# R Internals

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**R Development Core Team**

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# 1 R Internal Structures

This chapter is the beginnings of documentation about R internal structures. It is written for the R core team and others studying the code in the 'src/main' directory.

It is a work-in-progress, first begun for R 2.4.0, and should be checked against the current version of the source code.

## 1.1 SEXPs

What R users think of as *variables* or *objects* are symbols which are bound to a value. The value can be thought of as either a SEXP (a pointer), or the structure it points to, a SEXPREC (and there are alternative forms used for vectors, namely VECSXP pointing to VECTOR_SEXPREC structures). So the basic building blocks of R objects are often called *nodes*, meaning SEXPRECs or VECTOR_SEXPRECs.

Note that the internal structure of the SEXPREC is not made available to R Extensions: rather SEXP is an opaque pointer, and the internals can only be accessed by the functions provided.

Both types of node structure have as their first three fields a 32-bit sxpinfo header and then three pointers (to the attributes and the previous and next node in a doubly-linked list), and then some further fields. On a 32-bit platform a node[1] occupies 28 bytes: on a 64-bit platform typically 56 bytes (depending on alignment constraints).

The first five bits of the sxpinfo header specify one of up to 32 SEXPTYPEs.

### 1.1.1 SEXPTYPEs

Currently SEXPTYPEs 0:10 and 13:25 are in use. Values 11 and 12 were used for internal factors and ordered factors and have since been withdrawn. Note that the SEXPTYPEs are stored in saved objects and that the ordering of the types is used, so the gap cannot easily be reused.

| no | SEXPTYPE | Description |
|---|---|---|
| 0 | NILSXP | NULL |
| 1 | SYMSXP | symbols |
| 2 | LISTSXP | pairlists |
| 3 | CLOSXP | closures |
| 4 | ENVSXP | environments |
| 5 | PROMSXP | promises |
| 6 | LANGSXP | language objects |
| 7 | SPECIALSXP | special functions |
| 8 | BUILTINSXP | builtin functions |
| 9 | CHARSXP | internal character strings |
| 10 | LGLSXP | logical vectors |
| 13 | INTSXP | integer vectors |
| 14 | REALSXP | numeric vectors |
| 15 | CPLXSXP | complex vectors |
| 16 | STRSXP | character vectors |
| 17 | DOTSXP | dot-dot-dot object |
| 18 | ANYSXP | make "any" args work |
| 19 | VECSXP | list (generic vector) |
| 20 | EXPRSXP | expression vector |
| 21 | BCODESXP | byte code |
| 22 | EXTPTRSXP | external pointer |

[1] strictly, a SEXPREC node; VECTOR_SEXPREC nodes are slightly smaller but followed by data in the node.

| | | |
|---|---|---|
| 23 | WEAKREFSXP | weak reference |
| 24 | RAWSXP | raw vector |
| 25 | S4SXP | S4 classes not of simple type |

Many of these will be familiar from R level: the atomic vector types are LGLSXP, INTSXP, REALSXP, CPLXSP, STRSXP and RAWSXP. Lists are VECSXP and names (also known as symbols) are SYMSXP. Pairlists (LISTSXP, the name going back to the origins of R as a Scheme-like language) are rarely seen at R level, but are for example used for argument lists. Character vectors are effectively lists all of whose elements are CHARSXP, a type that is rarely visible at R level.

Language objects (LANGSXP) are calls (including formulae and so on). Internally they are pairlists with first element a reference[2] to the function to be called with remaining elements the actual arguments for the call (and with the tags if present giving the specified argument names). Although this is not enforced, many places in the code assume that the pairlist is of length one or more, often without checking.

Expressions are of type EXPRSXP: they are a vector of (usually language) objects most often seen as the result of parse().

The functions are of types CLOSXP, SPECIALSXP and BUILTINSXP: where SEXPTYPEs are stored in an integer these are sometimes lumped into a pseudo-type FUNSXP with code 99. Functions defined via function are of type CLOSXP and have formals, body and environment.

The SEXPTYPE S4SXP was introduced in R 2.4.0 for S4 classes which were previously represented as empty lists, that is objects which do not consist solely of a simple type such as an atomic vector or function.

### 1.1.2 Rest of header

The sxpinfo header is defined as a 32-bit C structure by

```
struct sxpinfo_struct {
    SEXPTYPE type      :  5;  /* discussed above */
    unsigned int obj   :  1;  /* is this an object with a class attribute? */
    unsigned int named :  2;  /* used to control copying */
    unsigned int gp    : 16;  /* general purpose, see below */
    unsigned int mark  :  1;  /* mark object as 'in use' in GC */
    unsigned int debug :  1;
    unsigned int trace :  1;
    unsigned int spare :  1;  /* unused */
    unsigned int gcgen :  1;  /* generation for GC */
    unsigned int gccls :  3;  /* class of node for GC */
};  /*              Tot: 32 */
```

The debug bit is used for closures and environments. For closures it is set by debug() and unset by undebug(), and indicates that evaluations of the function should be run under the browser. For environments it indicates whether the browsing is in single-step mode.

The trace bit is used for functions for trace() and for other objects when tracing duplications (see tracemem).

The named field is set and accessed by the SET_NAMED and NAMED macros, and take values 0, 1 and 2. R has a 'call by value' illusion, so an assignment like

```
b <- a
```

appears to make a copy of a and refer to it as b. However, if neither a nor b are subsequently altered there is no need to copy. What really happens is that a new symbol b is bound to the same value as a and the named field on the value object is set (in this case to 2). When an

[2] a pointer to a function or a symbol to look up the function by name, or a language object to be evaluated to give a function.

object is about to be altered, the named field is consulted. A value of 2 means that the object must be duplicated before being changed. (Note that this does not say that it is necessary to duplicate, only that it should be duplicated whether necessary or not.) A value of 0 means that it is known that no other SEXP shares data with this object, and so it may safely be altered. A value of 1 is used for situations like

```
dim(a) <- c(7, 2)
```

where in principle two copies of a exist for the duration of the computation as (in principle)

```
a <- `dim<-`(a, c(7, 2))
```

but for no longer, and so some primitive functions can be optimized to avoid a copy in this case.

The gp bits are by definition 'general purpose'. We label these from 0 to 15. As of version 2.4.0 of R, bit 4 is turned on to mark S4 objects. Bits 0-3 and bits 14-15 have been used previously as described below (from detective work on the sources).

The bits can be accessed and set by the LEVELS and SETLEVELS macros, which names appear to date back to the internal factor and ordered types and are now used in only a few places in the code. The gp field is serialized/unserialized for the SEXPTYPEs other than NILSXP, SYMSXP and ENVSXP.

Bits 14 and 15 of gp are used for 'fancy bindings'. Bit 14 is used to lock a binding or an environment, and bit 15 is used to indicate an active binding. (For the definition of an 'active binding' see the header comments in file 'src/main/envir.c'.) Bit 15 is used for an environment to indicate if it participates in the global cache.

Almost all other uses seem to be only of bits 0 and 1, although one reserves the first four bits.

The macros ARGUSED and SET_ARGUSED are used when matching actual and formal function arguments, and take the values 0, 1 and 2.

The macros MISSING and SET_MISSING are used for pairlists of arguments. Four bits are reserved, but only two are used (and exactly what for is not explained). It seems that bit 0 is used by matchArgs to mark missingness on the returned argument list, and bit 1 is used to mark the use of a default value for an argument copied to the evaluation frame of a closure.

Bit 0 is used by macros DDVAL and SET_DDVAL. This indicates that a SYMSXP is one of the symbols ..n which are implicitly created when ... is processed, and so indicates that it may need to be looked up in a DOTSXP.

Bit 0 is used for PRSEEN, a flag to indicate if a promise has already been seen during the evaluation of the promise (and so to avoid recursive loops).

Bit 0 is used for HASHASH, on the PRINTNAME of the TAG of the frame of an environment.

Bits 0 and 1 are used for weak references (to indicate 'ready to finalize', 'finalize on exit').

Bit 0 is used by the condition handling system (on a VECSXP) to indicate a calling handler.

As from R 2.5.0, bits 2 and 3 for a CHARSXP are used to note that it is known to be in Latin-1 and UTF-8 respectively. (These are not usually set if it is also known to be in ASCII, since code does not need to know the charset to handle ASCII strings. From R 2.8.0 it is guaranteed that they will not be set for CHARSXPs created by R itself.) As from R 2.8.0 bit 5 is used to indicate that a CHARSXP is hashed by its address, that is NA_STRING or in the CHARSXP cache.

### 1.1.3 The 'data'

A SEXPREC is a C structure containing the 32-bit header as described above, three pointers (to the attributes, previous and next node) and the node data, a union

```
union {
    struct primsxp_struct primsxp;
```

```
        struct symsxp_struct symsxp;
        struct listsxp_struct listsxp;
        struct envsxp_struct envsxp;
        struct closxp_struct closxp;
        struct promsxp_struct promsxp;
    } u;
```

All of these alternatives apart from the first (an `int`) are three pointers, so the union occupies three words.

The vector types are `RAWSXP`, `CHARSXP`, `LGLSXP`, `INTSXP`, `REALSXP`, `CPLXSXP`, `STRSXP`, `VECSXP`, `EXPRSXP` and `WEAKREFSXP`. Remember that such types are a `VECTOR_SEXPREC`, which again consists of the header and the same three pointers, but followed by two integers giving the length and 'true length'[3] of the vector, and then followed by the data (aligned as required: on most 32-bit systems with a 24-byte `VECTOR_SEXPREC` node the data can follow immediately after the node). The data are a block of memory of the appropriate length to store 'true length' elements (rounded up to a multiple of 8 bytes, with the 8-byte blocks being the 'Vcells' referred in the documentation for `gc()`).

The 'data' for the various types are given in the table below. A lot of this is interpretation, i.e. the types are not checked.

`NILSXP`
: There is only one object of type `NILSXP`, `R_NilValue`, with no data.

`SYMSXP`
: Pointers to three nodes, the name, value and internal, accessed by `PRINTNAME` (a `CHARSXP`), `SYMVALUE` and `INTERNAL`. (If the symbol's value is a `.Internal` function, the last is a pointer to the appropriate `SEXPREC`.) Many symbols have `SYMVALUE` `R_UnboundValue`.

`LISTSXP`
: Pointers to the CAR, CDR (usually a `LISTSXP` or `NULL`) and TAG (usually a `SYMSXP`).

`CLOSXP`
: Pointers to the formals (a pairlist), the body and the environment.

`ENVSXP`
: Pointers to the frame, enclosing environment and hash table (`NULL` or a `VECSXP`). A frame is a tagged pairlist with tag the symbol and CAR the bound value.

`PROMSXP`
: Pointers to the value, expression and environment (in which to evaluate the expression). Once an promise has been evaluated, the environment is set to `NULL`.

`LANGSXP`
: A special type of `LISTSXP` used for function calls. (The CAR references the function (perhaps via a symbol or language object), and the CDR the argument list with tags for named arguments.) R-level documentation references to 'expressions' / 'language objects' are mainly `LANGSXP`s, but can be symbols (`SYMSXP`s) or expression vectors (`EXPRSXP`s).

`SPECIALSXP`
`BUILTINSXP`
: An integer giving the offset into the table of primitives/`.Internal`s.

`CHARSXP`
: `length`, `truelength` followed by a block of bytes (allowing for the `nul` terminator).

`LGLSXP`
`INTSXP`
: `length`, `truelength` followed by a block of C `int`s (which are 32 bits on all R platforms).

`REALSXP`
: `length`, `truelength` followed by a block of C `double`s

[3] This is almost unused. The only current use is for hash tables of environments (`VECSXP`s), where `length` is the size of the table and `truelength` is the number of primary slots in use, and for the reference hash tables in serialization (`VECSXP`s), where `truelength` is the number of slots in use.

`CPLXSXP` `length`, `truelength` followed by a block of C99 `double complex`s, or equivalent structures.

`STRSXP` `length`, `truelength` followed by a block of pointers (`SEXP`s pointing to `CHARSXP`s).

`DOTSXP` A special type of `LISTSXP` for the value bound to a `...` symbol: a pairlist of promises.

`ANYSXP` This is used as a place holder for any type: there are no actual objects of this type.

`VECSXP`
`EXPRSXP` `length`, `truelength` followed by a block of pointers. These are internally identical (and identical to `STRSXP`) but differ in the interpretations placed on the elements.

`BCODESXP` For the future byte-code compiler.

`EXTPTRSXP`
Has three pointers, to the pointer, the protection value (an R object which if alive protects this object) and a tag (a `SYMSXP`?).

`WEAKREFSXP`
A `WEAKREFSXP` is a special `VECSXP` of length 4, with elements '`key`', '`value`', '`finalizer`' and '`next`'. The '`key`' is `NULL`, an environment or an external pointer, and the '`finalizer`' is a function or `NULL`.

`RAWSXP` `length`, `truelength` followed by a block of bytes.

`S4SXP` two unused pointers and a tag.

### 1.1.4 Allocation classes

As we have seen, the field `gccls` in the header is three bits to label up to 8 classes of nodes. Non-vector nodes are of class 0, and 'small' vector nodes are of classes 1 to 6, with 'large' vector nodes being of class 7. The 'small' vector nodes are able to store vector data of up to 8, 16, 32, 48, 64 and 128 bytes: larger vectors are `malloc`-ed individually whereas the 'small' nodes are allocated from pages of about 2000 bytes.

## 1.2 Environments and variable lookup

What users think of as 'variables' are symbols which are bound to objects in 'environments'. The word 'environment' is used ambiguously in R to mean *either* the frame of an `ENVSXP` (a pairlist of symbol-value pairs) *or* an `ENVSXP`, a frame plus an enclosure.

There are additional places that 'variables' can be looked up, called 'user databases' in comments in the code. These seem undocumented in the R sources, but apparently refer to the **RObjectTable** package at http://www.omegahat.org/RObjectTables/.

The base environment is special. There is an `ENVSXP` environment with enclosure the empty environment `R_EmptyEnv`, but the frame of that environment is not used. Rather its bindings are part of the global symbol table, being those symbols in the global symbol table whose values are not `R_UnboundValue`. When R is started the internal functions are installed (by C code) in the symbol table, with primitive functions having values and `.Internal` functions having what would be their values in the field accessed by the `INTERNAL` macro. Then `.Platform` and `.Machine` are computed and the base package is loaded into the base environment followed by the system profile.

The frames of environments (and the symbol table) are normally hashed for faster access (including insertion and deletion).

By default R maintains a (hashed) global cache of 'variables' (that is symbols and their bindings) which have been found, and this refers only to environments which have been marked to participate, which consists of the global environment (aka the user workspace), the base

environment plus environments[4] which have been `attach`ed. When an environment is either `attach`ed or `detach`ed, the names of its symbols are flushed from the cache. The cache is used whenever searching for variables from the global environment (possibly as part of a recursive search).

### 1.2.1 Search paths

S has the notion of a 'search path': the lookup for a 'variable' leads (possibly through a series of frames) to the 'session frame' the 'working directory' and then along the search path. The search path is a series of databases (as returned by `search()`) which contain the system functions (but not necessarily at the end of the path, as by default the equivalent of packages are added at the end).

R has a variant on the S model. There is a search path (also returned by `search()`) which consists of the global environment (aka user workspace) followed by environments which have been attached and finally the base environment. Note that unlike S it is not possible to attach environments before the workspace nor after the base environment.

However, the notion of variable lookup is more general in R, hence the plural in the title of this subsection. Since environments have enclosures, from any environment there is a search path found by looking in the frame, then the frame of its enclosure and so on. Since loops are not allowed, this process will eventually terminate: until R 2.2.0 it always terminated at the base environment, but nowadays it can terminate at either the base environment or the empty environment. (It can be conceptually simpler to think of the search always terminating at the empty environment, but with an optimization to stop at the base environment.) So the 'search path' describes the chain of environments which is taken once the search reaches the global environment.

### 1.2.2 Name spaces

Name spaces are environments associated with packages (and once again the base package is special and will be considered separately). A package *pkg* with a name space defines two environments `namespace:`*pkg* and `package:`*pkg*: it is `package:`*pkg* that can be `attach`ed and form part of the search path.

The objects defined by the R code in the package are symbols with bindings in the `namespace:`*pkg* environment. The `package:`*pkg* environment is populated by selected symbols from the `namespace:`*pkg* environment (the exports). The enclosure of this environment is an environment populated with the explicit imports from other name spaces, and the enclosure of *that* environment is the base name space. (So the illusion of the imports being in the name space environment is created via the environment tree.) The enclosure of the base name space is the global environment, so the search from a package name space goes via the (explicit and implicit) imports to the standard 'search path'.

The base name space environment `R_BaseNamespace` is another `ENVSXP` that is special-cased. It is effectively the same thing as the base environment `R_BaseEnv` *except* that its enclosure is the global environment rather than the empty environment: the internal code diverts lookups in its frame to the global symbol table.

## 1.3 Attributes

As we have seen, every `SEXPREC` has a pointer to the attributes of the node (default `R_NilValue`). The attributes can be accessed/set by the macros/functions `ATTRIB` and `SET_ATTRIB`, but such direct access is normally[5] only used to check if the attributes are `NULL` or to reset them. Otherwise

[4] Remember that attaching a list or a saved image actually creates and populates an environment and attaches that.

[5] An exception is the internal code for `terms.formula` which directly manipulates the attributes.

access goes through the functions `getAttrib` and `setAttrib` which impose restrictions on the attributes. One thing to watch is that if you copy attributes from one object to another you may (un)set the `"class"` attribute and so need to copy the object and S4 bits as well. There is a macro/function `DUPLICATE_ATTRIB` to automate this.

The code assumes that the attributes of a node are either `R_NilValue` or a pairlist of non-zero length (and this is checked by `SET_ATTRIB`). The attributes are named (via tags on the pairlist). The replacement function `attributes<-` ensures that `"dim"` precedes `"dimnames"` in the pairlist. Attribute `"dim"` is one of several that is treated specially: the values are checked, and any `"names"` and `"dimnames"` attributes are removed. Similarly, you cannot set `"dimnames"` without having set `"dim"`, and the value assigned must be a list of the correct length and with elements of the correct lengths (and all zero-length elements are replaced by `NULL`).

The other attributes which are given special treatment are `"names"`, `"class"`, `"tsp"`, `"comment"` and `"row.names"`. For pairlist-like objects the names are not stored as an attribute but (as symbols) as the tags: however the R interface makes them look like conventional attributes, and for one-dimensional arrays they are stored as the first element of the `"dimnames"` attribute. The C code ensures that the `"tsp"` attribute is an `REALSXP`, the frequency is positive and the implied length agrees with the number of rows of the object being assigned to. Classes and comments are restricted to character vectors, and assigning a zero-length comment or class removes the attribute. Setting or removing a `"class"` attribute sets the object bit appropriately. Integer row names are converted to and from the internal compact representation.

Care needs to be taken when adding attributes to objects of the types with non-standard copying semantics. There is only one object of type `NILSXP`, `R_NilValue`, and that should never have attributes (and this is enforced in `installAttrib`). For environments, external pointers and weak references, the attributes should be relevant to all uses of the object: it is for example reasonable to have a name for an environment, and also a `"path"` attribute for those environments populated from R code in a package.

When should attributes be preserved under operations on an object? Becker, Chambers & Wilks (1988, pp. 144–6) give some guidance. Scalar functions (those which operate element-by-element on a vector and whose output is similar to the input) should preserve attributes (except perhaps class, and if they do preserve class they need to preserve the `OBJECT` and S4 bits). Binary operations normally call `copyMostAttributes` to copy most attributes from the longer argument (and if they are of the same length from both, preferring the values on the first). Here 'most' means all except the `names`, `dim` and `dimnames` which are set appropriately by the code for the operator.

Subsetting (other than by an empty index) generally drops all attributes except `names`, `dim` and `dimnames` which are reset as appropriate. On the other hand, subassignment generally preserves such attributes even if the length is changed. Coercion drops all attributes. For example:

```
> x <- structure(1:8, names=letters[1:8], comm="a comment")
> x[]
a b c d e f g h
1 2 3 4 5 6 7 8
attr(,"comm")
[1] "a comment"
> x[1:3]
a b c
1 2 3
> x[3] <- 3
> x
a b c d e f g h
```

```
1 2 3 4 5 6 7 8
attr(,"comm")
[1] "a comment"
> x[9] <- 9
> x
a b c d e f g h
1 2 3 4 5 6 7 8 9
attr(,"comm")
[1] "a comment"
```

## 1.4 Contexts

*Contexts* are the internal mechanism used to keep track of where a computation has got to (and from where), so that control-flow constructs can work and reasonable information can be produced on error conditions, (such as *via* traceback) and otherwise (the `sys.xxx` functions).

Execution contexts are a stack of C `structs`:

```
typedef struct RCNTXT {
    struct RCNTXT *nextcontext; /* The next context up the chain */
    int callflag;               /* The context 'type' */
    JMP_BUF cjmpbuf;            /* C stack and register information */
    int cstacktop;              /* Top of the pointer protection stack */
    int evaldepth;              /* Evaluation depth at inception */
    SEXP promargs;              /* Promises supplied to closure */
    SEXP callfun;               /* The closure called */
    SEXP sysparent;             /* Environment the closure was called from */
    SEXP call;                  /* The call that effected this context */
    SEXP cloenv;                /* The environment */
    SEXP conexit;               /* Interpreted on.exit code */
    void (*cend)(void *);       /* C on.exit thunk */
    void *cenddata;             /* Data for C on.exit thunk */
    char *vmax;                 /* Top of the R_alloc stack */
    int intsusp;                /* Interrupts are suspended */
    SEXP handlerstack;          /* Condition handler stack */
    SEXP restartstack;          /* Stack of available restarts */
    struct RPRSTACK *prstack;   /* Stack of pending promises */
} RCNTXT, *context;
```

plus additional fields for the future byte-code compiler. The 'types' are from

```
enum {
    CTXT_TOPLEVEL = 0,  /* toplevel context */
    CTXT_NEXT     = 1,  /* target for next */
    CTXT_BREAK    = 2,  /* target for break */
    CTXT_LOOP     = 3,  /* break or next target */
    CTXT_FUNCTION = 4,  /* function closure */
    CTXT_CCODE    = 8,  /* other functions that need error cleanup */
    CTXT_RETURN   = 12, /* return() from a closure */
    CTXT_BROWSER  = 16, /* return target on exit from browser */
    CTXT_GENERIC  = 20, /* rather, running an S3 method */
    CTXT_RESTART  = 32, /* a call to restart was made from a closure */
    CTXT_BUILTIN  = 64  /* builtin internal function */
};
```

where the `CTXT_FUNCTION` bit is on wherever function closures are involved.

Contexts are created by a call to `begincontext` and ended by a call to `endcontext`: code can search up the stack for a particular type of context via `findcontext` (and jump there) or jump to a specific context via `R_JumpToContext`. `R_ToplevelContext` is the 'idle' state (normally the command prompt), and `R_GlobalContext` is the top of the stack.

Note that whilst all calls to closures set a context, those to special internal functions never do, and those to builtin internal functions have done so only recently (and prior to that only when profiling).

Dispatching from a S3 generic (via `UseMethod` or its internal equivalent) or calling `NextMethod` sets the context type to `CTXT_GENERIC`. This is used to set the `sysparent` of the method call to that of the `generic`, so the method appears to have been called in place of the generic rather than from the generic.

The R `sys.frame` and `sys.call` work by counting calls to closures (type `CTXT_FUNCTION`) from either end of the context stack.

Note that the `sysparent` element of the structure is not the same thing as `sys.parent()`. Element `sysparent` is primarily used in managing changes of the function being evaluated, i.e. by `Recall` and method dispatch.

`CTXT_CCODE` contexts are currently used in `cat()`, `load()`, `scan()` and `write.table()` (to close the connection on error), by `PROTECT`, serialization (to recover from errors, e.g. free buffers) and within the error handling code (to raise the C stack limit and reset some variables).

## 1.5 Argument evaluation

As we have seen, functions in R come in three types, closures (`SEXPTYPE CLOSXP`), specials (`SPECIALSXP`) and builtins (`BUILTINSXP`). In this section we consider when (and if) the actual arguments of function calls are evaluated. The rules are different for the internal (special/builtin) and R-level functions (closures).

For a call to a closure, the actual and formal arguments are matched and a matched call (another `LANGSXP`) is constructed. This process first replaces the actual argument list by a list of promises to the values supplied. It then constructs a new environment which contains the names of the formal parameters matched to actual or default values: all the matched values are promises, the defaults as promises to be evaluated in the environment just created. That environment is then used for the evaluation of the body of the function, and promises will be forced (and hence actual or default arguments evaluated) when they are encountered. (Evaluating a promise sets `NAMED = 2` on its value, so if the argument was a symbol its binding is regarded as having multiple references during the evaluation of the closure call.)

If the closure is an S3 generic (that is, contains a call to `UseMethod`) the evaluation process is the same until the `UseMethod` call is encountered. At that point the argument on which to do dispatch (normally the first) will be evaluated if it has not been already. If a method has been found which is a closure, a new evaluation environment is created for it containing the matched arguments of the method plus any new variables defined so far during the evaluation of the body of the generic. (Note that this means changes to the values of the formal arguments in the body of the generic are discarded when calling the method, but *actual* argument promises which have been forced retain the values found when they were forced. On the other hand, missing arguments have values which are promises to use the default supplied by the method and not the generic.) If the method found is a special or builtin it is called with the matched argument list of promises (possibly already forced) used for the generic.

The essential difference[6] between special and builtin functions is that the arguments of specials are not evaluated before the C code is called, and those of builtins are. In each case

[6] There is currently one other difference: when profiling builtin functions are counted as function calls but specials are not.

positional matching of arguments is used. Note that being a special/builtin is separate from being primitive or `.Internal`: `function` is a special primitive, `+` is a builtin primitive, `switch` is a special `.Internal` and `grep` is a builtin `.Internal`.

Many of the internal functions are internal generics, which for specials means that they do not evaluate their arguments on call, but the C code starts with a call to `DispatchOrEval`. The latter evaluates the first argument, and looks for a method based on its class. (If S4 dispatch is on, S4 methods are looked for first, even for S3 classes.) If it finds a method, it dispatches to that method with a call based on promises to evaluate the remaining arguments. If no method is found, the remaining arguments are evaluated before return to the internal generic.

The other way that internal functions can be generic is to be group generic. All such functions are builtins (so immediately evaluate all their arguments), and contain a call to the C function `DispatchGeneric`. There are some peculiarities over the number of arguments for the `"Math"` group generic, with some members allowing only one argument, some having two (with a default for the second) and `trunc` allows one or more but the default only accepts one.

### 1.5.1 Missingness

Actual arguments to (non-internal) R functions can be fewer than are required to match the formal arguments of the function. Having unmatched formal arguments will not matter if the argument is never used (by lazy evaluation), but when the argument is evaluated, either its default value is evaluated (within the evaluation environment of the function) or an error is thrown with a message along the lines of

```
argument "foobar" is missing, with no default
```

Internally missingness is handled by two mechanisms. The object `R_MissingArg` is used to indicate that a formal argument has no (default) value. When matching the actual arguments to the formal arguments, a new argument list is constructed from the formals all of whose values are `R_MissingArg` with the first `MISSING` bit set. Then whenever a formal argument is matched to an actual argument, the corresponding member of the new argument list has its value set to that of the matched actual argument, and if that is not `R_MissingArg` the missing bit is unset.

This new argument list is used to form the evaluation frame for the function, and if named arguments are subsequently given a new value (before they are evaluated) the missing bit is cleared.

Missingness of arguments can be interrogated via the `missing()` function. An argument is clearly missing if its missing bit is set or if the value is `R_MissingArg`. However, missingness can be passed on from function to function, for using a formal argument as an actual argument in a function call does not count as evaluation. So `missing()` has to examine the value (a promise) of a non-yet-evaluated formal argument to see if it might be missing, which might involve investigating a promise and so on ....

### 1.5.2 Dot-dot-dot arguments

Dot-dot-dot arguments are convenient when writing functions, but complicate the internal code for argument evaluation.

The formals of a function with a `...` argument represent that as a single argument like any other argument, with tag the symbol `R_DotsSymbol`. When the actual arguments are matched to the formals, the value of the `...` argument is of `SEXPTYPE` `DOTSXP`, a pairlist of promises (as used for matched arguments) but distinguished by the `SEXPTYPE`.

Recall that the evaluation frame for a function initially contains the *`name=value`* pairs from the matched call, and hence this will be true for `...` as well. The value of `...` is a (special) pairlist whose elements are referred to by the special symbols `..1`, `..2`, ... which have the `DDVAL` bit set: when one of these is encountered it is looked up (via `ddfndVar`) in the value of the `...` symbol in the evaluation frame.

Values of arguments matched to a `...` argument can be missing.

## 1.6 Autoprinting

Whether the returned value of a top-level R expression is printed is controlled by the global boolean variable `R_Visible`. This is set (to true or false) on entry to all primitive and internal functions based on the `eval` column of the table in '`names.c`': the appropriate setting can be extracted by the macro `PRIMPRINT`.

The R primitive function `invisible` makes use of this mechanism: it just sets `R_Visible = FALSE` before entry and returns its argument.

For most functions the intention will be that the setting of `R_Visible` when they are entered is the setting used when they return, but there need to be exceptions. The R functions `identify`, `options`, `system` and `writeBin` determine whether the result should be visible from the arguments or user action. Other functions themselves dispatch functions which may change the visibility flag: examples[7] are `.Internal`, `do.call`, `eval`, `eval.with.vis`[8], `if`, `NextMethod`, `Recall`, `recordGraphics`, `standardGeneric`, `switch` and `UseMethod`.

'Special' primitive and internal functions evaluate their arguments internally *after* `R_Visible` has been set, and evaluation of the arguments (e.g. an assignment as in PR#9263)) can change the value of the flag. Prior to R 2.5.0, known instances of such functions reset the flag after the internal evaluation of arguments: examples include `[`, `[[`, `$`, `c`, `cbind`, `dump`, `rbind` and `unlist`, as well as the language constructs (which are primitives) `for`, `while` and `repeat`.

The `R_Visible` flag can also get altered during the evaluation of a function, with comments in the code about `warning`, `writeChar` and graphics functions calling `GText` (PR#7397). (Since the C-level function `eval` sets `R_Visible`, this could apply to any function calling it. Since it is called when evaluating promises, even object lookup can change `R_Visible`.) From R 2.1.0 internal functions that were marked to set `R_Visible = FALSE` enforced this when the function returned. As from R 2.5.0 both internal and primitive functions force the documented setting of `R_Visible` on return, unless the C code is allowed to change it (the exceptions above are indicated by `PRIMPRINT` having value 2).

The actual autoprinting is done by `PrintValueEnv` in '`print.c`'. If the object to be printed has the S4 bit set and S4 methods dispatch is on, `show` is called to print the object. Otherwise, if the object bit is set (so the object has a `"class"` attribute), `print` is called to dispatch methods: for objects without a class the internal code of `print.default` is called.

## 1.7 The write barrier and the garbage collector

R has since version 1.2.0 had a generational garbage collector, and bit `gcgen` in the `sxpinfo` header is used in the implementation of this. This is used in conjunction with the `mark` bit to identify two previous generations.

There are three levels of collections. Level 0 collects only the youngest generation, level 1 collects the two youngest generations and level 2 collects all generations. After 20 level-0 collections the next collection is at level 1, and after 5 level-1 collections at level 2. Further, if a level-*n* collection fails to provide 20% free space (for each of nodes and the vector heap), the next collection will be at level *n+1*. (The R-level function `gc()` performs a level-2 collection.)

A generational collector needs to efficiently 'age' the objects, especially list-like objects (including `STRSXP`s). This is done by ensuring that the elements of a list are regarded as at least as old as the list *when they are assigned*. This is handled by the functions `SET_VECTOR_ELT` and `SET_STRING_ELT`, which is why they are functions and not macros. Ensuring the integrity of

[7] the other current example is left brace, which is implemented as a primitive.

[8] a `.Internal`-only function used in `source`, `withVisible` and a few other places.

such operations is termed the *write barrier* and is done by making the SEXP opaque and only providing access via functions (which cannot be used as lvalues in assignments in C).

All code in R extensions is by default behind the write barrier. The only way to obtain direct access to the internals of the SEXPRECs is to define 'USE_RINTERNALS' before including 'Rinternals.h', which is normally defined in 'Defn.h'. To enable a check on the way that the access is used, R can be compiled with flag '--enable-strict-barrier' which ensures that 'Defn.h' does not define 'USE_RINTERNALS' and hence that SEXP is opaque in most of R itself. (There are some necessary exceptions: foremost 'memory.c' where the accessor functions are defined and also 'size.c' which needs access to the sizes of the internal structures.)

For background papers see http://www.stat.uiowa.edu/~luke/R/barrier.html and http://www.stat.uiowa.edu/~luke/R/gengcnotes.html.

## 1.8 Serialization Formats

Serialized versions of R objects are used by load/save and also at a lower level by .saveRDS/.readRDS and serialize/unserialize. These differ in what they serialize to (a file, a connection, a raw vector) and whether they are intended to serialize a single object or a collection of objects (typically a workspace). save writes a header indicating the format at the beginning of the file (a single LF-terminated line) which the lower-level versions do not.

R has used the same serialization format since R 1.4.0 in December 2001. Reading of earlier formats is still supported via load, but they are not described here. (Files of most of these formats can still be found in 'data' directories of packages.) The current serialization format is called 'version 2', and has been expanded in back-compatible ways since R 1.4.0, for example to support additional SEXPTYPEs.

save() works by first creating a tagged pairlist of objects to be saved, and then saving that single object preceded by a single-line header (typically RDX2\n for a binary save). load() reads the header line, unserializes a single object (a pairlist or a vector list) and assigns the elements of the list in the appropriate environment.

Serialization in R needs to take into account that objects may contain references to environments, which then have enclosing environments and so on. (Environments recognized as package or name space environments are saved by name.) Further, there are 'reference objects' which are not duplicated on copy and should remain shared on unserialization. These are weak references, external pointers and environments other than those associated with packages, name spaces and the global environment. These are handled via a hash table, and references after the first are written out as a reference marker indexed by the table entry.

Serialization first writes a header indicating the format (normally 'X\n' for an XDR format binary save, but 'A\n', ASCII, and 'B\n', native word-order binary[9], can also occur) and the version number of the format and of two R versions (as integers). (Unserialization interprets the two versions as the version of R which wrote the file followed by the minimal version of R needed to read the format.) Serialization then writes out the object recursively using function WriteItem in file 'src/main/serialize.c'.

Some objects are written as if they were SEXPTYPEs: such pseudo-SEXPTYPEs cover R_NilValue, R_EmptyEnv, R_BaseEnv, R_GlobalEnv, R_UnboundValue, R_MissingArg and R_BaseNamespace.

For all SEXPTYPEs except NILSXP, SYMSXP and ENVSXP serialization starts with an integer with the SEXPTYPE in bits 0:7[10] followed by the object bit, two bits indicating if there are any attributes and if there is a tag (for the pairlist types), an unused bit and then the gp field[11] in bits

[9] there is no R-level interface to this format

[10] only 0:4 will currently be used for SEXPTYPEs but values 241:255 are used for pseudo-SEXPTYPEs.

[11] Currently the only relevant bits are 0:1, 4, 14:15.

12:27. Pairlist-like objects write their attributes (if any), tag (if any), CAR and then CDR (using tail recursion): other objects write their attributes after themselves. Atomic vector objects write their length followed by the data: generic vector-list objects write the length followed by a call to `WriteItem` for each element. The code for `CHARSXP`s special-cases `NA_STRING` and writes it as length `-1` with no data.

Environments are treated in several ways: as we have seen, some are written as specific pseudo-`SEXPTYPE`s. Package and name space environments are written with pseudo-`SEXPTYPE`s followed by the name. 'Normal' environments are written out as `ENVSXP`s with an integer indicating if the environment is locked followed by the enclosure, frame, 'tag' (the hash table) and attributes.

In the 'XDR' format integers and doubles are written in bigendian order: however the format is not fully XDR as defined in RFC 1832 as byte quantities (such as the contents of `CHARSXP` and `RAWSXP` types) are written as-is and not padded to a multiple of four bytes.

The 'ASCII' format writes 7-bit characters. Integers are formatted with `%d` (except that `NA_integer_` is written as `NA`), doubles formatted with `%.16g` (plus `NA`, `Inf` and `-Inf`) and bytes with `%02x`. Strings are written using standard escapes (e.g. `\t` and `\013` for non-printing and non-ASCII bytes.

## 1.9 Encodings for CHARSXPs

Character data in R are stored in the sexptype `CHARSXP`. Until R 2.1.0 it was assumed that the data were in the platform's native 8-bit encoding, and furthermore it was quite often assumed that the encoding was ISO Latin-1 or a superset (such as Windows' CP1252 or Latin-9).

As from R 2.1.0 there was support for other encodings, in particular UTF-8 and the multi-byte encodings used on Windows for CJK languages. However, there was no way of indicating which encoding had been used, even if this was known (and e.g. `scan` would not know the encoding of the file it was reading). This lead to packages with data in French encoded in Latin-1 in `.rda` files which could not be read in other locales (and they would be able to be displayed in a French UTF-8 locale, if not in non-UTF-8 Japanese locales).

R 2.5.0 introduced a limited means to indicate the encoding of a `CHARSXP` via two of the 'general purpose' bits which are used to declare the encoding to be either Latin-1 or UTF-8. (Note that it is possible for a character vector to contain elements in different encodings.) Both printing and plotting notice the declaration and convert the string to the current locale (possibly using `<xx>` to display in hexadecimal bytes that are not valid in the current locale). Many (but not all) of the character manipulation functions will either preserve the declaration or re-encode the character string.

Strings that refer to the OS such as file names need to be passed through a wide-character interface on some OSes (e.g. Windows), which is to a large extent done as from R 2.7.0.

When are character strings declared to be of known encoding? One way is to do so directly via `Encoding`. The parser declares the encoding if this is known, either via the `encoding` argument to `parse` or from the locale within which parsing is being done at the R command line. (Other ways are recorded on the help page for `Encoding`.)

It is not necessary to declare the encoding of ASCII strings as they will work in any locale. As from R 2.8.0, ASCII strings should never have a marked encoding, as any encoding will be ignored when entering such strings into the `CHARSXP` cache.

The rationale behind considering only UTF-8 and Latin-1 is that most systems are capable of producing UTF-8 strings and this is the nearest we have to a universal format. For those that do not (for example those lacking a powerful enough `iconv`), it is likely that they work in Latin-1, the old R assumption.

This was taken further in R 2.7.0. There the parser can return a UTF-8-encoded string if it encounters a '`\uxxx`' escape for a Unicode point that cannot be represented in the current charset. (This needs MBCS support, and is currently only enabled[12] on Windows.) Many of the character manipulation functions now preserve UTF-8 encodings.

Graphics devices are offered the possibility of handing UTF-8-encoded strings without re-encoding to the native character set, by setting `hasTextUTF8` to be '`TRUE`'[13] and supplying functions `textUTF8` and `strWidthUTF8` that expect UTF-8-encoded inputs. Normally the symbol font is encoded in Adobe Symbol encoding, but that can be re-encoded to UTF-8 by setting `wantSymbolUTF8` to '`TRUE`'.

Windows has no UTF-8 locales, but rather expects to work with UCS-2[14] strings. R (being written in standard C) would not work internally with UCS-2 without extensive changes. As from R 2.7.0 the '`Rgui`' console[15] uses UCS-2 internally, but communicates with the R engine in the native encoding. To allow UTF-8 strings to be printed in UTF-8 in '`Rgui.exe`', an escape convention is used (see header '`rgui_UTF8.h`') which is used by `cat`, `print` and autoprinting.

'Unicode' (UCS-2LE) files are common in the Windows world, and `readLines` and `scan` will read them into UTF-8 strings on Windows if the encoding is declared explicitly on an unopened connection passed to those functions.

## 1.10 The CHARSXP cache

A global cache for `CHARSXP`s created by `mkChar` was introduced in R 2.6.0 – the cache ensures that most `CHARSXP`s with the same contents share storage ('contents' including any declared encoding). Not all `CHARSXP`s are part of the cache – notably '`NA_STRING`' is not.

In R 2.6.x and 2.7.x character strings created by `mkCharLen` were not part of the cache: these were intended to be those containing embedded nuls. As from R 2.8.0 the cache can handle any content, although embedded nuls are now disallowed.

There are a few other ways in which `CHARSXP`s could or can escape the cache. `CHARSXP`s reloaded from the `save` formats of R prior to 0.99.0 are not cached (since the code used is frozen and few examples still exist). Prior to R 2.8.0, `CHARSXP`s were used to hold the finalizer function of a C finalizer (uncached) – now `RAWSXP`s are used. Finally, user code could create uncached `CHARSXP`s via `allocString` (removed in R2.8.0) and `allocVector(CHARSXP ...)` (deprecated in R2.8.0, removed in R 2.9.0).

The cache records the encoding of the string as well as the bytes: all requests to create a `CHARSXP` should be *via* a call to `mkCharLenCE`. As from R 2.8.0 any encoding given in `mkCharLenCE` call will be ignored if the string's bytes are all ASCII characters.

## 1.11 Warnings and errors

Each of `warning` and `stop` have two C-level equivalents, `warning`, `warningcall`, `error` and `errorcall`. The relationship between the pairs is similar: `warning` tries to fathom out a suitable call, and then calls `warningcall` with that call as the first argument if it succeeds, and with `call = R_NilValue` it is does not. When `warningcall` is called, it includes the deparsed call in its printout unless `call = R_NilValue`.

`warning` and `error` look at the context stack. If the topmost context is not of type `CTXT_BUILTIN`, it is used to provide the call, otherwise the next context provides the call. This means

[12] See define `USE_UTF8_IF_POSSIBLE` in '`gram.c`'.

[13] To maximize back-compatibility with devices installed prior to R 2.7.0 it has to be exactly that value: all others are equivalent to '`FALSE`'.

[14] or UTF-16 if support for surrogates is enabled in the OS, which it is not normally at least for Western versions of Windows, despite some claims to the contrary on the Microsoft site.

[15] but not the GraphApp toolkit.

that when these function are called from a primitive or `.Internal`, the imputed call will not be to primitive/`.Internal` but to the function calling the primitive/`.Internal` . This is exactly what one wants for a `.Internal`, as this will give the call to the closure wrapper. (Further, for a `.Internal`, the call is the argument to `.Internal`, and so may not correspond to any R function.) However, it is unlikely to be what is needed for a primitive.

The upshot is that that `warningcall` and `errorcall` should normally be used for code called from a primitive, and `warning` and `error` should be used for code called from a `.Internal` (and necessarily from `.Call`, `.C` and so on, where the call is not passed down). However, there are two complications. One is that code might be called from either a primitive or a `.Internal`, in which case probably `warningcall` is more appropriate. The other involves replacement functions, where the call will be of the form (from R < 2.6.0)

```
> length(x) <- y ~ x
Error in "length<-"(`*tmp*`, value = y ~ x) : invalid value
```

which is unpalatable to the end user. For replacement functions there will be a suitable context at the top of the stack, so `warning` should be used. (The results for `.Internal` replacement functions such as `substr<-` are not ideal.)

## 1.12 S4 objects

[This section is currently a preliminary draft and should not be taken as definitive. The description assumes that `R_NO_METHODS_TABLES` has not been set.]

### 1.12.1 Representation of S4 objects

[The internal representation of objects from S4 classes changed in R 2.4.0. It is possible that objects from earlier representations still exist, but there is no guarantee that they will be handled correctly. An attempt is made to detect old-style S4 objects and warn when binary objects are `load`ed or a workspace is restored.]

S4 objects can be of any `SEXPTYPE`. They are either an object of a simple type (such as an atomic vector or function) with S4 class information or of type `S4SXP`. In all cases, the 'S4 bit' (bit 4 of the 'general purpose' field) is set, and can be tested by the macro/function `IS_S4_OBJECT`.

S4 objects are created via `new()`[16] and thence via the C function `R_do_new_object`. This duplicates the prototype of the class, adds a class attribute and sets the S4 bit. All S4 class attributes should be character vectors of length one with an attribute giving (as a character string) the name of the package (or `.GlobalEnv`) containing the class definition. Since S4 objects have a class attribute, the `OBJECT` bit is set.

It is currently unclear what should happen if the class attribute is removed from an S4 object, or if this should be allowed.

### 1.12.2 S4 classes

S4 classes are stored as R objects in the environment in which they are created, with names `.__C__`*`classname`*: as such they are not listed by default by `ls`.

The objects are S4 objects of class `"classRepresentation"` which is defined in the **methods** package.

Since these are just objects, they are subject to the normal scoping rules and can be imported and exported from name spaces like other objects. The directives `importClassesFrom` and `exportClasses` are merely convenient ways to refer to class objects without needing to know their internal 'metaname' (although `exportClasses` does a little sanity checking via `isClass`).

[16] This can also create non-S4 objects, as in `new("integer")`.

### 1.12.3 S4 methods

Details of methods are stored in S4 objects of class `"MethodsList"`. They have a non-syntactic name of the form `.__M__`*generic*`:`*package* for all methods defined in the current environment for the named generic derived from a specific package (which might be `.GlobalEnv`).

There is also environment `.__T__`*generic*`:`*package* which has names the signatures of the methods defined, and values the corresponding method functions. This is often referred to as a 'methods table'.

When a package without a name space is attached these objects become visible on the search path. `library` calls `methods:::cacheMetaData` to update the internal tables.

During an R session there is an environment associated with each non-primitive generic containing objects `.AllMTable`, `.Generic`, `.Methods`, `.MTable`, `.SigArgs` and `.SigLength`. `.MTable` and `AllMTable` are merged methods tables containing all the methods defined directly and via inheritance respectively. `.Methods` is a merged methods list.

Exporting methods from a name space is more complicated than exporting a class. Note first that you do not export a method, but rather the directive `exportMethods` will export all the methods defined in the name space for a specified generic: the code also adds to the list of generics any that are exported directly. For generics which are listed via `exportMethods` or exported themselves, the corresponding `"MethodsList"` and environment are exported and so will appear (as hidden objects) in the package environment.

Methods for primitives which are internally S4 generic (see below) are always exported, whether mentioned in the 'NAMESPACE' file or not.

Methods can be imported either via the directive `importMethodsFrom` or via importing a namespace by `import`. Also, if a generic is imported via `importFrom`, its methods are also imported. In all cases the generic will be imported if it is in the namespace, so `importMethodsFrom` is most appropriate for methods defined on generics in other packages. Since methods for a generic could be imported from several different packages, the methods tables are merged.

When a package with a name space is attached `methods:::cacheMetaData` is called to update the internal tables: only the visible methods will be cached.

### 1.12.4 Mechanics of S4 dispatch

This subsection does not discuss how S4 methods are chosen: see http://developer.r-project.org/howMethodsWork.pdf.

For all but primitive functions, setting a method on an existing function that is not itself S4 generic creates a new object in the current environment which is a call to `standardGeneric` with the old definition as the default method. Such S4 generics can also be created *via* a call to `setGeneric`[17] and are standard closures in the R language, with environment the environment within which they are created. With the advent of name spaces this is somewhat problematic: if `myfn` was previously in a package with a name space there will be two functions called `myfn` on the search paths, and which will be called depends on which search path is in use. This is starkest for functions in the base name space, where the original will be found ahead of the newly created function from any other package with a name space.

Primitive functions are treated quite differently, for efficiency reasons: this results in different semantics. `setGeneric` is disallowed for primitive functions. The **methods** namespace contains a list `.BasicFunsList` named by primitive functions: the entries are either `FALSE` or a standard S4 generic showing the effective definition. When `setMethod` (or `setReplaceMethod`) is called, it either fails (if the list entry is `FALSE`) or a method is set on the effective generic given in the list.

[17] although this is not recommended as it is less future-proof.

Actual dispatch of S4 methods for almost all primitives piggy-backs on the S3 dispatch mechanism, so S4 methods can only be dispatched for primitives which are internally S3 generic. When a primitive that is internally S3 generic is called with a first argument which is an S4 object and S4 dispatch is on (that is, the **methods** name space is loaded), `DispatchOrEval` calls `R_possible_dispatch` (defined in '`src/main/objects.c`'). (Members of the S3 group generics, which includes all the generic operators, are treated slightly differently: the first two arguments are checked and `DispatchGroup` is called.) `R_possible_dispatch` first checks an internal table to see if any S4 methods are set for that generic (and S4 dispatch is currently enabled for that generic), and if so proceeds to S4 dispatch using methods stored in another internal table. All primitives are in the base name space, and this mechanism means that S4 methods can be set for (some) primitives and will always be used, in contrast to setting methods on non-primitives.

The exception is `%*%`, which is S4 generic but not S3 generic as its C code contains a direct call to `R_possible_dispatch`.

The primitive `as.double` is special, as `as.numeric` and `as.real` are copies of it. The **methods** package code partly refers to generics by name and partly by function, and was modified in R 2.6.0 to map `as.double` and `as.real` to `as.numeric` (since that is the name used by packages exporting methods for it).

Some elements of the language are implemented as primitives, for example `}`. This includes the subset and subassignment 'functions' and they are S4 generic, again piggybacking on S3 dispatch.

`.BasicFunsList` is generated when **methods** is installed, by computing all primitives, initially disallowing methods on all and then setting generics for members of `.GenericArgsEnv`, the S4 group generics and a short exceptions list in '`BasicFunsList.R`': this currently contains the subsetting and subassignment operators and an override for `c`.

## 1.13 Memory allocators

R's memory allocation is almost all done via routines in '`src/main/memory.c`'. It is important to keep track of where memory is allocated, as the Windows port (by default) makes use of a memory allocator that differs from `malloc` etc as provided by MinGW. Specifically, there are entry points `Rm_malloc`, `Rm_free`, `Rm_calloc` and `Rm_free` provided by `src/gnuwin32/malloc.c`. This was done for two reasons. The primary motivation was performance: the allocator provided by MSVCRT *via* MinGW was far too slow at handling the many small allocations that the current (since R 1.2.0) allocation system for `SEXPREC`s uses. As a side benefit, we can set a limit on the amount of allocated memory: this is useful as whereas Windows does provide virtual memory it is relatively far slower than many other R platforms and so limiting R's use of swapping is highly advantageous. The high-performance allocator is only called from '`src/main/memory.c`', '`src/main/regex.c`', '`src/extra/pcre`' and '`src/extra/xdr`': note that this means that it is not used in packages.

The rest of R should where possible make use of the allocators made available by '`src/main/memory.c`', which are also the methods recommended in section "Memory allocation" in *Writing R Extensions* for use in R packages, namely the use of `R_alloc`, `Calloc`, `Realloc` and `Free`. Memory allocated by `R_alloc` is freed by the garbage collector once the 'watermark' has been reset by calling `vmaxset`. This is done automatically by the wrapper code calling primitives and `.Internal` functions (and also by the wrapper code to `.Call` and `.External`), but `vmaxget` and `vmaxset` can be used to reset the watermark from within internal code if the memory is only required for a short time.

All of the methods of memory allocation mentioned so far are relatively expensive. All R platforms support `alloca`, and in almost all cases[18] this is managed by the compiler, allocates memory on the C stack and is very efficient.

[18] but apparently not on Windows.

There are two disadvantages in using `alloca`. First, it is fragile and care is needed to avoid writing (or even reading) outside the bounds of the allocation block returned. Second, it increases the danger of overflowing the C stack. It is suggested that it is only used for smallish allocations (up to tens of thousands of bytes), and that

```
R_CheckStack();
```

is called immediately after the allocation (as R's stack checking mechanism will warn far enough from the stack limit to allow for modest use of alloca). (`do_makeunique` in '`src/main/unique.c`' provides an example of both points.)

An alternative strategy has been used for various functions which require intermediate blocks of storage of varying but usually small size, and this has been consolidated into the routines in the header file '`src/main/RBufferUtils.h`'. This uses a structure which contains a buffer, the current size and the default size. A call to

```
R_AllocStringBuffer(size_t blen, R_StringBuffer *buf);
```

sets `buf->data` to a memory area of at least `blen+1` bytes. At least the default size is used, which means that for small allocations the same buffer can be reused. A call to `R_FreeStringBufferL` releases memory if more than the default has been allocated whereas a call to `R_FreeStringBuffer` frees any memory allocated.

The `R_StringBuffer` structure needs to be initialized, for example by

```
static R_StringBuffer ex_buff = {NULL, 0, MAXELTSIZE};
```

which uses a default size of `MAXELTSIZE` = `8192` bytes. Most current uses have a static `R_StringBuffer` structure, which allows the (default-sized) buffer to be shared between calls to e.g. `grep` and even between functions: this will need to be changed if R ever allows concurrent evaluation threads. So the idiom is

```
static R_StringBuffer ex_buff = {NULL, 0, MAXELTSIZE};
...
    char *buf;
    for(i = 0; i < n; i++) {
        compute len
        buf = R_AllocStringBuffer(len, &ex_buff);
        use buf
    }
    /*  free allocation if larger than the default, but leave
        default allocated for future use */
   R_FreeStringBufferL(&ex_buff);
```

### 1.13.1 Internals of R_alloc

The memory used by `R_alloc` is allocated as R vectors, of type `RAWSXP` for 'small' allocations (less than 2^31 - 1 bytes) and of type `REALSXP` for allocations up to 2^34 - 1 bytes on 64-bit machines. Thus the allocation is in units of 8 bytes, and is rounded up. (Prior to R 2.6.0 `CHARSXP`s were used, and so one byte was added prior to rounding up. This had the effect of over-allocating areas for `double`s by one and thereby masked several subtle programming errors.)

The vectors allocated are protected via the setting of `R_VStack`, as the garbage collector marks everything that can be reached from that location. When a vector is `R_alloc`ated, its `ATTRIB` pointer is set to the current `R_VStack`, and `R_VStack` is set to the latest allocation. Thus `R_VStack` is a single-linked chain of vectors currently allocated via `R_alloc`. Function `vmaxset` resets the location `R_VStack`, and should be to a value that has previously be obtained *via* `vmaxget`: allocations after the value was obtained will no longer be protected and hence available for garbage collection.

## 1.14 Internal use of global and base environments

This section notes known use by the system of these environments: the intention is to minimize or eliminate them.

### 1.14.1 Base environment

The graphics devices system maintains two variables `.Device` and `.Devices` in the base environment: both are always set. The variable `.Devices` gives a list of character vectors of the names of open devices, and `.Device` is the element corresponding to the currently active device. The null device will always be open.

There appears to be a variable `.Options`, a pairlist giving the current options settings. But in fact this is just a symbol with a value assigned, and so shows up as a base variable.

Similarly, the evaluator creates a symbol `.Last.value` which appears as a variable in the base environment.

Errors can give rise to objects `.Traceback` and `last.warning` in the base environment.

### 1.14.2 Global environment

The seed for the random number generator is stored in object `.Random.seed` in the global environment.

Some error handlers may give rise to objects in the global environment: for example `dump.frames` by default produces `last.dump`.

The `windows()` device makes use of a variable `.SavedPlots` to store display lists of saved plots for later display. This is regarded as a variable created by the user.

## 1.15 Modules

R makes use of a number of shared objects/DLLs stored in the '`modules`' directory. These are parts of the code which have been chosen to be loaded 'on demand' rather than linked as dynamic libraries or incorporated into the main executable/dynamic library.

For a few of these (e.g. `vfonts`) the issue is size: the database for the Hershey fonts is included in the C code of the module and was at one time an appreciable part of the codebase for a rarely used feature. However, for most of the modules the motivation has been the amount of (often optional) code they will bring in via libraries to which they are linked.

`internet` The internal HTTP and FTP clients and socket support, which link to system-specific support libraries.

`lapack` The code which makes use of the LAPACK library, and is linked to '`libRlapack`' or an external LAPACK library.

`vfonts` The Hershey font databases and the code to draw from them.

`X11` (Unix-alikes only.) The `X11()`, `jpeg()` and `png()` devices. These are optional, and link to the `X11`, `jpeg` and `libpng` libraries.

'`Rbitmap.dll`'
(Windows only.) The code for the BMP, JPEG and PNG devices and for saving on-screen graphs to those formats. This is technically optional, and needs source code not in the tarball.

'`Rchtml.dll`'
(Windows only.) A link to an ActiveX control that displays Compiled HTML help. This is optional, and only compiled if CHTML is specified.

‘`iconv.dll`’
: (Windows only.) A DLL compiled via Visual C++ which contains the routines to convert between character sets.

‘`internet2.dll`’
: (Windows only.) An alternative version of the internet access routines, compiled against Internet Explorer internals (and so loads ‘`wininet.dll`’ and ‘`wsock32.dll`’).

# 2 .Internal vs .Primitive

C code compiled into R at build time can be called "directly" or via the `.Internal` interface, which is very similar to the `.External` interface except in syntax. More precisely, R maintains a table of R function names and corresponding C functions to call, which by convention all start with '`do_`' and return a SEXP. Via this table (`R_FunTab` in file '`src/main/names.c`') one can also specify how many arguments to a function are required or allowed, whether the arguments are to be evaluated before calling or not, and whether the function is "internal" in the sense that it must be accessed via the `.Internal` interface, or directly accessible in which case it is printed in R as `.Primitive`.

R's functionality can also be extended by providing corresponding C code and adding to this function table.

In general, all such functions use `.Internal()` as this is safer and in particular allows for transparent handling of named and default arguments. For example, `axis` is defined as

```
axis <- function(side, at = NULL, labels = NULL, ...)
    .Internal(axis(side, at, labels, ...))
```

However, for reasons of convenience and also efficiency (as there is some overhead in using the `.Internal` interface wrapped in a function closure), there are exceptions which can be accessed directly. Note that these functions make no use of R code, and hence are very different from the usual interpreted functions. In particular, `args`, `formals` and `body` return `NULL` for such objects, and argument matching is purely positional (with two exceptions described below).

The list of these "primitive" functions is subject to change: currently, it includes the following.

1. "Special functions" which really are *language* elements, however exist as "primitive" functions in R:

   ```
   {       (         if     for      while  repeat  break  next
   return  function  quote  on.exit
   ```

2. Language elements and basic *operator*s (i.e., functions usually *not* called as `foo(a, b, ...)`) for subsetting, assignment, arithmetic and logic. These are the following 1-, 2-, and $N$-argument functions:

   ```
                    [    [[    $    @
   <-   <<-  =      [<-  [[<-  $<-

   +    -    *     /     ^     %%   %*%  %/%
   <    <=   ==    !=    >=    >
   |    ||   &     &&    !
   ```

3. "Low level" 0- and 1-argument functions which belong to one of the following groups of functions:

   a. Basic mathematical functions with a single argument, i.e.,

      ```
      abs     sign    sqrt
      floor   ceiling

      exp     expm1
      log2    log10   log1p
      cos     sin     tan
      acos    asin    atan
      cosh    sinh    tanh
      acosh   asinh   atanh

      gamma   lgamma  digamma trigamma
      ```

```
cumsum  cumprod cummax  cummin

Im  Re  Arg  Conj  Mod
```

`log` is a function of one or two arguments, but was made primitive as from R 2.6.0 and so has named rather than positional matching for back compatibility.

`trunc` is a difficult case: it is a primitive that can have zero or more arguments: the default method handled in the primitive has only one.

b. Functions rarely used outside of "programming" (i.e., mostly used inside other functions), such as

```
nargs        missing
interactive  is.xxx
as.call      as.character as.complex  as.double
as.environment
as.integer   as.logical   as.raw
.Primitive   .Internal
globalenv    baseenv      emptyenv     pos.to.env
unclass      invisible
seq_along    seq_len
```

(where *xxx* stands for 27 different notions, such as `function`, `vector`, `numeric`, and so forth, but not `is.loaded`).

c. The programming and session management utilities

```
debug  undebug browser  proc.time  gc.time
tracemem retracemem untracemem
```

4. The following basic replacement and extractor functions

```
length      length<-
class       class<-
oldClass    oldCLass<-
attr        attr<-
attributes  attributes<-
names       names<-
dim         dim<-
dimnames    dimnames<-
            environment<-
            levels<-
            storage.mode<-
```

Note that optimizing `NAMED = 1` is only effective within a primitive (as the closure wrapper of a `.Internal` will set `NAMED = 2` when the promise to the argument is evaluated) and hence replacement functions should where possible be primitive to avoid copying (at least in their default methods).

5. The following few $N$-argument functions are "primitive" for efficiency reasons:

```
:           ~           c           list
call        expression substitute
UseMethod   standardGeneric
.C          .Fortran    .Call       .External
.Call.graphics          .External.graphics
.subset     .subset2    .primTrace  .primUntrace
round       signif       rep        seq.int
lazyLoadDBfetch
```

round, signif, rep and seq.int manage their own argument matching and so do work in the standard way.

## 2.1 Special primitives

A small number of primitives are *specials* rather than *builtins*, that is they are entered with unevaluated arguments. This is clearly necessary for the language constructs and the assignment operators. && and || conditionally evaluate their second argument, and ~, .Internal, call, expression and missing do not evaluate their arguments.

rep and seq.int are special as they evaluate some of their arguments conditional on which are non-missing. c is special to allow it to be used with language objects.

The subsetting, subassignment and @ operators are all special. (For both extraction and replacement forms, $ and @ take a symbol argument, and [ and [[ allow missing arguments.)

UseMethod is special to avoid the additional contexts added to calls to builtins when profiling (via Rprof).

## 2.2 Special internals

There are also special .Internal functions: switch, Recall, cbind, rbind (to allow for the deparse.level argument), lapply, eapply and NextMethod.

## 2.3 Prototypes for primitives

As from R 2.5.0, prototypes are available for the primitive functions and operators, and there are used for printing, args and package checking (e.g. by tools::checkS3methods and by package **codetools**). There are two environments in the **base** package (and name space), '.GenericArgsEnv' for those primitives which are internal S3 generics, and '.ArgsEnv' for the rest. Those environments contain closures with the same names as the primitives, formal arguments derived (manually) from the help pages, a body which is a suitable call to UseMethod or NULL and environment the base name space.

The C code for print.default and args uses the closures in these environments in preference to the definitions in base (as primitives).

The QC function undoc checks that all the functions prototyped in these environments are currently primitive, and that the primitives not included are better thought of as language elements (at the time of writing

```
$  $<-  &&  (  :  @  [  [[  [[<-  [<-  {  ||  ~  <-  <<-  =
break  for function  if  next  repeat  return  while
```

. One could argue about ~, but it is known to the parser and has semantics quite unlike a normal function. And : is documented with different argument names in its two meanings.)

The QC functions codoc and checkS3methods also make use of these environments (effectively placing them in front of base in the search path), and hence the formals of the functions they contain are checked against the help pages by codoc. However, there are two problems with the generic primitives. The first is that many of the operators are part of the S3 group generic Ops and that defines their arguments to be e1 and e2: although it would be very unusual, an operator could be called as e.g. "+"(e1=a, e2=b) and if method dispatch occurred to a closure, there would be an argument name mismatch. So the definitions in environment .GenericArgsEnv have to use argument names e1 and e2 even though the traditional documentation is in terms of x and y: codoc makes the appropriate adjustment via tools:::.make_S3_primitive_generic_env. The second discrepancy is with the Math group generics, where the group generic is defined with argument list (x, ...), but most of the members only allow one argument when used as the default method (and round and signif allow two as default methods): again fix-ups are used.

Those primitives which are in `.GenericArgsEnv` are checked (via '`tests/primitives.R`' to be generic *via* defining methods for them, and a check is made that the remaining primitives are probably not generic, by setting a method and checking it is not dispatched to (but this can fail for other reasons). However, there is no certain way to know that if other `.Internal` or primitive functions are not internally generic except by reading the source code.

# 3 Internationalization in the R sources

The process of marking messages (errors, warnings etc) for translation in an R package is described in section "Localization" in *Writing R Extensions*, and the standard packages included with R have (with an exception in **grDevices** for the menus of the `windows()` device) been internationalized in the same way as other packages.

## 3.1 R code

Internationalization for R code is done in exactly the same way as for extension packages. As all standard packages which have R code also have a namespace, it is never necessary to specify `domain`, but for efficiency calls to `message`, `warning` and `stop` should include `domain = NA` when the message is constructed *via* `gettextf`, `gettext` or `ngettext`.

For each package, the extracted messages and translation sources are stored under package directory '`po`' in the source package, and compiled translations under '`inst/po`' for installation to package directory '`po`' in the installed package. This also applies to C code in packages.

## 3.2 Main C code

The main C code (e.g. that in '`src/*/*.c`' and in the modules) is where R is closest to the sort of application for which '`gettext`' was written. Messages in the main C code are in domain `R` and stored in the top-level directory '`po`' with compiled translations under '`share/locale`'.

The list of files covered by the R domain is specified in file '`po/POTFILES.in`'.

The normal way to mark messages for translation is via `_("msg")` just as for packages. However, sometimes one needs to mark passages for translation without wanting them translated at the time, for example when declaring string constants. This is the purpose of the `N_` macro, for example

```
{ ERROR_ARGTYPE,            N_("invalid argument type")},
```

from '`src/main/errors.c`'.

A macro

```
#ifdef ENABLE_NLS
#define P_(StringS, StringP, N) ngettext (StringS, StringP, N)
#else
#define P_(String, StringP, N) (N > 1 ? StringP: String)
#endif
```

as a wrapper for `ngettext`: however in some cases the preferred approach has been to conditionalize (on `ENABLE_NLS`) code using `ngettext`.

The macro `_("msg")` can safely be used in '`src/appl`'; the header for standalone '`nmath`' skips possible translation. (This does not apply to `N_` or `P_`).

## 3.3 Windows-GUI-specific code

Messages for the Windows GUI are in a separate domain '`RGui`'. This was done for two reasons:

- The translators for the Windows version of R might be separate from those for the rest of R (familiarity with the GUI helps), and
- Messages for Windows are most naturally handled in the native charset for the language, and in the case of CJK languages the charset is Windows-specific. (It transpires that as the `iconv` we ported works well under Windows, this is less important than anticipated.)

Messages for the '`RGui`' domain are marked by `G_("msg")`, a macro that is defined in '`src/gnuwin32/win-nls.h`'. The list of files that are considered is hardcoded in the `RGui.pot-update` target of '`po/Makefile.in.in`': note that this includes '`devWindows.c`' as the menus

on the `windows` device are considered to be part of the GUI. (There is also `GN_("msg")`, the analogue of `N_("msg")`.)

The template and message catalogs for the 'RGui' domain are in the top-level 'po' directory.

## 3.4 MacOS X GUI

This is handled separately: see http://developer.r-project.org/Translations.html.

## 3.5 Updating

See 'po/README' for how to update the message templates and catalogs.

# 4 Graphics

R's graphics internals were revised for version 1.4.0 (and tidied up for 2.7.0). This was to enable multiple graphics systems to be installed on top on the graphics 'engine' – currently there are two such systems, one supporting 'base' graphics (based on that in S and whose R code[1] is in package **graphics**) and one implemented in package **grid**.

Some notes on the changes for 1.4.0 can be found at http://www.stat.auckland.ac.nz/~paul/R/basegraph.html and http://www.stat.auckland.ac.nz/~paul/R/graphicsChanges.html.

At the lowest level is a graphics device, which manages a plotting surface (a screen window or a representation to be written to a file). This implements a set of graphics primitives, to 'draw'

- a circle, optionally filled
- a rectangle, optionally filled
- a line
- a set of connected lines
- a polygon, optionally filled
- text
- and to set a clipping rectangle

as well as requests for information such as

- the width of a string if plotted
- the metrics (width, ascent, descent) of a single character
- the current size of the plotting surface

and requests/opportunities to take action such as

- start a new 'page', possibly after responding to a request to ask the user for confirmation.
- return the position of the device pointer (if any).
- when a device become the current device or stops being the current device (this is usually used to change the window title on a screen device).
- when drawing starts or finishes (e.g. used to flush graphics to the screen when drawing stops).
- wait for an event, for example a mouse click or keypress.
- an 'onexit' action, to clean up if plotting is interrupted (by an error or by the user).
- close the device.

The device also sets a number of variables, mainly Boolean flags indicating its capabilities. Devices work entirely in 'device units' which are up to its developer: they can be in pixels, big points (1/72 inch), twips, ..., and can differ[2] in the '`x`' and '`y`' directions.

The next layer up is the graphics 'engine' that is the main interface to the device (although the graphics subsystems do talk directly to devices). This is responsible for clipping, converting the `pch` values `0...26` to sets of lines/circles, centring (and otherwise adjusting) text, rendering mathematical expressions ('plotmath') and mapping colour descriptions such as names to the internal representation.

[1] The C code is in files '`base.c`', `graphics.c`, `par.c`, `plot.c` and `plot3d.c` in directory '`src/main`'.

[2] although that needs to be handled carefully, as for example the `xspline` functions used prior to R 2.7.0 to depend on the aspect ratio of the pixels, and the `circle` callback is given a radius (and that should be interpreted as in the x units).

Another function of the engine is to manage display lists and snapshots. Some but not all instances of graphics devices maintain display lists, a 'list' of operations that have been performed on the device to produce the current plot (since the device was opened or the plot was last cleared, e.g. by `plot.new`). Screen devices generally maintain a display list to handle repaint and resize events where as file-based formats do not—display lists are also used to implement `dev.copy()` and friends. The display list is a pairlist of `.Internal` (base graphics) or `.Call.graphics` (grid graphics) calls, which means that the C code implementing a graphics operation will be re-called when the display list is replayed: apart from the part which records the operation if successful.

Snapshots of the current graphics state are taken by `GEcreateSnapshot` and replayed later in the session by `GEplaySnapshot`. These are used by `recordPlot()`, `replayPlot()` and the GUI menus of the `windows()` device. The 'state' includes the display list.

The top layer comprises the graphics subsystems. Although there is provision for 24 subsystems, after 6 years only two exist, 'base' and 'grid'. The base subsystem is registered with the engine when R is initialized, and unregistered (via `KillAllDevices`) when an R session is shut down. The grid subsystem is registered in its `.onLoad` function and unregistered in the `.onUnload` function. The graphics subsystem may also have 'state' information saved in a snapshot (currently base does and grid does not).

Package **grDevices** was originally created to contain the basic graphics devices (although `X11` is in a separate load-on-demand module because of the volume of external libraries it brings in). Since then it has been used for other functionality that was thought desirable for use with **grid**, and hence has been transferred from package **graphics** to **grDevices**. This is principally concerned with the handling of colours and recording and replaying plots.

## 4.1 Graphics Devices

R ships with several graphics devices, and there is support for third-party packages to provide additional devices—several packages now do. This section describes the device internals from the viewpoint of a would-be writer of a graphics device.

### 4.1.1 Device structures

There are two types used internally which are pointers to structures related to graphics devices.

The `DevDesc` type[3] is a structure defined in the header file '`R_ext/GraphicsDevice.h`' (which is included by '`R_ext/GraphicsEngine.h`'). This describes the physical characteristics of a device, the capabilities of the device driver and contains a set of callback functions that will be used by the graphics engine to obtain information about the device and initiate actions (e.g. a new page, plotting a line or some text). Type `pDevDesc` is a pointer to this type.

The relationship of device units to physical dimensions is set by the element `ipr` of the `DevDesc` structure: a '`double`' array of length 2.

The `GEDevDesc` type is a structure defined in '`R_ext/GraphicsEngine.h`' (with comments in the file) as

```
typedef struct _GEDevDesc GEDevDesc;
struct _GEDevDesc {
    DevDesc dev;
    Rboolean displayListOn;
    SEXP displayList;
    SEXP DLlastElt;
    SEXP savedSnapshot;
    Rboolean dirty;
```

[3] `NewDevDesc` from R1.4.0, renamed in R2.8.0.

```
    Rboolean recordGraphics;
    GESystemDesc *gesd[MAX_GRAPHICS_SYSTEMS];
    Rboolean ask;
}
```

So this is essentially a device structure plus information about the device maintained by the graphics engine and normally[4] visible to the engine and not to the device. Type `pGEDevDesc` is a pointer to this type.

The graphics engine maintains an array of devices, as pointers to `GEDevDesc` structures. The array is of size 64 but the first element is always occupied by the `"null device"` and the final element is kept as NULL as a sentinel.[5] This array is reflected in the R variable '`.Devices`'. Once a device is killed its element becomes available for reallocation (and its name will appear as `""` in '`.Devices`'). Exactly one of the devices is 'active': this is the the null device if no other device has been opened and not killed.

Each instance of a graphics device needs to set up a `GEDevDesc` structure by code very similar to

```
pGEDevDesc gdd;

R_GE_checkVersionOrDie(R_GE_version);
R_CheckDeviceAvailable();
BEGIN_SUSPEND_INTERRUPTS {
    pDevDesc dev;
    /* Allocate and initialize the device driver data */
    if (!(dev = (pDevDesc) calloc(1, sizeof(DevDesc))))
        return 0; /* or error() */
    /* set up device driver or free 'dev' and error() */
    gdd = GEcreateDevDesc(dev);
    GEaddDevice2(gdd, "dev_name");
} END_SUSPEND_INTERRUPTS;
```

The `DevDesc` structure contains a `void *` pointer '`deviceSpecific`' which is used to store data specific to the device. Setting up the device driver includes initializing all the non-zero elements of the `DevDesc` structure.

Note that the device structure is zeroed when allocated: this provides some protection against future expansion of the structure since the graphics engine can add elements that need to be non-NULL/non-zero to be 'on' (and the structure ends with 64 reserved bytes which will be zeroed and allow for future expansion).

Rather more protection is provided by the version number of the engine/device API, `R_GE_version` defined in '`R_ext/GraphicsEngine.h`' together with access functions

```
int R_GE_getVersion(void);
void R_GE_checkVersionOrDie(int version);
```

If a graphics device calls `R_GE_checkVersionOrDie(R_GE_version)` it can ensure it will only be used in versions of R which provide the API it was designed for and compiled against.

### 4.1.2 Device capabilities

The following 'capabilities' can be defined for the device's `DevDesc` structure.

- canChangeGamma – `Rboolean`: can the display gamma be adjusted? This is not true for any current device, and as from R 2.8.0 there is no user-level function to change gamma. So '`FALSE`' is the only useful value.

[4] It is possible for the device to find the `GEDevDesc` which points to its `DevDesc`, and this is done often enough that there is a convenience function `desc2GEDesc` to do so.

[5] Calling `R_CheckDeviceAvailable()` ensures there is a free slot or throws an error.

- canHadj – `integer`: can the device do horizontal adjustment of text *via* the `text` callback, and if so, how precisely? 0 = no adjustment, 1 = `{`0, 0.5, 1`}` (left, centre, right justification) or 2 = continuously variable (in [0,1]) between left and right justification.
- canGenMouseDown – `Rboolean`: should mouse down events be sent to the `getEvent` callback?
- canGenMouseMove – `Rboolean`: ditto for mouse move events.
- canGenMouseUp – `Rboolean`: ditto for mouse up events.
- canGenKeybd – `Rboolean`: ditto for keyboard events.
- hasTextUTF8 – `Rboolean`: should non-symbol text be sent (in UTF-8) to the `textUTF8` and `strWidthUTF8` callbacks, and sent as Unicode points (negative values) to the `metricInfo` callback?
- wantSymbolUTF8 – `Rboolean`: should symbol text be handled in UTF-8 in the same way as other text? Requires `textUTF8 = TRUE`.

### 4.1.3 Handling text

Handling text is probably the hardest task for a graphics device, and the design allows for the device to optionally indicate that it has additional capabilities. (If the device does not, these will if possible be handled in the graphics engine.)

The three callbacks for handling text that must be in all graphics devices are `text`, `strWidth` and `metricInfo` with declarations

```
void text(double x, double y, const char *str, double rot, double hadj,
          pGgcontext gc, pDevDesc dd);

double strWidth(const char *str, pGEcontext gc, pDevDesc dd);

void metricInfo(int c, pGEcontext gc,
                double* ascent, double* descent, double* width,
                pDevDesc dd);
```

The '`gc`' parameter provides the graphics context, most importantly the current font and fontsize, and '`dd`' is a pointer to the active device's structure.

The `text` callback should plot '`str`' at '`(x, y)`'[6] with an anti-clockwise rotation of '`rot`' degrees. (For '`hadj`' see below.) The interpretation for horizontal text is that the baseline is at `y` and the start is a `x`, so any left bearing for the first character will start at `x`.

The `strWidth` callback computes the width of the string which it would occupy if plotted horizontally in the current font. (Width here is expected to include both (preferably) or neither of left and right bearings.)

The `metricInfo` callback computes the size of a single character: `ascent` is the distance it extends above the baseline and `descent` how far it extends below the baseline. `width` is the amount by which the cursor should be advanced when the character is placed. For `ascent` and `descent` this is intended to be the bounding box of the 'ink' put down by the glyph and not the box which might be used when assembling a line of conventional text (it needs to be for e.g. `hat(beta)` to work correctly). However, the `width` is used in plotmath to advance to the next character, and so needs to include left and right bearings.

The *interpretation* of '`c`' depends on the locale. Using `c = 0` used to give an indication of the size of the font: it often returned the measurements for character `"M"`—however it is no longer used as from R 2.7.0. In a single-byte locale values `32...255` indicate the corresponding character in the locale (if present). For the symbol font (as used by '`graphics::par(font=5)`',

[6] in device coordinates

'grid::gpar(fontface=5') and by 'plotmath'), values 32...126, 161...239, 241...254 indicate glyphs in the Adobe Symbol encoding. In a multibyte locale, c represents a Unicode point (except in the symbol font). So the function needs to include code like

```
Rboolean Unicode = mbcslocale && (gc->fontface != 5);
if (c < 0) { Unicode = TRUE; c = -c; }
if(Unicode) UniCharMetric(c, ...); else CharMetric(c, ...);
```

In addition, if device capability hasTextUTF8 (see below) is true, Unicode points will be passed as negative values: the code snippet above shows how to handle this. (This applies to the symbol font only if device capability wantSymbolUTF8 is true.)

If possible, the graphics device should handle clipping of text. It indicates this by the structure element canClip which if true will result in calls to the callback clip to set the clipping region. If this is not done, the engine will clip very crudely (by omitting any text that does not appear to be wholly inside the clipping region).

The device structure has an integer element canHadj, which indicates if the device can do horizontal alignment of text. If this is one, argument 'hadj' to text will be called as 0 ,0.5, 1 to indicate left-, centre- and right-alignment at the indicated position. If it is two, continuous values in the range [0, 1] are assumed to be supported.

A new capability in R 2.7.0 (graphics API version 4) is hasTextUTF8. If this is true, it has two consequences. First, there are callbacks textUTF8 and strWidthUTF8 that should behave identically to text and strWidth except that 'str' is assumed to be in UTF-8 rather than the current locale's encoding. The graphics engine will call these for all text except in the symbol font. Second, Unicode points will be passed to the metricInfo callback as negative integers. If your device would prefer to have UTF-8-encoded symbols, define wantSymbolUTF8 as well as hasTextUTF8. In that case text in the symbol font is sent to textUTF8 and strWidthUTF8.

Some devices can produce high-quality rotated text, but those based on bitmaps often cannot. Those which can should set useRotatedTextInContour to be true from graphics API version 4.

Several other elements relate to the precise placement of text by the graphics engine:

```
double xCharOffset;
double yCharOffset;
double yLineBias;
double cra[2];
```

These are more than a little mysterious. Element cra provides an indication of the character size, par("cra") in base graphics, in device units. The mystery is what is meant by 'character size': which character, which font at which size? Some help can be obtained by looking at what this is used for. The first element, 'width', is not used by R except to set the graphical parameters. The second, 'height', is use to set the line spacing, that is the relationship between par("mai") and par("mai") and so on. It is suggested that a good choice is

```
dd->cra[0] = 0.9 * fnsize;
dd->cra[1] = 1.2 * fnsize;
```

where 'fnsize' is the 'size' of the standard font (cex=1) on the device, in device units. So for a 12-point font (the usual default for graphics devices), 'fnsize' should be 12 points in device units.

The remaining elements are yet more mysterious. The postscript() device says

```
/* Character Addressing Offsets */
/* These offsets should center a single */
/* plotting character over the plotting point. */
/* Pure guesswork and eyeballing ... */

dd->xCharOffset =  0.4900;
```

```
dd->yCharOffset =  0.3333;
dd->yLineBias = 0.2;
```

It seems that `xCharOffset` is not currently used, and `yCharOffset` is used by the base graphics system to set vertical alignment in `text()` when `pos` is specified, and in `identify()`. It is occasionally used by the graphic engine when attempting exact centring of text, such as character string values of `pch` in `points()` or `grid.points()`—however, it is only used when precise character metric information is not available or for multi-line strings.

`yLineBias` is used in the base graphics system in `axis()` and `mtext()` to provide a default for their '`padj`' argument.

### 4.1.4 Conventions

The aim is to make the (default) output from graphics devices as similar as possible, and further steps were taken in that direction in R 2.7.0. Generally people follow the model of the `postscript` and `pdf` devices (which share most of their internal code).

The following conventions have become established:

- The default size of a device should be 7 inches square.
- There should be a '`pointsize`' argument which defaults to 12, and it should give the pointsize in big points (1/72 inch). How exactly this is interpreted is font-specific, but it should use a font which works with lines packed 1/6 inch apart, and looks good with lines 1/5 inch apart (that is with 2pt leading).
- The default font family should be a sans serif font, e.g Helvetica or similar (e.g. Arial on Windows).
- `lwd = 1` should correspond to a line width of 1/96 inch. This will be a problem with pixel-based devices, and generally there is a minimum line width of 1 pixel (although this may not be appropriate where anti-aliasing of lines is used, and `cairo` prefers a minimum of 2 pixels).
- Even very small circles should be visible, e.g. by using a minimum radius of 1 pixel or replacing very small circles by a single filled pixel.
- How RGB colour values will be interpreted should be documented, and preferably be sRGB.
- The help page should describe its policy on these conventions.

These conventions are less clear-cut for bitmap devices, especially where the bitmap format does not have a design resolution.

The interpretation of the line texture (`par("lty")`) is described in the header '`GraphicsEngine.h`' and in the help for `par`: note that the 'scale' of the pattern should be proportional to the line width (at least for widths above the default).

### 4.1.5 'Mode'

One of the device callbacks is a function `mode`, documented in the header as

```
* device_Mode is called whenever the graphics engine
* starts drawing (mode=1) or stops drawing (mode=0)
* GMode (in graphics.c) also ways that
* mode = 2 (graphical input on) exists.
* The device is not required to do anything
```

Since `mode = 2` has only recently been documented at device level, it is not surprising that was it not used by any device: prior to R 2.7.0 it was not set by `grid::grid.locator`. It could be used to change the graphics cursor, but devices currently do that in the `locator` callback. (In base graphics the mode is set for the duration of a `locator` call, but if `type != "n"` is switched back for each point whilst annotation is being done.)

Many devices do indeed do nothing on this call, but some screen devices ensure that drawing is flushed to the screen when called with `mode = 0`. It is tempting to use it for some sort of buffering, but note that 'drawing' is interpreted at quite a low level and a typical single figure will stop and start drawing many times.

### 4.1.6 Specific devices

Specific devices are mostly documented by comments in their sources, although for devices of many years' standing those comments can be in need of updating. This subsection is a repository of notes on design decisions.

#### 4.1.6.1 X11()

The `X11(type="Xlib")` device dates back to the mid 1990's and was written then in `Xlib`, the most basic X11 toolkit. It has since optionally made use of a few features from other toolkits: `libXt` is used to read X11 resources, and `libXmu` is used in the handling of clipboard selections.

Using basic `Xlib` code makes drawing fast, but is limiting. There is no support of translucent colours (that came in the `Xrender` toolkit of 2000) nor for rotated text (which R implements by rendering text to a bitmap and rotating the latter).

The hinting for the X11 window asks for backing store to be used, and some windows managers may use it to handle repaints, but it seems that most repainting is done by replaying the display list (and here the fast drawing is very helpful).

There are perennial problems with finding fonts. Many users fail to realize that fonts are a function of the X server and not of the machine that R is running on. After many difficulties, R tries first to find the nearest size match in the sizes provided for Adobe fonts in the standard 75dpi and 100dpi X11 font packages—even that will fail to work when users of near-100dpi screens have only the 75dpi set installed. The 75dpi set allows sizes down to 6 points on a 100dpi screen, but some users do try to use smaller sizes and even 6 and 8 point bitmapped fonts do not look good.

Introduction of UTF-8 locales has caused another wave of difficulties. X11 has very few genuine UTF-8 fonts, and produces composite fontsets for the `iso10646-1` encoding. Unfortunately these seem to have low coverage apart from a few monospaced fonts in a few sizes (which are not suitable for graph annotation), and where glyphs are missing what is plotted is often quite unsatisfactory.

The approach being taken for R2.7.0 is to make use of more modern toolkits, namely `cairo` for rendering and `Pango` for font management—because these are associated with `Gtk+2` they are widely available. Cairo supports translucent colours and alpha-blending (*via* `Xrender`), and anti-aliasing for the display of lines and text. Pango's font management is based on `fontconfig` and somewhat mysterious, but it seems mainly to use Type 1 and TrueType fonts on the machine running R and send grayscale bitmaps to cairo.

#### 4.1.6.2 windows()

The `windows()` device is a family of devices: it supports plotting to Windows (enhanced) metafiles, `BMP`, `JPEG`, `PNG` and `TIFF` files as well as to Windows printers.

In most of these cases the primary plotting is to a bitmap: this is used for the (default) buffering of the screen device, which also enables the current plot to be saved to BMP, JPEG, PNG or TIFF (it is the internal bitmap which is copied to the file in the appropriate format).

The device units are pixels (logical ones on a metafile device).

The code was originally written by Guido Masarotto with extensive use of macros, which can make it hard to disentangle.

For a screen device, `xd->gawin` is the canvas of the screen, and `xd->bm` is the off-screen bitmap. So macro `DRAW` arranges to plot to `xd->bm`, and if buffering is off, also to `xd->gawin`.

For all other device, `xd->gawin` is the canvas, a bitmap for the `jpeg()` and `png()` device, and an internal representation of a Windows metafile for the `win.metafile()` and `win.print` device. Since 'plotting' is done by Windows GDI calls to the appropriate canvas, its precise nature is hidden by the GDI system.

Buffering on the screen device is achieved by running a timer, which when it fires copies the internal bitmap to the screen. This is set to fire every 500ms (by default) and is reset to 100ms after plotting activity.

Repaint events are handled by copying the internal bitmap to the screen canvas (and then reinitializing the timer), unless there has been a resize. Resizes are handled by replaying the display list: this might not be necessary if a fixed canvas with scrollbars is being used, but that is the least popular of the three forms of resizing.

Text on the device has moved to 'Unicode' (UCS-2) in recent years. As from R 2.7.0, UTF-8 is requested (`hasTextUTF8 = TRUE`) for standard text, and converted to UCS-2 in the plotting functions in file '`src/extra/graphapp/gdraw.c`'. However, GDI has no support for Unicode symbol fonts, and symbols are handled in Adobe Symbol encoding.

Support for translucent colours (with alpha channel between 0 and 255) was introduced in R 2.6.0 for the screen device only, and extended to the bitmap devices in R 2.7.0.[7] This is done by drawing on a further internal bitmap, `xd->bm2`, in the opaque version of the colour then alpha-blending that bitmap to `xd->bm`. The alpha-blending routine is in a separate DLL, '`msimg32.dll`', which is loaded on first use.[8] As small a rectangular region as reasonably possible is alpha-blended (this is rectangle `r` in the code), but things like mitre joins make estimation of a tight bounding box too much work for lines and polygonal boundaries. Translucent-coloured lines are not common, and the performance seems acceptable.

The support for a transparent background in `png()` predates full alpha-channel support in `libpng` (let alone in PNG viewers), so makes use of the limited transparency support in earlier versions of PNG. Where 24-bit colour is used, this is done by marking a single colour to be rendered as transparent. R chose '`#fdfefd`', and uses this as the background colour (in `GA_NewPage` if the specified background colour is transparent (and all non-opaque background colours are treated as transparent). So this works by marking that colour in the PNG file, and viewers without transparency support see a slightly-off-white background, as if there were a near-white canvas. Where a palette is used in the PNG file (if less than 256 colours were used) then this colour is recorded with full transparency and the remaining colours as opaque. If 32-bit colour were available then we could add a full alpha channel, but this is dependent on the graphics hardware and undocumented properties of GDI.

## 4.2 Colours

Devices receive colours as an `unsigned int` (in the `GPar` structure and some of the devices as the `typedef rcolor`): the comments in file '`R_ext/GraphicsDevice.h`' are the primary documentation. The 4 bytes in the `unsigned int` are $R,G,B$ and *alpha* from least to most significant. So each of RGB has 256 levels of luminosity from 0 to 255. The alpha byte represents (from R 2.0.0) opacity, so value 255 is fully opaque and 0 fully transparent: many but not all devices handle semi-transparent colours.

Colors can be created in C via the macro `R_RGBA`, and a set of macros are defined in '`R_ext/GraphicsDevice.h`' to extract the various components.

Colours in the base graphics system were originally borrowed from S (and before that the GRZ library from Bell Labs), with the concept of a (variable-sized) palette of colours referenced

[7] It is technically possible to use alpha-blending on metafile devices such as printers, but it seems few drivers have support for this.

[8] It is avaliable on Windows 2000 or later, and so had to be optional in R 2.6.0.

by numbers '`1...N`' plus '`0`' (the background colour). R introduced the idea of referring to colours by character strings, either in the forms '`#RRGGBB`' or '`#RRGGBBAA`' (representing the bytes in hex) as given by function `rgb()` or via names: the 657 known names are given in the character vector `colors` and in a table in file '`colors.c`'. Note that semi-transparent colours are not 'premultiplied', so 50% transparent white is '`#ffffff80`'.

What is not clear is how the RGB values are to be mapped to display colours in the graphics device. There is a proposal (http://developer.r-project.org/sRGB-RFC.html) to regard the mapping as the colorspace 'sRGB', but this is not currently done. The sRGB colorspace is an industry standard: it is used by Web browsers and JPEGs from all but high-end digital cameras. The interpretation is a matter for graphics devices and for code that manipulates colours, but not for the graphics engine or subsystems.

R uses a painting model similar to PostScript and PDF. This means that where shapes (circles, rectangles and polygons) can both be filled and have a stroked border, the fill should be painted first and then the border (or otherwise only half the border will be visible). Where both the fill and the border are semi-transparent there is some room for interpretation of the intention. Most devices first paint the fill and then the border, alpha-blending at each step. However, PDF does some automatic grouping of objects, and *when the fill and the border have the same alpha*, they are painted onto the same layer and then alpha-blended in one step. (See p. 569 of the PDF Reference Sixth Edition, version 1.7. Unfortunately, although this is what the PDF standard says should happen, it is not correctly implemented by some viewers.)

## 4.3 Base graphics

The base graphics system is likely to move to package **graphics** at some stage, but it currently implemented in files in '`src/main`'.

For historical reasons it is largely implemented in two layers. Files '`plot.c`', `plot3d.c` and `par.c` contain the code for the around 30 `.Internal` calls that implement the basic graphics operations. This code then calls functions with names starting with `G` and declared in header '`Rgraphics.h`' in file '`graphics.c`', which in turn call the graphics engine (whose functions almost all have names starting with `GE`).

A large part of the infrastructure of the base graphics subsystem are the graphics parameters (as set/read by `par()`). These are stored in a `GPar` structure declared in the private header '`Graphics.h`'. This structure has two variables (`state` and `valid`) tracking the state of the base subsystem on the device, and many variables recording the graphics parameters and functions of them.

The base system state is contained in `baseSystemState` structure defined in '`R_ext/GraphicsBase.h`'. This contains three `GPar` structures and a Boolean variable used to record if `plot.new()` (or `persp`) has been used successfully on the device.

The three copies of the `GPar` structure are used to store the current parameters (accessed via `gpptr`), the 'device copy' (accessed via `dpptr`) and space for a saved copy of the 'device copy' parameters. The current parameters are, clearly, those currently in use and are copied from the 'device copy' whenever `plot.new()` is called (whether or not that advances to the next 'page'). The saved copy keeps the state when the device was last completely cleared (e.g. when `plot.new()` was called with `par(new=TRUE)`), and is used to replay the display list.

The separation is not completely clean: the 'device copy' is altered if a plot with log scale(s) is set up via `plot.window()`.

There is yet another copy of most of the graphics parameters in `static` variables in '`graphics.c`' which are used to preserve the current parameters across the processing of in-line parameters in high-level graphics calls (handled by `ProcessInlinePars`).

Snapshots of the base subsystem record the 'saved device copy' of the `GPar` structure.

There remain quite a number of anomalies. For example, function `GEcontourLines` is (despite its name) coded in file '`plot3d.c`' and used to support function `contourLines` in package **grDevices**.

## 4.4 Grid graphics

[At least pointers to documentation.]

# 5 R coding standards

R is meant to run on a wide variety of platforms, including Linux and most variants of Unix as well as 32-bit Windows versions and on MacOS X. Therefore, when extending R by either adding to the R base distribution or by providing an add-on package, one should not rely on features specific to only a few supported platforms, if this can be avoided. In particular, although most R developers use GNU tools, they should not employ the GNU extensions to standard tools. Whereas some other software packages explicitly rely on e.g. GNU make or the GNU C++ compiler, R does not. Nevertheless, R is a GNU project, and the spirit of the *GNU Coding Standards* should be followed if possible.

The following tools can "safely be assumed" for R extensions.

- An ISO C99 C compiler. Note that extensions such as POSIX 1003.1 must be tested for, typically using Autoconf unless you are sure they are supported on all mainstream R platforms (including Windows and MacOS X). Packages will be more portable if written assuming only C89, but this should not be done where using C99 features will make for cleaner or more robust code.
- A FORTRAN 77 compiler (but not Fortran 9x).
- A simple `make`, considering the features of `make` in 4.2 BSD systems as a baseline.

  GNU or other extensions, including pattern rules using '`%`', the automatic variable '`$^`', the '`+=`' syntax to append to the value of a variable, the ("safe") inclusion of makefiles with no error, conditional execution, and many more, must not be used (see Chapter "Features" in the *GNU Make Manual* for more information). On the other hand, building R in a separate directory (not containing the sources) should work provided that `make` supports the `VPATH` mechanism.

  Windows-specific makefiles can assume GNU `make` 3.79 or later, as no other `make` is viable on that platform.
- A Bourne shell and the "traditional" Unix programming tools, including `grep`, `sed`, and `awk`.

  There are POSIX standards for these tools, but these may not fully be supported. Baseline features could be determined from a book such as *The UNIX Programming Environment* by Brian W. Kernighan & Rob Pike. Note in particular that '`|`' in a regexp is an extended regexp, and is not supported by all versions of `grep` or `sed`. The Open Group Base Specifications, Issue 6, which is technically identical to ISO/IEC 9945 and IEEE Std 1003.1 (POSIX), 2004, are available at `http://www.opengroup.org/onlinepubs/009695399/mindex.html`.

Under Windows, most users will not have these tools installed, and you should not require their presence for the operation of your package. However, users who install your package from source will have them, as they can be assumed to have followed the instructions in "the Windows toolset" appendix of the "R Installation and Administration" manual to obtain them. Redirection cannot be assumed to be available via `system` as this does not use a standard shell (let alone a Bourne shell).

In addition, the following tools are needed for certain tasks.

- Perl version 5 is needed for converting documentation written in Rd format to plain text, HTML, LaTeX, and to extract the examples. In addition, several other tools, in particular `check` and `build` require Perl.

  The R Core Team has decided that Perl (version 5) can safely be assumed for building R from source, building and checking add-on packages, and for installing add-on packages from source. On the other hand, Perl cannot be assumed at all for installing *binary* (pre-built) versions of add-on packages, or at run time.

- Makeinfo version 4.7 or later is needed to build the Info files for the R manuals written in the GNU Texinfo system. (Future distributions of R may contain the Info files.)

It is also important that code is written in a way that allows others to understand it. This is particularly helpful for fixing problems, and includes using self-descriptive variable names, commenting the code, and also formatting it properly. The R Core Team recommends to use a basic indentation of 4 for R and C (and most likely also Perl) code, and 2 for documentation in Rd format. Emacs users can implement this indentation style by putting the following in one of their startup files. Alternatively, (for GNU Emacs 21 or later), use customization to set the `c-default-style` to `"bsd"` and `c-basic-offset` to 4.)

```
;;; C
(add-hook 'c-mode-hook
          (lambda () (c-set-style "bsd")))
;;; ESS
(add-hook 'ess-mode-hook
          (lambda ()
            (ess-set-style 'C++ 'quiet)
            ;; Because
            ;;                                DEF GNU BSD K&R C++
            ;; ess-indent-level                 2   2   8   5   4
            ;; ess-continued-statement-offset   2   2   8   5   4
            ;; ess-brace-offset                 0   0  -8  -5  -4
            ;; ess-arg-function-offset          2   4   0   0   0
            ;; ess-expression-offset            4   2   8   5   4
            ;; ess-else-offset                  0   0   0   0   0
            ;; ess-close-brace-offset           0   0   0   0   0
            (add-hook 'local-write-file-hooks
                      (lambda ()
                        (ess-nuke-trailing-whitespace)))))
(setq ess-nuke-trailing-whitespace-p 'ask)
;; or even
;; (setq ess-nuke-trailing-whitespace-p t)
;;; Perl
(add-hook 'perl-mode-hook
          (lambda () (setq perl-indent-level 4)))
```

(The 'GNU' styles for Emacs' C and R modes use a basic indentation of 2, which has been determined not to display the structure clearly enough when using narrow fonts.)

# 6 Testing R code

When you (as R developer) add new functions to the R base (all the packages distributed with R), be careful to check if `make test-Specific` or particularly, `cd tests; make no-segfault.Rout` still works (without interactive user intervention, and on a standalone computer). If the new function, for example, accesses the Internet, or requires GUI interaction, please add its name to the "stop list" in '`tests/no-segfault.Rin`'.

[To be revised: use `make check-devel`, check the write barrier if you change internal structures.]

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