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Anatomy of a macro (tutorial)

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Abstrakt

V článku dopodrobna rozebíráme makro naprogramované v $\text{T}_{\text{E}}\text{X}$ u, které vypočítá a vypíše prvních n prvočísel. To nám dává prostor k poukázání na některé technické detaily, které jsou častokrát začátečníky přehlíženy. Redakce navíc přidala shrnutí příkazů Plain $\text{T}_{\text{E}}\text{X}$ u jako přílohu tohoto článku.

Klíčová slova: Plain $\text{T}_{\text{E}}\text{X}$, prvočísla.

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This article is dedicated to Chrystel Barraband for whom the first version was written in 1993.

Introduction

A $\text{T}_{\text{E}}\text{X}$ macro can be seen as the definition of a command by other commands. Both the definition of a command and the way arguments are passed obey rules which are both precise and simple, but which are often overlooked, though indispensable to a good understanding of $\text{T}_{\text{E}}\text{X}$.

Moreover, the call of a $\text{T}_{\text{E}}\text{X}$ macro is a very different process from what happens in classical languages. It is similar to a macro call in the C preprocessor and it is hard to imagine programming with such a language! A macro call merely entails a replacement or a substitution, but it can also call other macros, including itself, which allows recursion.

Computing prime numbers

We will focus on the computation of prime numbers. $n > 1$ is prime if n is divisible only by itself and 1. If n is odd, it is sufficient to divide n by 3, 5, 7, \dots , $p \leq \lfloor \sqrt{n} \rfloor$. For, if n can be divided by $p > \lfloor \sqrt{n} \rfloor$, then n can also be divided by $q < \lfloor \sqrt{n} \rfloor$. The divisors p will be tried until $p^2 > n$.

Macros

The following example, from *The $\text{T}_{\text{E}}\text{X}$ book* [1], is of an advanced level but will allow us to go straight to the heart of the matter. The macro `\primes` makes it

*Previously published in *TUGboat* 22:1/2 (March/June 2001), pp. 78–82; translation by the author from the original in *Les Cahiers GUTenberg* number 31, December 1998, pp. 19–27.

possible to determine the first n prime numbers, starting with 2. For instance, `\primes{30}` returns the first 30 prime numbers. Here are all the definitions.

We will then analyze them in detail:

```

\newif\ifprime \newif\ifunknown
\newcount\n \newcount\p
\newcount\d \newcount\a
\def\primes#1{2,~3% assume that #1>2
  \n=#1 \advance\n by-2 % n more to go
  \p=5 % odd primes starting with p
  \loop\ifnum\n>0 \printifprime
    \advance\p by2 \repeat}
\def\printp{, % invoked if p is prime
  \ifnum\n=1 and~\fi
  \number\p \advance\n by -1 }
\def\printifprime{\testprimality
  \ifprime\printp\fi}
\def\testprimality{{\d=3 \global\primetrue
  \loop\trialdivision
    \ifunknown\advance\d by2 \repeat}}
\def\trialdivision{\a=\p \divide\a by\d
  \ifnum\a>\d \unknowntrue
  \else\unknownfalse\fi
  \multiply\a by\d
  \ifnum\a=\p \global\primefalse
  \unknownfalse\fi}

```

Declarations

First, we declare two booleans, or more precisely two tests.

```
\newif\ifprime
```

`\ifprime` is equivalent to `\iftrue` if “prime” is true. This boolean will make it possible to see if a number must be printed; thus, in `\printifprime`, the expression `\ifprime\printp\fi` means that if `\ifprime` is evaluated to `\iftrue`, then `\printp` (that is, the macro that will print the number of interest to us, namely `\p`) will be executed, otherwise nothing will happen.

```
\newif\ifunknown
```

“unknown” will be true if we are not yet sure whether `\p` is composed or not. Neither is known. Initially, “unknown” is thus true and the `\ifunknown` test succeeds. If “unknown” is false, we have knowledge about `\p`’s primality, that is, we know if `\p` is prime or not.

Next, we define a few integer variables useful in what follows:

- `\newcount\n`
`\n` is the number of prime numbers that remain to be printed.
- `\newcount\p`
`\p` is the current number for which primality is tested.
- `\newcount\d`
`\d` is a variable containing the sequence of trials of divisors of `\p`.
- `\newcount\a`
`\a` is an auxiliary variable.

Main macro

The main macro is `\primes`. It takes an argument. When the macro is defined, this argument has the name `#1`. If there were a second argument, it would be `#2`, etc. (It is not possible to have—directly—more than nine arguments; indirectly however, one can have as many arguments as one wants, including a variable number, which could for instance be a function of one of the arguments.)

```
\def\primes#1{2,~3%
  \n=#1 \advance\n by-2 %
  \p=5 %
  \loop\ifnum\n>0 \printifprime
    \advance\p by2 \repeat}
```

When the `\primes` macro is called, for instance with `30`, `\primes{30}` is replaced by the body of `\primes` (that is, the group between braces which follows the list of `\primes`' formal arguments), in which `#1` is replaced by the two characters `3` and `0`. `\primes{30}` hence becomes (we have removed spaces at the beginning of the lines, because they are ignored by `TEX`):

```
2,~3%
\n=30 \advance\n by-2 %
\p=5 %
\loop\ifnum\n>0 \printifprime
  \advance\p by2 \repeat
```

What happens now? We print “`2,~3`”, that is, `2` followed by a comma, followed by an unbreakable space (i.e., the line will *in no case* be split after the comma); then `30` is assigned to `\n`. Immediately, `2` is subtracted from `\n`, and `\n` then contains the number of primes that remain to be printed. To keep it simple, we have assumed that at least the three first primes must be displayed. Therefore, we are sure that `\n` is at least equal to `1`. This is also why it was possible to put a comma between `2` and `3`, because we know that `3` is not the last number to be printed. We want the last number printed to be preceded by “`and`”. Hence, when

we ask `\primes{3}`, we want to obtain “2, 3, and 5”. It should also be noticed that the “%” after “3” is essential to prevent insertion of a spurious space. “3” will be followed by a comma when `\printp` is called. The “%” after the second and third lines are not really needed since \TeX gobbles all spaces after explicit numbers; these “%” signs appear only as remnants of comments.

We said that `\p` is the current number whose primality must be tested. We must therefore initialize `\p` to 5, since it is the first odd number after 3 (which we don’t bother to check if it is prime or not).

The body of `\primes{30}` ends with a loop:

```
\loop\ifnum\n>0 \printifprime
  \advance\p by2 \repeat
```

It is a `\loop/\repeat` loop. In general, these loops have the form

```
\loop A text \if... B text \repeat
```

This loop executes as follows: it starts with `\loop`, the A text is executed, then the `\if...` test. If this test succeeds, the B text is executed, then `\repeat` makes us return to `\loop`. If the test fails, the loop is over.

Hence, in the case of `\primes{30}`, it amounts to execute

```
\printifprime\advance\p by2
```

as long as `\n` is strictly positive, that is, as long as prime numbers remain to be printed. In order for this to produce the expected result, it is of course necessary to decrement the value of `\n`. This is done every time a number is printed with the call to `\printifprime`.

As a consequence, if at least one number remains to be printed, `\printifprime` will be called and will print `\p` if `\p` is prime. Whatever the result, we pass then to the next odd number with `\advance\p by2`.

Printing

The prime numbers are printed with `\printp`:

```
\def\printp{, %
  \ifnum\n=1 and~\fi
  \number\p \advance\n by -1 }
```

This macro is called only when `\p` is prime (see its call in `\printifprime`). In any case, this macro has no arguments and gets expanded into

```
, %
\ifnum\n=1 and~\fi
\number\p \advance\n by -1
```

that is a comma and a space, followed by “and ” if `\n` equals 1 (in the case where the number to be printed is the last one), followed by `\p` (the `\number` function is analogous to `\the` and converts a variable into a sequence of printable characters);

finally, `\n` is decremented by 1, as announced, and this allows a normal unfolding of the `\loop... \repeat` loop in the `\primes` macro.

The macro `\printifprime` is called by `\primes`. It calls the function computing the primality of `\p` and this determines if `\p` must be printed or not.

```
\def\printifprime{\testprimality
  \ifprime\printp\fi}
```

As one can guess, the `\testprimality` macro sets the “**prime**” boolean to “**true**” or “**false**,” or if one prefers, it makes the `\ifprime` test succeed or fail.

Primality test

The macro testing `\p`’s primality uses the classical algorithm where divisions are tried by numbers smaller than `\p`’s square root.

```
\def\testprimality{{\d=3 \global\primetrue
  \loop\trialdivision
  \ifunknown\advance\d by2 \repeat}}
```

This macro is more complex because it involves an additional “group,” shown here by the braces. Therefore, when `\testprimality` is expanded, we are left with

```
{\d=3 \global\primetrue
  \loop\trialdivision
  \ifunknown\advance\d by2 \repeat}
```

meaning that what happens between the braces will be—when not otherwise specified—local to that group. This was not the case in the expansions seen previously.

Let us first ignore the group. What are we doing? 3 is first assigned to `\d` where `\d` is the divisor being tested. We will test 3, 5, 7, etc., in succession, and this will go on as long as it is not known for certain whether `\p` is prime or not. As soon as we know if `\p` is prime or composed, the “**unknown**” boolean will become false and the `\ifunknown` test will fail.

Now, let us look at this again: we start with `\d=3`; the default is to consider `\p` prime, hence the “**true**” value is given to the “**prime**” boolean. This is normally done with

```
\primetrue
but in our case, it would not be sufficient. Indeed, at the end of
{\d=3 \primetrue
  \loop\trialdivision
  \ifunknown\advance\d by2 \repeat}
```

all variables take again their former value, because the assignments are *local* to the group. But the “prime” boolean is used when the `\ifprime...` test is being done in `\printifprime`, which is called after `\testprimality`. The group must therefore be *transcended* and the assignment is coerced to be global. This is obtained with

```
\global\primetrue
```

The remainder is then obvious: an attempt is made to divide `\p` by `\d`, and this is the purpose of `\trialdivision`. If nothing more has been discovered, that is, if “unknown” is still “true”, the value of the trial divisor is set to the next value with `\advance\d by2`. Sooner or later this process stops, as shown by the `\trialdivision` definition.

The additional group in `\testprimality` can now be explained. If the group is not introduced, the expansion of `\primes{30}` leads to

```
...
\loop\ifnum\n>0 \printifprime
  \advance\p by2 \repeat
  Plain TEX defines \loop as follows:
\def\loop#1\repeat{\def\body{#1}\iterate}
\def\iterate{\body\let\next\iterate
  \else\let\next\relax\fi \next}
  Therefore, the initial text is expanded into
\def\body{\ifnum\n>0 \printifprime
  \advance\p by2 }\iterate
Hence, the \loop... \repeat construct becomes
\ifnum\n>0 \printifprime\advance\p by2
  \let\next\iterate
\else \let\next\relax\fi \next
If \n > 0, this leads to
\printifprime ...
\let\next\iterate \next
and hence to
\testprimality ...
\let\next\iterate \next
and to
... \loop\trialdivision
  \ifunknown\advance\d by2 \repeat ...
\let\next\iterate \next
```

Now, `\iterate` will call `\body`, but the `\body` definition called will be the one defined by the second (inner) `\loop`, and chaos will follow! This explains why a group has been introduced. The group keeps the inner `\body` definition away from the outer `\loop` construct, hence each `\iterate` call produces the appropriate result.

Division trials

The last macro is where the actual division of $\backslash p$ by $\backslash d$ is made. An auxiliary variable $\backslash a$ is used.

```
\def\trialdivision{\a=\p \divide\a by\d
  \ifnum\a>\d \unknowntrue
  \else\unknownfalse\fi
  \multiply\a by\d
  \ifnum\a=\p \global\primefalse
  \unknownfalse\fi}
```

$\backslash p$ is copied into $\backslash a$, then $\backslash a$ is divided by $\backslash d$. This puts into $\backslash a$ the *integer part* of $\frac{\backslash p}{\backslash d}$. Two cases must then be considered:

1. if $\backslash a > \backslash d$, that is, if $\backslash d$ is smaller than the square root of $\backslash p$, we are still in unknown territory. $\backslash d$ may be a divisor of $\backslash p$, or there might be another divisor of $\backslash p$ larger than $\backslash d$ and smaller than the square root of $\backslash p$ root. The “unknown” boolean is therefore set to “true” with `\unknowntrue`.
2. if $\backslash a \leq \backslash d$, we assume that we know, or at least, that we will know momentarily. We write therefore `\unknownfalse`.

In order to be sure, we must check if there is a remainder to $\backslash p$'s division by $\backslash d$, or rather to $\backslash a$'s division by $\backslash d$: $\backslash a$ is therefore multiplied by $\backslash d$:

```
\multiply\a by\d
\ifnum\a=\p \global\primefalse
\unknownfalse\fi
```

If $\backslash p$ is found again, it means that $\backslash d$ is one of $\backslash p$'s divisors. In that case, $\backslash p$ is of course not prime and the “prime” boolean is set to false with `\primefalse`. Since `\trialdivision` is actually located in the group surrounding the body of the `\testprimality` macro, and since the “prime” is needed outside `\testprimality`, the group must once again be transcended and the “prime” assignment must be forced to be global. Hence:

```
\global\primefalse
```

Finally, in the case where $\backslash d$ divides $\backslash p$, we set `\unknownfalse`, which has the sole effect of causing the loop to end:

```
\loop\trialdivision
  \ifunknown\advance\d by2 \repeat
```

that is, no other divisor is tested. One can observe that there is no `\global` in front of `\unknownfalse`, because `\ifunknown` is used within and not outside the group.

If $\backslash p$ is not found again after the multiplication, it means that $\backslash d$ is not a divisor of $\backslash p$. At that time, we had

- either $\backslash a \leq \backslash d$, and therefore $\backslash a < \backslash d$ (otherwise $\backslash p$ would have been found after the multiplication), and hence `\unknownfalse`, therefore the loop


```

\loop\trialdivision
  \ifunknown\advance\d by2 \repeat
stops and since this happens in the context
\d=3 \global\primetrue
\loop\trialdivision

```

```

  \ifunknown\advance\d by2 \repeat

```

where “prime” had been set to true, we conclude naturally that, no divisor having been found up to $\backslash p$ ’s square root, $\backslash p$ is prime.

Therefore, at the end of $\backslash\text{testprimality}$ ’s call, $\backslash\text{ifprime}$ succeeds and $\backslash p$ is printed.

- or $\backslash a > \backslash d$: in that case, we know nothing more, $\backslash\text{unknowntrue}$, and the next divisor must be tried.

Conclusion

This ends the explanation of these macros, apart from a few subtleties which were not mentioned.

It takes $\text{T}_{\text{E}}\text{X}$ a lot of time to do complex operations such as the ones described. In order to execute $\backslash\text{primes}\{30\}$, $\text{T}_{\text{E}}\text{X}$ spends more time than it needs on average to typeset a whole page with plain $\text{T}_{\text{E}}\text{X}$. $\backslash\text{trialdivision}$ is expanded 132 times. With $\backslash\text{primes}\{1000\}$ there are 41331 expansions and with $\backslash\text{primes}\{10000\}$ there are 1441624 expansions.

It should be stressed that the previous macros are given in *The $\text{T}_{\text{E}}\text{X}$ book* [1, pp. 218–219], with the following lines as the only explanation:

The computation is fairly straightforward, except that it involves a loop inside a loop; therefore $\backslash\text{testprimality}$ introduces an extra set of braces, to keep the inner loop control from interfering with the outer loop. The braces make it necessary to say ‘ $\backslash\text{global}$ ’ when $\backslash\text{ifprime}$ is being set true or false. $\text{T}_{\text{E}}\text{X}$ spent more time constructing that sentence than it usually spends on an entire page; the $\backslash\text{trialdivision}$ macro was expanded 132 times.

$\text{T}_{\text{E}}\text{X}$ ’s programming language is quite peculiar and we gave only a glimpse of it. The interested reader should dive into $\text{T}_{\text{E}}\text{X}$ ’s “bible”, namely Donald Knuth’s *$\text{T}_{\text{E}}\text{X}$ book* [1].

Acknowledgments

I would like to thank an anonymous referee for noticing an important error in the French version of the article.

References

- [1] Knuth, Donald Ervin. *The T_EXbook*. (Computers and Typesetting, Volume A). Reading, Massachusetts: Addison-Wesley, 1984. ISBN 0-201-13448-9.

Summary: Anatomy of a macro (tutorial)

In this article, we explain in detail a T_EX macro computing prime numbers. This gives us an opportunity to illustrate technical aspects often ignored by beginners in the T_EX world.

The source codes are included as small parts in the article commented in detail. You may find the original English version of the article in *TUGboat*, see <http://www.tug.org/TUGboat/Articles/tb22-1-2/tb70roeg.pdf>.

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TeX Reference Card

(for Plain TeX)

Greek Letters

α	alpha	ι	iota
β	beta	κ	kappa
γ	gamma	λ	lambda
δ	delta	μ	mu
ϵ	epsilon	ν	nu
ζ	zeta	ξ	xi
η	eta	π	pi
θ	theta	ρ	rho
Γ	Gamma	Ξ	Xi
Δ	Delta	Π	Pi
Λ	Lambda	Σ	Sigma
		Υ	Upsilon

Symbols of Type Ord

\aleph	aleph
\beth	beth
\imath	imaginary i
\jmath	imaginary j
\kern	horizontal kern
\lrcorner	left corner
\llcorner	lower left corner
\lrcorner	right corner
\llcorner	lower right corner
\ulcorner	upper left corner
\urcorner	upper right corner
∞	infinity

Large Operators

\sum	sum
\prod	product
\coprod	coproduct
\int	integrate
\oint	ointegral
\bigcap	bigcap
\bigcup	bigcup
\bigoplus	bigoplus
\bigotimes	bigotimes
\bigcircledast	bigcircledast
\bigcircledcirc	bigcircledcirc
\bigcircledR	bigcircledR
\bigcircledS	bigcircledS
\bigcircledT	bigcircledT
\bigcircledU	bigcircledU
\bigcircledV	bigcircledV
\bigcircledW	bigcircledW
\bigcircledX	bigcircledX
\bigcircledY	bigcircledY
\bigcircledZ	bigcircledZ
\bigcircledast	bigcircledast
\bigcircledcirc	bigcircledcirc
\bigcircledR	bigcircledR
\bigcircledS	bigcircledS
\bigcircledT	bigcircledT
\bigcircledU	bigcircledU
\bigcircledV	bigcircledV
\bigcircledW	bigcircledW
\bigcircledX	bigcircledX
\bigcircledY	bigcircledY
\bigcircledZ	bigcircledZ

Binary Operations

\mp	minus
\pm	plus
\times	times
\cdot	dot
\ast	asterisk
\diamond	diamond
\circ	circle
\oslash	circle slash
\div	divide
\dagger	dagger
\ddagger	dagger double
\S	section
\P	paragraph
\R	real
\Im	imaginary
\Re	real part
\Im	imaginary part
\Re	real axis
\Im	imaginary axis
\Re	real line
\Im	imaginary line
\Re	real plane
\Im	imaginary plane
\Re	real space
\Im	imaginary space
\Re	real time
\Im	imaginary time
\Re	real world
\Im	imaginary world
\Re	real universe
\Im	imaginary universe
\Re	real infinity
\Im	imaginary infinity
\Re	real eternity
\Im	imaginary eternity
\Re	real forever
\Im	imaginary forever
\Re	real always
\Im	imaginary always
\Re	real never
\Im	imaginary never
\Re	real sometimes
\Im	imaginary sometimes
\Re	real rarely
\Im	imaginary rarely
\Re	real seldom
\Im	imaginary seldom
\Re	real hardly
\Im	imaginary hardly
\Re	real scarcely
\Im	imaginary scarcely
\Re	real barely
\Im	imaginary barely
\Re	real almost
\Im	imaginary almost
\Re	real nearly
\Im	imaginary nearly
\Re	real quite
\Im	imaginary quite
\Re	real very
\Im	imaginary very
\Re	real extremely
\Im	imaginary extremely
\Re	real super
\Im	imaginary super
\Re	real ultra
\Im	imaginary ultra
\Re	real mega
\Im	imaginary mega
\Re	real giga
\Im	imaginary giga
\Re	real tera
\Im	imaginary tera
\Re	real peta
\Im	imaginary peta
\Re	real exa
\Im	imaginary exa
\Re	real zetta
\Im	imaginary zetta
\Re	real yotta
\Im	imaginary yotta
\Re	real ronna
\Im	imaginary ronna
\Re	real quetta
\Im	imaginary quetta
\Re	real sept
\Im	imaginary sept
\Re	real oct
\Im	imaginary oct
\Re	real non
\Im	imaginary non
\Re	real dec
\Im	imaginary dec
\Re	real cent
\Im	imaginary cent
\Re	real mil
\Im	imaginary mil
\Re	real micro
\Im	imaginary micro
\Re	real nano
\Im	imaginary nano
\Re	real pico
\Im	imaginary pico
\Re	real femto
\Im	imaginary femto
\Re	real atto
\Im	imaginary atto
\Re	real zepto
\Im	imaginary zepto
\Re	real yocto
\Im	imaginary yocto
\Re	real ronto
\Im	imaginary ronto
\Re	real quatto
\Im	imaginary quatto
\Re	real sonto
\Im	imaginary sonto
\Re	real qonto
\Im	imaginary qonto
\Re	real tonto
\Im	imaginary tonto
\Re	real pent
\Im	imaginary pent
\Re	real hex
\Im	imaginary hex
\Re	real sept
\Im	imaginary sept
\Re	real oct
\Im	imaginary oct
\Re	real non
\Im	imaginary non
\Re	real dec
\Im	imaginary dec
\Re	real cent
\Im	imaginary cent
\Re	real mil
\Im	imaginary mil
\Re	real micro
\Im	imaginary micro
\Re	real nano
\Im	imaginary nano
\Re	real pico
\Im	imaginary pico
\Re	real femto
\Im	imaginary femto
\Re	real atto
\Im	imaginary atto
\Re	real zepto
\Im	imaginary zepto
\Re	real yocto
\Im	imaginary yocto
\Re	real ronto
\Im	imaginary ronto
\Re	real quatto
\Im	imaginary quatto
\Re	real sonto
\Im	imaginary sonto
\Re	real qonto
\Im	imaginary qonto
\Re	real tonto
\Im	imaginary tonto
\Re	real pent
\Im	imaginary pent
\Re	real hex
\Im	imaginary hex
\Re	real sept
\Im	imaginary sept
\Re	real oct
\Im	imaginary oct
\Re	real non
\Im	imaginary non
\Re	real dec
\Im	imaginary dec
\Re	real cent
\Im	imaginary cent
\Re	real mil
\Im	imaginary mil
\Re	real micro
\Im	imaginary micro
\Re	real nano
\Im	imaginary nano
\Re	real pico
\Im	imaginary pico
\Re	real femto
\Im	imaginary femto
\Re	real atto
\Im	imaginary atto
\Re	real zepto
\Im	imaginary zepto
\Re	real yocto
\Im	imaginary yocto
\Re	real ronto
\Im	imaginary ronto
\Re	real quatto
\Im	imaginary quatto
\Re	real sonto
\Im	imaginary sonto
\Re	real qonto
\Im	imaginary qonto
\Re	real tonto
\Im	imaginary tonto
\Re	real pent
\Im	imaginary pent
\Re	real hex
\Im	imaginary hex
\Re	real sept
\Im	imaginary sept
\Re	real oct
\Im	imaginary oct
\Re	real non
\Im	imaginary non
\Re	real dec
\Im	imaginary dec
\Re	real cent
\Im	imaginary cent
\Re	real mil
\Im	imaginary mil
\Re	real micro
\Im	imaginary micro
\Re	real nano
\Im	imaginary nano
\Re	real pico
\Im	imaginary pico
\Re	real femto
\Im	imaginary femto
\Re	real atto
\Im	imaginary atto
\Re	real zepto
\Im	imaginary zepto
\Re	real yocto
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\Im	imaginary sonto
\Re	real qonto
\Im	imaginary qonto
\Re	real tonto
\Im	imaginary tonto
\Re	real pent
\Im	imaginary pent
\Re	real hex
\Im	imaginary hex
\Re	real sept
\Im	imaginary sept
\Re	real oct
\Im	imaginary oct
\Re	real non
\Im	imaginary non
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