70
```

- `iterationElites`: A vector containing the best candidate configuration internal identifier of each iteration. The best configuration found corresponds to the last one of this vector.

```
> print(iraceResults$iterationElites)

# [1]   8  47  47  47 118 118  95
```

Obtain the full configuration with:

```
> last <- length(iraceResults$iterationElites)
> id <- iraceResults$iterationElites[last]
> getConfigurationById(irace.logFile="irace-output.Rdata",
+                      ids=id)

#    .ID. algorithm localsearch  alpha   beta   rho ants nnls
# 95   95       acs           3 2.1078 3.5827 0.399   44   30
#        q0 dlb rasrank elitistants .PARENT.
# 95 0.3813   1      NA          NA       47
```

- `experiments`: A matrix with configurations as columns and instances as rows. Column names correspond to the internal identifier of the configuration (`allConfigurations$.ID.`), to obtain the experiment results of a particular configuration use:

```
> # As an example, we use the best configuration found
> best.config <- getFinalElites(iraceResults=iraceResults,
+                               n=1)
> id <- best.config$.ID.
> # Obtain the configurations using the identifier
> # of the best configuration
> all.exp <- iraceResults$experiments[,as.character(id)]
> all.exp[!is.na(all.exp)]

#        1        2        3        4        5        6
# 23143448 22959710 23284140 22858335 23226582 23264551
#        7        8        9       10       11       12
# 23439606 23108045 23388942 23097102 23069267 23300829
#       13       14       15
# 23079207 23384244 23104481
```

When a configuration was not executed on an instance there is a `NA` value in the corresponding matrix cell. A configuration is not executed on an instance for three different reasons: 1) because it was not created yet when the instance was used (only for the non elitist **irace**) or 2) because it was discarded by the statistical test or 3) the race was terminated before the instance could reach the execution of the instance.

The row names correspond to the identifier of the `<instance, seed>` pairs defined in `scenario$instancesList`. To obtain the instance and seed used for a particular experiment use:

```
> # As an example, we get seed and instance of the experiments
> # of the best candidate.
> # Get index of the instances
> pair.id <- names(all.exp[!is.na(all.exp)])
> index <-
+     iraceResults$scenario$instancesList[pair.id,"instance"]
> # Obtain the instance names
> iraceResults$scenario$instances[index]

#  [1] "~/tuning/instances/1000-2.tsp"
#  [2] "~/tuning/instances/1000-6.tsp"
#  [3] "~/tuning/instances/1000-5.tsp"
#  [4] "~/tuning/instances/1000-8.tsp"
#  [5] "~/tuning/instances/1000-9.tsp"
#  [6] "~/tuning/instances/1000-4.tsp"
#  [7] "~/tuning/instances/1000-1.tsp"
#  [8] "~/tuning/instances/1000-7.tsp"
#  [9] "~/tuning/instances/1000-10.tsp"
# [10] "~/tuning/instances/1000-3.tsp"
# [11] "~/tuning/instances/1000-7.tsp"
# [12] "~/tuning/instances/1000-5.tsp"
# [13] "~/tuning/instances/1000-3.tsp"
```

```
# [14] "~/tuning/instances/1000-10.tsp"
# [15] "~/tuning/instances/1000-2.tsp"

> # Get the seeds
> iraceResults$scenario$instancesList[index,"seed"]

#  [1] 1046825803  836798880 1634370426  230520034 2067328642
#  [6]  754546337 1798805136  980356358 2121921850  236946902
# [11]  980356358 1634370426  236946902 2121921850 1046825803
```

- `experimentLog`: A matrix with columns:

  `<iteration, instance, configuration>`.

  This matrix contains the log of all the experiments that **irace** performs during its execution. The instance column refers to the index of the `scenario$instancesList` data frame.

- `softRestart`: A logical vector that indicates if a soft restart was performed on each iteration. If `FALSE`, then no soft restart was performed. For info about soft restart see Section 11.

- `state`: A list that contains the state of **irace**, the recovery (Section 8) is done using the information contained in this object. The probabilistic model of the last elite configurations can be found here doing:

```
> # As an example, we get the model probabilities for the
> # localsearch parameter.
> iraceResults$state$model["localsearch"]

# $localsearch
# $localsearch$`118`
# [1] 0.0002285714 0.0002285714 0.0002285714 1.0000000000
#
# $localsearch$`47`
# [1] 0.0002285714 0.0002285714 0.0002285714 1.0000000000
#
# $localsearch$`95`
# [1] 0.0002285714 0.0002285714 0.0002285714 1.0000000000
#
# $localsearch$`164`
# [1] 0.0002285714 0.0002285714 0.0002285714 1.0000000000
#
# $localsearch$`156`
# [1] 0.0002285714 0.0002285714 0.0002285714 1.0000000000

> # The order of the probabilities corresponds to:
> iraceResults$parameters$domain$localsearch

# [1] "0" "1" "2" "3"
```

The example shows a list that has one element per elite configuration (id as element name). In this case `localsearch` is a categorical parameter, it has a probability per each value.

- `testing`: A list that contains the testing results. The list contains the following elements:
  - `experiments`: Matrix of experiments in the same format as the tuning `experiment` matrix. The column names indicate the candidate configuration identifier and the row names contain the name of the instances.

```
> # Get the experiments of the testing
> iraceResults$testing$experiments

#                   95       47      164      156      118
# 1000-1.tsp  23409880 23410576 23422748 23404330 23366881
# 1000-2.tsp  23126916 23144708 23212491 23100817 23196172
# 1000-3.tsp  23084684 23076230 23110653 23086263 23098047
# 1000-4.tsp  23251050 23232485 23232201 23228093 23234648
# 1000-5.tsp  23278985 23287118 23330620 23295181 23336133
# 1000-6.tsp  22983127 22959425 23073906 22989811 22951321
# 1000-7.tsp  23087699 23124945 23115738 23122621 23084600
# 1000-8.tsp  22893110 22850619 22863202 22865437 22913600
# 1000-9.tsp  23180624 23174994 23209675 23227996 23205438
# 1000-10.tsp 23367381 23333064 23405137 23341862 23356161
```

  - `seeds`: The seeds used for the experiments, each seed corresponds to each instance in the rows of the test `experiments` matrix.

```
> # Get the experiments of the testing
> iraceResults$testing$seeds

#  [1]  716498671  999094119 1613704058  978659676 1046072282
#  [6] 1418237375  466610226  249199596  828014021 1647202103
```

    In the example instance `1000-1.tsp` is executed with seed `1815573416`.

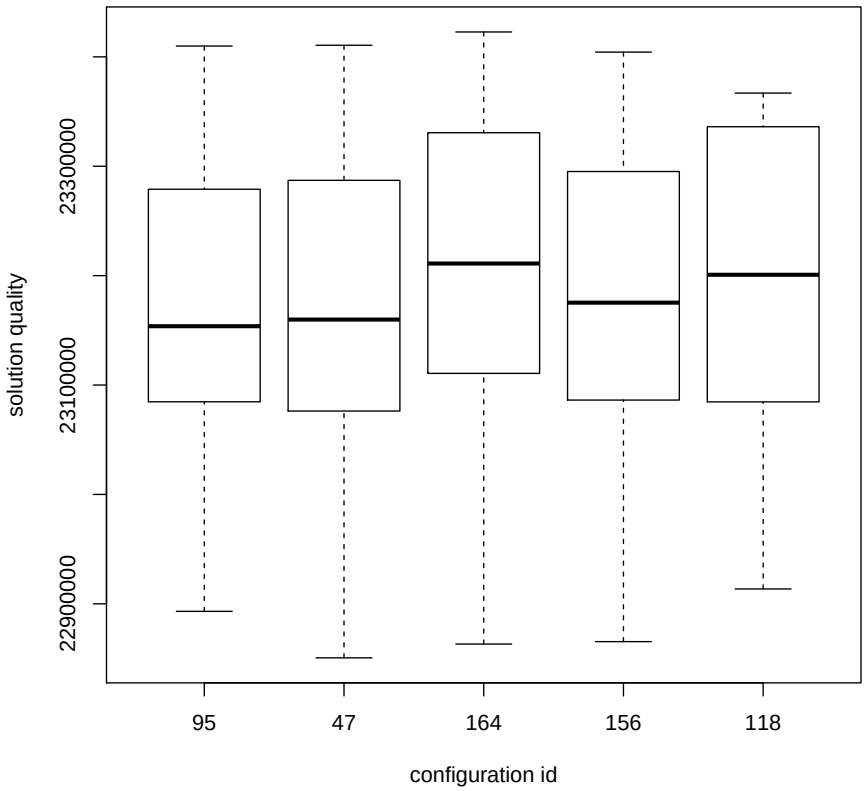
9.3 Analysis of results

The best configurations provided by **irace** are configurations that where found to be not statistically different. The configurations are reported in average performance order, that is, the best by mean configuration is reported first.

If testing is performed you can further analyze the resulting best configurations by performing statistical tests in R or just plotting the results:

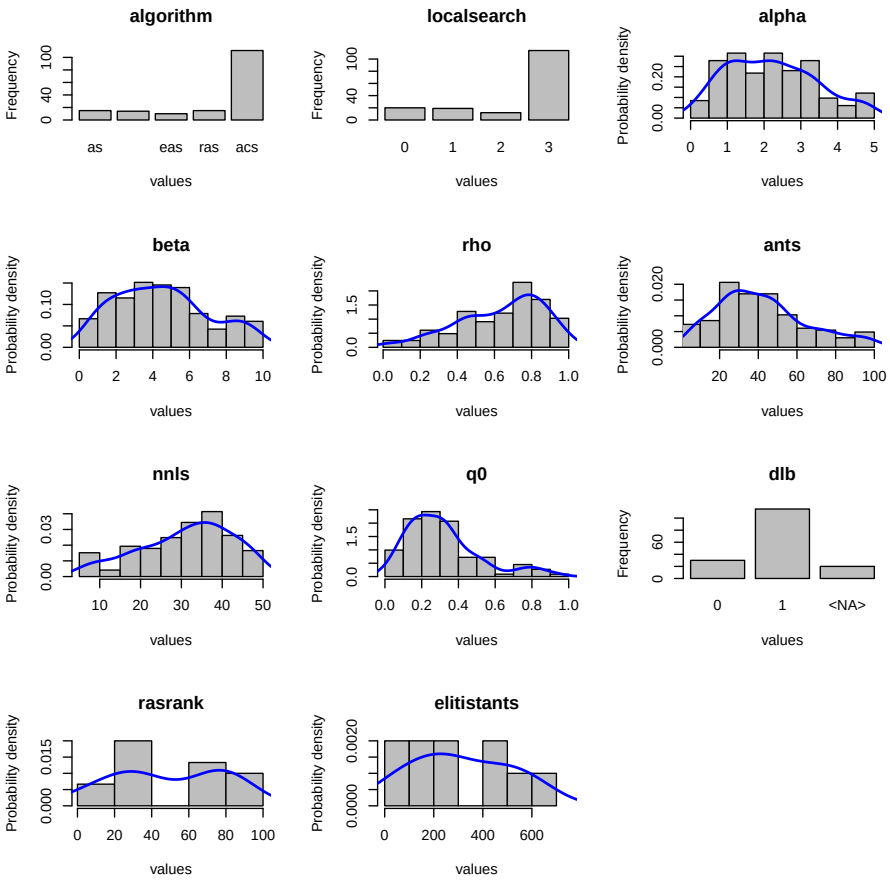
```
> results <- iraceResults$testing$experiments
> # Wilcoxon paired test
> conf <- gl(ncol(results), #number of configurations
+            nrow(results), #number of instances
+            labels=colnames(results))
```

```
> pairwise.wilcox.test (as.vector(results),
+                       conf,
+                       paired=TRUE,
+                       p.adj = "bonf")

#
#  Pairwise comparisons using Wilcoxon signed rank test
#
# data:  as.vector(results) and conf
#
#     95    47    164   156
# 47  1.000 -     -     -
# 164 0.488 0.098 -     -
# 156 1.000 1.000 0.488 -
# 118 1.000 1.000 1.000 1.000
#
# P value adjustment method: bonferroni

> # Plot the results
> boxplot (iraceResults$testing$experiments,
+          ylab="solution quality",
+          xlab="configuration id")
```



During the tuning **irace** iteratively updates sampling models for the parameters focusing in the best areas of the parameter search space. The frequency of the sampled configurations can provide insight on the parameter search space, we provide a function that allows to create plots that show the frequency of the sampling of a set of configurations. The following example plots the frequency of the parameters sampled during all the **irace** execution:

```
> parameterFrequency(iraceResults$allConfigurations,
+                    iraceResults$parameters)
# Plotting: algorithm
# Plotting: localsearch
# Plotting: alpha
# Plotting: beta
# Plotting: rho
# Plotting: ants
# Plotting: nnls
# Plotting: q0
# Plotting: dlb
# Plotting: rasrank
# Plotting: elitistants
```

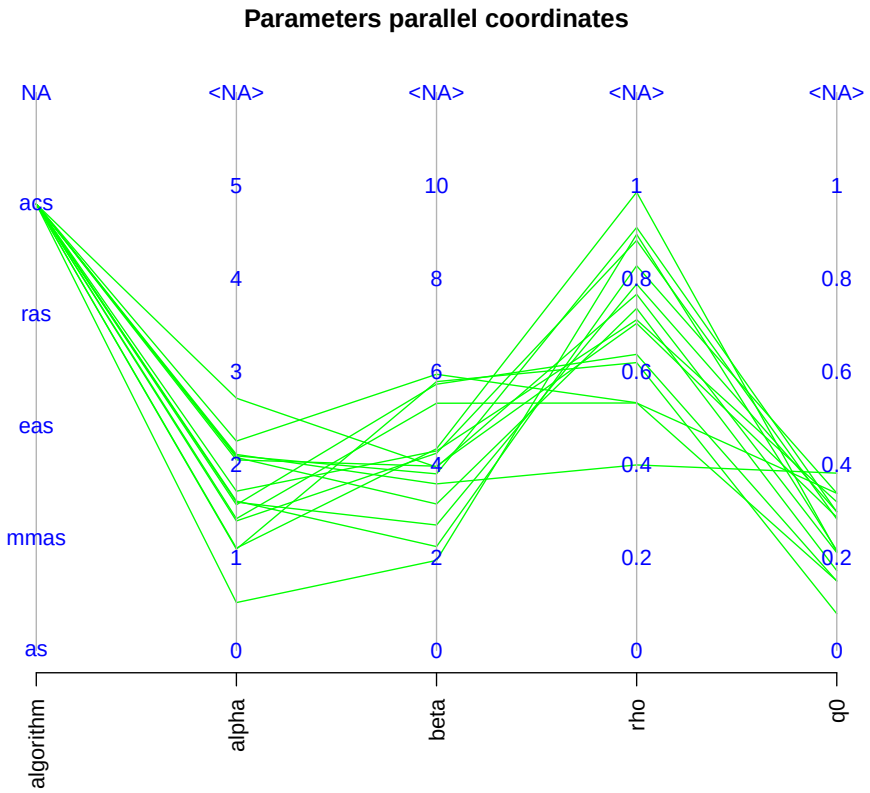


For more information of this function please see the R help, type in the R console: `?parameterFrequency`.

Using parallel coordinates plots is possible to analyze how the parameters interact with each other. The following example shows how to create a parallel coordinate plot of the candidates of the last two iterations of **irace**.

```
> # Get last iteration number
> last <- length(iraceResults$iterationElites)
> lasts <- c(last-1, last)
> # Get last iterations candidates
> conf <- getConfigurationByIteration(iraceResults = iraceResults,
+                                     iterations = lasts)
> parallelCoordinatesPlot (conf,
+                          iraceResults$parameters,
+                          param_names=c("algorithm",
+                                        "alpha",
+                                        "beta",
+                                        "rho",
+                                        "q0"),
```

```
+                                hierarchy=FALSE)
```



For more information of this function please see the R help, type in the R console: (`?parallelCoordinatesPlot`).

10 Advanced topics

10.1 Multi Objective tuning

irace performs the automatic configuration of an algorithm optimizing only one objective that can be solution quality, computation time or any other and that is obtained by **irace** through the `targetRunner`.

If you wish to tune your algorithm with **irace** for more than one objective there are two alternatives:

- Aggregate the objectives in one resulting number.
- Use the hypervolume indicator for evaluating the quality of the configurations.

The first option is simple, it requires to devise a formula that can aggregate the objectives in a way that balances the importance of all of them. This might not be an easy task in some scenarios, using a more adequate indicator like the hypervolume is strongly advised.

For using the hypervolume as evaluation **irace** needs to postpone the evaluation of the configurations in an instance until all of the executions have been completed. Once the executions are finalized the evaluation starts by obtaining reference points for each objective from the configuration results. This points are used to define the pareto front and the hypervolume of each configuration is calculated and the tuning process continues normally.

For setting up the multi objective tuning you must not return the evaluation of the experiment when finalizing the execution of `targetRunner` (see Section 5.2) and specify a `targetEvaluator` in which the reference points are obtained and the hypervolume is calculated. For more information about defininf a `targetEvaluator` see Section 5.3 For the hypervolume calculation we suggest the following implementation:

http://lopez-ibanez.eu/hypervolume

Examples of a multi objective tuning using the hypervolume can be found in the templates:

```
$IRACE_HOME/examples/hypervolume
   $IRACE_HOME/examples/moaco
```

10.2 Tuning computation time

irace was developed primarily for tuning solution quality, to use **irace** for tuning computation time the execution time must be returned as result by the `targetRunner`. Nevertheless other tuners available have better methods to handle the execution of the target algorithm by using "adaptive capping". When tuning for optimizing the computation time of an algorithm we recommend to try out `ParamILS` and `SMAC` tuners in the following links:

http://www.cs.ubc.ca/labs/beta/Projects/ParamILS/
http://www.cs.ubc.ca/labs/beta/Projects/SMAC/

10.3 Heterogeneous scenarios

We classify an scenario as homogeneous when the target algorithm has a consistent performance regarding the instances that is, good configurations are probably good for all the instances. On the contrary, for heterogeneous scenarios the target algorithm has an inconsistent performance on different instances, that is, some configurations are good for one or a subset of instances while are very bad for another subset of instances.

If you know your scenario has heterogeneous characteristics, the first question you should ask yourself is if the tuning objective is to find configurations that are good for all instances. If this is not the case, then separate executions of **irace**, one per instance type, is the best choice.

If finding a good configuration for all the instances is the objective then we recommend to always sample the instances initially (option `sampleInstances`)

unless you provide an instance order that does not bias the search. For example, assume you have an scenario that has two kinds of instances, if the ten first instances belong to only one class, the search will be biased to obtain configurations that are good for that instances. The best order in this case would be to intercalate different types of instances to avoid bias.

Another advice is to increase the number of instances executed per iteration, an heterogeneous scenario will need to gather more information about the different instances before discarding configurations. Use the option `elitistInstances` when the elitist **irace** version (option `elitist`) is used to increase the number of new instances executed in each iteration. When using the non elitist **irace** version you can indirectly increase the number of instances by increase the `firstTest` option.

When executing **irace** you can analyze the homogeneity of the scenario by observing the results of the Kendall W and Spearman's rho in the text output of **irace**. See Section 9.1 for more information.

10.4 Choosing the statistical test

The statistical test identifies statistically bad performing configurations that **irace** can discard of the race in order to save budget. The criterion which is used to assess the quality of the configurations might have effect on the tuning results.

irace provides two kinds of statistical tests, both test have different characteristics that could be beneficial for certain scenarios:

- Friedman test (`F-test`): This test uses the ranking of the configurations to analyze the difference between the performance. This makes the test suitable for scenarios where the numerical results and their scale are not significant to assess the quality of the configurations. For example if the results in different instances have high numerical differences and evaluating the performance of the configurations using, for example, the mean could be deceiving. We recommend to use the `F-test` (default) always when tuning for solution quality and whenever the best performing algorithm must solve as good as possible all the instances.

- Student's t-test (`t-test`): This test uses the mean performance of the configurations to analyze the difference between the configurations. This makes the test suitable for scenarios where the differences between values obtained for different instances are relevant to assess good configurations. We recommend using t-test when tuning for computation time, whenever the obtained configurations must solve the instances in the best averaged time.

Using the option `confidence` is possible to set the statistical significance of the test. Increase the value of `confidence` to have a more strict statistical test. Keep in mind that a strict test will require more budget to identify which configurations perform worse. While a less strict test discards configurations quickly by requiring less data against them and therefore it has more probability of discarding good configurations.

10.5 Complex parameters

Some parameters may have complex dependencies, we advice to always try to define the parameters in the way that is most suitable for the tuning objective. For example, when tuning a branch and bound algorithm one may have the following parameters:

- branching (`b`): This parameter can take the values `[0,1,2,3]`, 0 indicates no branching will be used and the rest are different types of branching.
- stabilization (`s`): This parameter can take the values `[0,1,2,3,4,5,6,7,8,9,10]`, of which for `b=0` only `[0,1,2,3,4,5]` are relevant.

In this case is not possible to describe the parameter space defining only two parameters for **irace**. An extra parameter must be introduced as follows:

```
<name> <label> <type> <range>                  [ | <condition>]
b      "-b "   c      [0,1,2,3]
s1     "-s "   c      [0,1,2,3,4,5]            | b \%in\% c("0")
s2     "-s "   c      [0,1,2,3,4,5,6,7,8,9,10] | b != "0"
```

Parameters whose values depend on the value of other parameters also could be described using extra parameters or changing the parameters and processing them in the `targetRunner`. For example the following parameters:

- Population size (`p`): This parameter can take the integer values `[2,100]`.
- Selection size (`s`): This parameter can take as maximum the population size, that is `[1,p]`.

In this case is possible to describe the parameters as a percentage as described below. The parameter values must be processed in the `targetRunner`. For example if `p=0.5` then we must transform this number to the interval `[2,100]` giving us that `p=51` then `s=0.3` will be transformed as `s=15`.

```
<name> <label> <type> <range>                  [ | <condition>]
p      "-p "   r      [0.0,1.0]
s      "-s "   r      [0.1,1.0]
```

More complex value dependencies could be also expressed by mixing extra parameters and transformations. Keep in mind that the `targetRunner` can also process the parameters. You can also split parameters and join them in the `targetRunner`, for example assume the following parameters:

```
<name> <label> <type> <range>                  [ | <condition>]
m      "-m "   i      [1,250]
e      "-e "   r      [0.0,2.0]
```

This parameters could be part of one parameters that has a multiplier and an exponent that has to be passed to your target algorithm as `--strenght` $m * e^1 0$. `targetRunner` can join the extra parameters `e` and `m` and provide them in the correct format.

10.6 Unreliable target algorithms

There are some situations in which the target algorithm may fail to execute correctly. This could be due to system problems or bugs for which no fix is available or fixing them is impossible because there is no access to the source code.

The **irace** option `targetRunnerRetries` indicates the number of times a `targetRunner` execution is repeated if it fails. Use this option if you know new repetitions could be successful.

When the program consistently fails using a particular set of configurations and repeating the execution will cause always the program to crash, you can use the `forbiddenFile` option to specify the configurations that must be avoided. On the other hand, if you do not know which configurations cause the problems, we advise you to handle this in the `targetRunner` script, when the program crashes you can use a penalty evaluation (very big number for minimization) that will allow **irace** to discard the configuration based on that result. Adjust the penalty according to your objective and the results you consider appropriate, for example, if a configuration crashes for an instance you might still consider it as a good configuration if it gives very good results for other instances.

11 irace options

Most of the **irace** options can be specified by command line using a flag, by setting them in the **irace** scenario file using the option name or by directly setting them in the scenario R object. This section describes the **irace** options that can be specified by the user:

11.1 General options

- `scenarioFile` flag: `-s`, `--scenario` default: *./scenario.txt*
  File that contains the scenario setup and other irace settings. All the options listed in this section can be included in this file. See `$IRACE_HOME/templates/` for an example.

- `debugLevel` flag: `--debug-level` default: *0*
  Level of information to display in the text output of **irace**. A value of 0 silences all debug messages. Higher values provide more verbose debug messages. To see details about the text output of **irace** see Section 9.1.

- `seed` flag: `--seed` default: *NA*
  Seed to initiallize the random number generator, the seed must be a positive integer, if the seed is `NA` a random seed will be used.

- `execDir` flag: `--exec-dir` default: *./*
  Directory where the target algorithm executions will be performed. The default execDir is the current directory.

> **irace** *will not attempt to create the execution directory so it must exist before calling* **irace**.

- `logFile` flag: `-l`, `--log-file` default: *./irace.Rdata*
  File to save tuning results as an R dataset, the provided path must be either an absolute path or a relative to `execDir`. See Sectionr̃efsec:output r for details on the format of the R dataset.

11.2 Elitist irace

- `elitist` flag: `--elitist` default: *1*
  Enable/disable elitist **irace**.

  In the **elitist `irace` version** elite configurations cannot be discarded from the race until the new configurations have executed the same instances as the elite configurations.

  The race begins with a number of initial instances for which any configuration in race have been executed, this number of instances can be defined with the option `elitistInstances`. Once the new instances have been executed the instances executed in previous iterations are executed, elite configurations have already results for most of these instances and therefore do not need to be executed. Finally when the "previous instances" are executed new instances are executed.

  The statistical tests can be performed at any moment during the race according to the setting of the options `firstTest` and `eachTest`, the elitist rule forbids to discard elite configurations, even if the show bad performance, until the last "previous instance" has been executed.

  The **non-elitist irace version** can discard the elite configurations from the race at any time. Instances are not re-used from an iteration to another, new instances are always executed unless the `deterministic` option is active, for which the instances are repeated if all instances have been used.

- `elitistInstances` flag: `--elitist-instances` default:*1*
  Number of new instances to add to execution list before "previous instances" in elitist **irace**.

> *If* `deterministic` *is* `TRUE` *then the number of* `elitistInstances` *will be reduced or set to* `0` *in case no more instances are available.*

- `elitistLimit` flag: `--elitist-limit` default: *2*
  Limit for the elitist race, when the number statistical test performed without successful elimination reaches `elitistLimit` the race will be inmediately stopped. This limit has effect after all "previous instances" have been executed. Use 0 for disable the limit.

11.3 Internal irace options

- `sampleInstances` flag: `--sample-instances` default: *1*
  Enable/disable the sampleing of the the training instances. If the op-

tion `sampleInstaces` is disabled, the instances are used in the order provided in the `trainInstancesFile` or in the order that are read from the `trainInstancesDir` when`trainInstancesFile` is not provided. For more information about training instances see Section 5.4.

- `nbIterations` flag: `--iterations` default: *0*
  Number of iterations to be executed. By default **irace** calculates the number of iterations based on the scenario as described as follows where N^{param} is the number of non fixed parameters to be tuned. We recommend to use the default value.

$$N^{\text{iter}} = \lfloor 2 + \log_2 N^{\text{param}} \rfloor \tag{1}$$

- `nbExperimentsPerIteration` flag: `--experiments-per-iteration` default: *0*
  Number of experiments to execute per iteration. By default **irace** calculates the number of experiments per iteration based on the scenario as follows, where B_j is the budget for iteration j, B is the total tuning budget (`maxExperiments`), B_{used} is the used budget and N^{iter} is maximum between the planned number of iterations (`nbIterations`) and the current iteration (j). We recommend to use the default value.

$$B_j = \frac{(B - B_{\text{used}})}{(N^{\text{iter}} - j + 1)} \tag{2}$$

- `nbConfigurations` flag: `--num-configurations` default: *0*
  The number of configurations that should be sampled and evaluated at each iteration. By default **irace** calculates the number of configurations per iteration based on the scenario as follows, where N_j is the number of configurations that will be used in iteration j, B_j is the budget for iteration j and μ is the **irace** option `mu`. We recommend to use the default value.

$$N_j = \lfloor \frac{B_j}{(\mu + \min(5, j))} \rfloor \tag{3}$$

- `mu` flag: `--mu` default: *5*
  This value is used to determine the number of configurations to be sampled and evaluated at each iteration.

- `minNbSurvival` flag: `--min-survival` default: *0*
  The minimum number of configurations needed to continue the execution of an iteration.

- `softRestart` flag: `--soft-restart` default: *1*
  Enable/disable the soft restart strategy that avoids premature convergence of the probabilistic model. When a sampled configuration is *highly similar* to its parent configuration the probabilistic model of all the configurations is soft restarted. The similarity of categorical and ordered parameters is given by the hamming distance, the option `softRestartThreshold` defines the similatiry of numerical parameters.

- `softRestartThreshold` flag: `--soft-restart-threshold` default: *NA*
  Soft restart threshold value for numerical parameters. If `NA`, it computed as $10^{-digits}$, where `digits` corresponds to the **irace** option explained in this section.

11.4 Target algorithm parameters

- `parameterFile` flag: `-p` or `--param-file` default: `./parameters.txt`
  File that contains the description of the parameters of the target algorithm. See section 5.1.

- `digits` flag: `--digits` default: `4`
  Number of decimal places to be considered for the real parameters.

- `forbiddenFile` flag: `--forbidden-file`
  File containing a list of logical expressions that cannot be true for any evaluated configuration. If empty or `NULL`, no forbidden rules are considered. See Section 5.6 for more information.

11.5 Target algorithm execution

- `targetRunner` flag: `--target-runner` default: *./target-runner*
  This option defines a script or an R function that launches the program to be tuned for a particular experiment (configuration + instance). See Section 5.2 for details.

- `targetRunnerRetries` flag: `--target-runner-retries` default: *0*
  Number of times to retry a call to `targetRunner` if the call failed.

- `targetRunnerData` default: `NULL`
  Optional data passed to `targetRunner`. This is ignored by the default `targetRunner` function, but it may be used by custom `targetRunner` functions to pass persistent data around.

- `targetRunnerParallel` default: `NULL`
  Optional R function to provide custom parallelization of `targetRunner`. See Section 6 for more information.

- `targetEvaluator` flag: `--target-evaluator` default: `""`
  Optional script or R function that evaluates an experiment (configuration + instance), that is. The evaluation must consist of a numeric value. See Section 5.3 for details.

- `deterministic` flag: `--deterministic` default: `0`
  Enable/disable deterministic algorithm mode. If the target algorithm is deterministic, configurations will be evaluated only once per instance. See Section 5.4 for more information.

Note that if the number of instances provided is less than the value specified for the option `firstTest`*, no statistical test will be performed.*

- `parallel` flag: `--parallel` default: *0*
  Number of calls of the `targetRunner` to execute in parallel. A value of 0 means disabled. For more information on parallelization see Section 6.

- `loadBalancing` flag: `--load-balancing` default: *1*
  Enable/disable load-balancing when executing experiments in parallel. Load-balancing makes better use of computing resources, but increases communication overhead. If this overhead is large, disabling load-balancing may be faster. See Section 6.

- `mpi` flag: `--mpi` default: `0`
  Enable/disable MPI. Use **Rmpi** to execute the `targetRunner` in parallel. When `mpi` is enabled, the option `parallel` is the number of slaves. See Section 6.

- `sgeCluster` flag: `--sge-cluster` default: `0`
  Enable/disable SGE cluster mode. Use qstat to wait for cluster jobs to finish (`targetRunner` must invoke qsub). See Section 6.

11.6 Initial configurations

- `configurationsFile` flag: `--configurations-file`
  File containing a list of initial configurations. If empty or `NULL` **irace** will not use initial configurations. See section 5.5.

> *The provided configurations must not violate the constraints described in* `parameterFile` *and* `forbiddenFile`.

11.7 Training instances

- `trainInstancesDir` flag: `--train-instances-dir` default: *./Instances*
  Directory where tuning instances are located; either absolute path or relative to current directory. See Section 5.4.

- `trainInstancesFile` flag: `--train-instances-file`
  File containing a list of instances and optionally additional parameters for them. See Section 5.4.

> *If* `trainInstancesDir` *is specified the path contained in* `trainInstancesFile` *must be relative to the directory. For having the absolute path or for defining instances that are not files set* `trainInstancesDir=""`.

11.8 Tuning budget

- `maxExperiments` flag: `--max-experiments` default: *1000*
  The maximum number of runs (invocations of `targetRunner`) that will be performed. It determines the maximum budget of experiments for the tuning.

11.9 Statistical test

- `testType` flag: `--test-type` default: *F-test*
  Specifies the statistical test type:
  - `F-test` (Friedman test)
  - `t-test` (pairwise t-tests with no correction)
  - `t-test-bonferroni` (t-test with Bonferroniś correction for multiple comparisons)
  - `t-test-holm` (t-test with Holmś correction for multiple comparisons).

  See Section 10.4 to have more information about how to choose the statistical test.

- `firstTest` flag: `--first-test` default: *5*
  Specifies how many instances are executed before the first elimination test.

> *The value of* `firstTest` *must be a multiple of* `eachTest`.

- `eachTest` flag: `--each-test` default: *1*
  Specifies how many instances are executed between elimination tests.

- `confidence` flag: `--confidence` default: *0.95*
  Confidence level for the elimination test.

11.10 Recovery

- `recoveryFile` flag: `--recovery-file` Previously saved **irace** log file that should be used to recover the execution of irace, either absolute path or relative to the current directory. If empty or `NULL`, recovery is not performed. For more details about recovery see Section 11.10.

11.11 Testing

- `testNbElites` flag: `--test-num-elites` default: *0*
  Number of elite configurations returned by irace that will be tested. For more information about the testing see Section 7.

- `testIterationElites` flag: `--test-iteration-elites` default: *0*
  Enable/disable testing the elite configurations found at each iteration.

- `testInstancesDir` flag: `--test-instance-dir`
  Directory where testing instances are located, either absolute or relative to current directory.

- `testInstancesFile` flag: `--test-instance-file`
  File containing a list of test instances and optionally additional parameters for them.

12 FAQ

12.1 Is irace minimizing or maximizing the output of my algorithm?

By default, **irace** considers that the value returned by `targetRunner` (or by `targetEvaluator`, if used) should be minimized. In case of a maximization problem, one can simply multiply the value by -1 before returning it to irace. This is done, for example, when maximizing the hypervolume (see the last lines in `$IRACE_HOME/examples/hypervolume/target-evaluator`).

12.2 Is it possible to configure a MATLAB algorithm with irace?

Definitely. There are two main ways to achieve this:

1. Edit the `targetRunner` script to call MATLAB in a non-interactive way. See the MATLAB documentation, or the following links[2]. You would need to pass the parameter received by `targetRunner` to your MATLAB script: http://www.mathworks.nl/support/solutions/en/data/1-1BS5S/?solution=1-1BS5S. There is a minimal example in:

   `$IRACE_HOME/examples/matlab/`.

2. Call MATLAB code directly from R using the **R.matlab** package (http://cran.r-project.org/package=R.matlab). This is a better option if you are experienced in R. Define `targetRunner` as an R function instead of a path to a script. The function should call your MATLAB code with appropriate parameters.

12.3 My program works perfectly on its own, but not when running under irace. Is irace broken?

Every time this was reported, it was a difficult-to-reproduce bug in the program, not in **irace**. We recommend that in `targetRunner`, you use `valgrind` to run your program. That is, if you program is called like:

```
$EXE ${FIXED_PARAMS} -i $INSTANCE ${CAND_PARAMS} \
 1> ${STDOUT} 2> ${STDERR}
```

then replace that line with:

```
valgrind --error-exitcode=1 $EXE ${FIXED_PARAMS} \
 -i $INSTANCE ${CAND_PARAMS} 1> ${STDOUT} 2> ${STDERR}
```

If there are bugs in your program, they will appear in `$STDERR`, thus do not delete those files.

[2] http://stackoverflow.com/questions/1518072/suppress-start-message-of-matlab
http://stackoverflow.com/questions/4611195/how-to-call-matlab-from-command-line-and-print-to-stdout-before-exiting

12.4 My program may be buggy and run into an infinite loop. Is it possible to set a maximum timeout?

We are not aware of any way to achieve this using R. However, in GNU/Linux, it is easy to implement by using the `timeout` command in `targetRunner` when invoking your program.

13 Resources and contact information

More information of the package can be found on the **irace** webpage:

http://iridia.ulb.ac.be/irace/.

For questions and suggestions please contact the devolpment team through the mailing list:

irace@iridia.ulb.ac.be

or the **irace** package google group:

https://groups.google.com/d/forum/irace-package

14 Acknowledgements

We would like to thank all the people that directly or indirectly have colaborated in the development and improvement of **irace**.

- Mauro Birattari
- Thomas Stüzle
- add more people
- Manuel López-Ibáñez
- Jérémie Dubois-Lacoste
- Franco Mascia
- Leslie Pérez Cáceres
- Alberto Franzin
- Anthony Antoun

Appendix A R installation

In this section we give a quick R installation guide that will work in most cases. The official instructions are available at http://cran.r-project.org/doc/manuals/r-release/R-admin.html

A.1 GNU/Linux

You should install R from your package manager. On a Debian/Ubuntu system it will be something like:

```
sudo apt-get install r-base
```

Once R is installed, you can launch R from the Terminal and from the R prompt install the **irace** package (see Section 3.2).

A.2 OS X

You can install R directly from a CRAN mirror[3]. Alternatively, if you use homebrew, you can just brew the R formula from the science tap (unfortunately it does not come already bottled so you need to have Xcode[4] installed to compile it):

```
brew tap homebrew/science
brew install r
```

Once R is installed, you can launch R from the Terminal (or from your Applications), and from the R prompt install the **irace** package (see Section 3.2).

A.3 Windows

You can install R from a CRAN mirror[5]. Once R is installed, you can launch the R console and install the **irace** package from it (see Section 3.2).

Appendix B TargetRunner script check list

When the `targetRunner` script is not running properly can be difficult to detect where the problem is. The more your script provide descriptive errors, the more easy will be to debug. If you are using temporary files to redirect the output of your algorithm check that these are created properly. We recommend you to follow the structure of the example file (`target-runner`) provided in `$IRACE_HOME/templates`. The following examples are based in a file with that characteristics.

When you have problems with the `targetRunner` you will see an error on the **irace** output that says that the execution the `targetRunner` was not successful.

Follow this list to detect where the problem is:

[3] Belgian CRAN mirror: http://cran.freestatistics.org/bin/macosx/
[4] Xcode download webpage: https://developer.apple.com/xcode/download/
[5] Belgian CRAN mirror: http://cran.freestatistics.org/bin/windows/

1. Make sure that your `targetRunner script` is the specified location. If you see an error as follows:

   ```
   Error:  == irace == run program runner '~/tuning/target-runner' does
   not exist
   ```

   This means that **irace** is not finding the script file. Check that the file is in the path specified by the error.

2. Make sure that your `targetRunner` script is an executable if you see an error as follows:

   ```
   Error:  == irace == run program runner '~/tuning/target-runner' is
   a directory, not a file
   ```

   or

   ```
   Error:  == irace == run program runner '~/tuning/target-runner' is
   not executable
   ```

   This means that your `targetRunner` is not an executable file, in the first case the script is a folder and therefore there must be a problem with the name of the script. For the second case you must make the file an executable, in GNU/Linux you can do:

   ```
   cd ~/tuning/
   chmod +x target-runner
   ```

3. Make sure that your executable is in the location described in the script (variable `EXE` for the templates example). If you see an error like as follows this is your problem:

   ```
   Error:  == irace == running command ''~/tuning/target-runner'
   1 8 676651103 ~/tuning/Instances/1000-16.tsp --ras
   --localsearch 2 --alpha 4.03 --beta 1.89 --rho 0.02 --ants 37
   --nnls 48 --dlb 0 --rasranks 15 2>&1' had status 1

   == irace == The call to target.runner.default was:
   ~/tuning/target-runner 1 8 676651103 ~/tuning/Instances/1000-16.tsp
   --ras --localsearch 2 --alpha 4.03 --beta 1.89 --rho 0.02
   --ants 37 --nnls 48 --dlb 0 --rasranks 15

   == irace == The output was:
   Tue May 3 19:00:37 UTC 2016:  error:  ~/bin/acotsp:  not found
   or not executable (pwd:  ~/tuning/acotsp-arena)
   ```

For testing your script you can copy the line of execution and execute it directly in the command-line, in this case the line is:

```
~/tuning/target-runner 1 8 676651103 ~/tuning/Instances/1000-16.tsp
--ras --localsearch 2 --alpha 4.03 --beta 1.89 --rho 0.02 --ants 37
--nnls 48 --dlb 0 --rasranks 15
```

This line executes the `targetRunner` script as **irace** does, the output of this script must be only one number.

4. Check that your `targetRunner` script is actually returning one number as output. If you see an error as following this is your problem:

```
Error:  == irace == The output of '~/tuning/target-runner
1 25 365157769 ~/tuning/Instances/1000-31.tsp --ras
--localsearch 1 --alpha 0.26 --beta 6.95 --rho 0.69
--ants 56 --nnls 10 --dlb 0 --rasranks 7' is not numeric!

== irace == The output was:
Solution:  24479793
```

For testing your script you can copy the line of execution and execute it directly in the in the command-line, in this case is:

```
~/tuning/target-runner 1 25 365157769 ~/tuning/Instances/1000-31.tsp
--ras --localsearch 1 --alpha 0.26 --beta 6.95 --rho 0.69 --ants 56
--nnls 10 --dlb 0 --rasranks 7
```

This line executes the `targetRunner` script as **irace** does, the output of this script must be only one number. In this example the output of the script is "`Solution:  24479793`", that means that the regular expression used to obtain the result from the algorithm output file must be checked.

5. Check that your `targetRunner` script is creating the output files for your algorithm. If you see an error as follows:

```
== irace == The output was:  Tue May 3 19:41:40 UTC 2016:
error:  c1-9.stdout:  No such file or directory
```

It means that the output file of the execution of your algorithm has not been created (check permissions) or has been deleted before the result can be read.

6. Other errors can produce the follwing output:

```
== irace == The output was:  Tue May 3 19:49:06 UTC 2016:
error:  c1-23.stdout:  Output is not a number
```

This might be due that your `targetRunner` script is not executing your algorithm correctly. To further investigate comment the line that eliminates the temporary files where the output of your algorithm is redirected:

```
rm -f "${STDOUT}" "${STDERR}"
```

Execute the `targetRunner` command-line the error provides and search in your execution directory the files that are created. Check the `.stderr` file for errors and the `.stdout` file to see the output your algorithm produces.

Appendix C Glossary

1. Parameter tuning: Process of searching good settings for the parameters of an algorithm under a particular tuning scenario (instances, execution time, etc.).
2. Scenario: Settings of a tuning scenario, these settings include the algorithm to be tuned (target), budget for the execution of the target algorithm (execution time, evaluations, iterations, etc.), set of problem instances and all the information that is required to perform the tuning.
3. Target algorithm: algorithm whose parameters will be tuned.
4. Target parameter: parameter of the target algorithm that will be tuned.
5. **irace** option: configurable option of **irace**.
6. Elite configurations: best configurations found from whose probabilistic models new configurations are sampled for the next iteration. All elite configurations are also included in the next iteration.