2. Stack-based Programming

Oscar Nierstrasz

/Times-Roman findfont
18 scalefont
setfont
100 500 moveto
(Hello world) show
showpage

% look up Times Roman font
% scale it to 18 points
% set this to be the current font
% go to coordinate (100, 500)
% draw the string “Hello world”
% render the current page

Hello world
Roadmap

- PostScript objects, types and stacks
- Arithmetic operators
- Graphics operators
- Procedures and variables
- Arrays and dictionaries
References


> Display Postscript
  

> GSview for Windows & Linux
  
Roadmap

> PostScript objects, types and stacks
> Arithmetic operators
> Graphics operators
> Procedures and variables
> Arrays and dictionaries
What is PostScript?

PostScript “is a simple interpretive programming language ... to describe the appearance of text, graphical shapes, and sampled images on printed or displayed pages.”

> introduced in 1985 by Adobe
> display standard supported by all major printer vendors
> simple, stack-based programming language
> minimal syntax
> large set of built-in operators
> PostScript programs are usually generated from applications, rather than hand-coded
Although Postscript has been around for a while, it has been extremely successful, having established itself as the de facto standard for printers. Although hardly anyone programs in Postscript, programs are generated every time anyone prints a document.

The language is interesting to study as an example of a powerful and expressive stack-based language.
Postscript variants

> **Level 1:**
  — the original 1985 PostScript

> **Level 2:**
  — additional support for dictionaries, memory management ...

> **Display PostScript:**
  — special support for screen display

> **Level 3:**
  — adds “workflow” support
<table>
<thead>
<tr>
<th><strong>Comments:</strong></th>
<th>from “%” to next newline or formfeed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% This is a comment</td>
</tr>
<tr>
<td><strong>Numbers:</strong></td>
<td>signed integers, reals and radix numbers</td>
</tr>
<tr>
<td></td>
<td>123  -98  0  +17  -.002  34.5</td>
</tr>
<tr>
<td></td>
<td>123.6e10  1E-5  8#1777  16#FFE  2#1000</td>
</tr>
<tr>
<td><strong>Strings:</strong></td>
<td>text in parentheses or hexadecimal in angle brackets. Special characters are escaped: \n \t ( ( ) \ \ ...</td>
</tr>
<tr>
<td><strong>Names:</strong></td>
<td>tokens consisting of “regular characters” but which aren’t numbers</td>
</tr>
<tr>
<td></td>
<td>abc Offset $$ 23A 13-456 a.b</td>
</tr>
<tr>
<td></td>
<td>$MyDict @pattern</td>
</tr>
<tr>
<td><strong>Literal names:</strong></td>
<td>start with slash</td>
</tr>
<tr>
<td></td>
<td>/buffer /proc</td>
</tr>
<tr>
<td><strong>Arrays:</strong></td>
<td>enclosed in square brackets</td>
</tr>
<tr>
<td></td>
<td>[ 123 /abc (hello) ]</td>
</tr>
<tr>
<td><strong>Procedures:</strong></td>
<td>enclosed in curly brackets</td>
</tr>
<tr>
<td></td>
<td>{ add 2 div }</td>
</tr>
<tr>
<td></td>
<td>% add top two stack items and divide by 2</td>
</tr>
</tbody>
</table>
A PostScript program is a sequence of tokens, representing typed objects, that is interpreted to manipulate the display and *four stacks* that represent the execution state of a PostScript program:

<table>
<thead>
<tr>
<th>Stack Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operand stack:</strong></td>
<td>holds (arbitrary) <em>operands and results</em> of PostScript operators</td>
</tr>
<tr>
<td><strong>Dictionary stack:</strong></td>
<td>holds only <em>dictionaries</em> where keys and values may be stored</td>
</tr>
<tr>
<td><strong>Execution stack:</strong></td>
<td>holds <em>executable objects</em> (e.g. procedures) in stages of execution</td>
</tr>
<tr>
<td><strong>Graphics state stack:</strong></td>
<td>keeps track of <em>current coordinates</em> etc.</td>
</tr>
</tbody>
</table>
The first of these stacks is the most important as it is used for all computation.

The dictionary stack is used to encapsulate sets of local variables to be used by procedures we define. The execution stack is mostly hidden from us, and is used by Postscript to manage running procedures. The graphics state stack will make it easy for us to work in different coordinate systems.
Object types

Every object is either literal or executable:

**Literal objects** are pushed on the operand stack:
- integers, reals, string constants, literal names, arrays, procedures

**Executable objects** are interpreted:
- built-in operators
- names bound to procedures (in the current dictionary context)

**Simple Object Types** are copied by value
- boolean, fontID, integer, name, null, operator, real ...

**Composite Object Types** are copied by reference
- array, dictionary, string ...
Roadmap

- PostScript objects, types and stacks
- **Arithmetic operators**
- Graphics operators
- Procedures and variables
- Arrays and dictionaries
The operand stack

Compute the average of 40 and 60: $40 \ 60 \ \textit{add} \ 2 \ \textit{div}$

At the end, the result is left on the top of the operand stack.
Note that numbers are literal objects, so they are pushed on the operand stack, while the operators are executable, so they actually modify the stack.

Aside: note that computation is expressed in RPN — “Reverse Polish Notation” — this is easy to implement without the need for a parser, and was used extensively on HP calculators for this reason.
Stack and arithmetic operators

<table>
<thead>
<tr>
<th>Stack</th>
<th>Op</th>
<th>New Stack</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>num1 num2</td>
<td>add</td>
<td>sum</td>
<td>num1 + num2</td>
</tr>
<tr>
<td>num1 num2</td>
<td>sub</td>
<td>difference</td>
<td>num1 - num2</td>
</tr>
<tr>
<td>num1 num2</td>
<td>mul</td>
<td>product</td>
<td>num1 * num2</td>
</tr>
<tr>
<td>num1 num2</td>
<td>div</td>
<td>quotient</td>
<td>num1 / num2</td>
</tr>
<tr>
<td>int1 int2</td>
<td>idiv</td>
<td>quotient</td>
<td>integer divide</td>
</tr>
<tr>
<td>int1 int2</td>
<td>mod</td>
<td>remainder</td>
<td>int1 mod int2</td>
</tr>
<tr>
<td>num den</td>
<td>atan</td>
<td>angle</td>
<td>arctangent of num/den</td>
</tr>
<tr>
<td>any</td>
<td>pop</td>
<td>-</td>
<td>discard top element</td>
</tr>
<tr>
<td>any1 any2</td>
<td>exch</td>
<td>any2 any1</td>
<td>exchange top two elements</td>
</tr>
<tr>
<td>any</td>
<td>dup</td>
<td>any any</td>
<td>duplicate top element</td>
</tr>
<tr>
<td>any1 ... anyn n</td>
<td>copy</td>
<td>any1 ... anyn any1 ... anyn</td>
<td>duplicate top n elements</td>
</tr>
<tr>
<td>anyn ... any0 n</td>
<td>index</td>
<td>anyn ... any0 anyn</td>
<td>duplicate n+1th element</td>
</tr>
</tbody>
</table>

and many others ...


Roadmap

> PostScript objects, types and stacks
> Arithmetic operators
> **Graphics operators**
> Procedures and variables
> Arrays and dictionaries
Coordinates

Coordinates are measured in points:

72 points = 1 inch
= 2.54 cm.

A4 Paper

21 cm = 595 points
29.7 cm = 840 points
Drawing a Box

“A path is a set of straight lines and curves that define a region to be filled or a trajectory that is to be drawn on the current page.”

newpath % clear the current drawing path
100 100 moveto % move to (100,100)
100 200 lineto % draw a line to (100,200)
200 200 lineto
200 100 lineto
100 100 lineto
10 setlinewidth % set width for drawing
stroke % draw along current path
showpage % and display current page
If you have a computer that directly supports Display Postscript, you can execute these examples without sending them to a printer. Alternatively you may use a dedicated open source program, such as Ghostscript.

Why is the bottom left corner not perfectly closed? Simulate what postscript is doing with a pen of 10 points width.
## Path construction operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>newpath</td>
<td>Initialize current path to be empty</td>
</tr>
<tr>
<td>currentpoint</td>
<td>Return current coordinates</td>
</tr>
<tr>
<td>moveto</td>
<td>Set current point to ((x, y))</td>
</tr>
<tr>
<td>rmoveto</td>
<td>Relative moveto</td>
</tr>
<tr>
<td>lineto</td>
<td>Append straight line to ((x, y))</td>
</tr>
<tr>
<td>rlineto</td>
<td>Relative lineto</td>
</tr>
<tr>
<td>arc</td>
<td>Append counterclockwise arc</td>
</tr>
<tr>
<td>closepath</td>
<td>Connect subpath back to start</td>
</tr>
<tr>
<td>fill</td>
<td>-</td>
</tr>
<tr>
<td>stroke</td>
<td>Draw line along current path</td>
</tr>
<tr>
<td>showpage</td>
<td>Output and reset current page</td>
</tr>
</tbody>
</table>

Others: arcn, arcto, curveto, rcurveto, flattenpath, ...
“Hello World” in Postscript

Before you can print text, you must
1. look up the desired font,
2. scale it to the required size, and
3. set it to be the current font.

/Times-Roman findfont % look up Times Roman font
18 scalefont % scale it to 18 points
setfont % set this to be the current font
100 500 moveto % go to coordinate (100, 500)
(Hello world) show % draw the string “Hello world”
showpage % render the current page

Hello world
Note that \texttt{/Times-Roman} and \texttt{(Hello world)} are literal objects, so are pushed on the stack, not executed.
Encapsulated PostScript

EPSF is a standard format for importing and exporting PostScript files between applications.

%!PS–Adobe-3.0 EPSF-3.0
%%BoundingBox: 90 490 200 520
/Times-Roman findfont
  18 scalefont
  setfont
100 500 moveto
(Hello world) show
showpage

Hello world
# Character and font operators

<table>
<thead>
<tr>
<th>key</th>
<th><strong>findfont</strong></th>
<th>font</th>
<th>return font dict identified by key</th>
</tr>
</thead>
<tbody>
<tr>
<td>font scale</td>
<td><strong>scalefont</strong></td>
<td>font’</td>
<td>scale font by given scale to produce font’</td>
</tr>
<tr>
<td>font</td>
<td><strong>setfont</strong></td>
<td>-</td>
<td>set font dictionary</td>
</tr>
<tr>
<td>-</td>
<td><strong>currentfont</strong></td>
<td>font</td>
<td>return current font</td>
</tr>
<tr>
<td>string</td>
<td><strong>show</strong></td>
<td>-</td>
<td>print string</td>
</tr>
<tr>
<td>string</td>
<td><strong>stringwidth</strong></td>
<td>wx wy</td>
<td>width of string in current font</td>
</tr>
</tbody>
</table>

**Others:** definefont, makefont, FontDirectory, StandardEncoding ....
Roadmap

- PostScript objects, types and stacks
- Arithmetic operators
- Graphics operators
- Procedures and variables
- Arrays and dictionaries
Variables and procedures are defined by binding names to literal or executable objects.

Define a general procedure to compute averages:

```
def
   associate key and value in current dictionary

/average { add 2 div } def
% bind the name "average" to "\{ add 2 div \}"
40 60 average
```
Note that once the literal `/average` is defined, `average` becomes an executable operator.
A Box procedure

Most PostScript programs consist of a prologue and a script.

% Prologue -- application specific procedures
/box { % grey x y -> __
  newpath
  moveto % x y -> __
  0 150 rlineto % relative lineto
  150 0 rlineto
  0 -150 rlineto
  closepath % cleanly close path!
  setgray % grey -> __
  fill % colour in region
} def
% Script -- usually generated
0 100 100 box
0.4 200 200 box
0.6 300 300 box
0 setgray % set drawing color back to black!
showpage
Postscript programs are typically generated by document authoring systems. The programs they generate consist of prologues that were originally hand-written, and scripts that are generated.
## Graphics state and coordinate operators

<table>
<thead>
<tr>
<th>Action</th>
<th>Command</th>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Save</td>
<td><code>gsave</code></td>
<td>-</td>
<td>Saves the current path, gray value, line width and user coordinate system</td>
</tr>
<tr>
<td>Restore</td>
<td><code>grestore</code></td>
<td>-</td>
<td>Restores the graphics state</td>
</tr>
<tr>
<td>Set</td>
<td><code>setlinewidth</code></td>
<td><code>num</code></td>
<td>Sets the line width</td>
</tr>
<tr>
<td>Set</td>
<td><code>setgray</code></td>
<td><code>num</code></td>
<td>Sets the color to gray value</td>
</tr>
<tr>
<td>Scale</td>
<td><code>scale</code></td>
<td><code>sx</code>, <code>sy</code></td>
<td>Scales the user space by <code>sx</code> and <code>sy</code></td>
</tr>
<tr>
<td>Rotate</td>
<td><code>rotate</code></td>
<td><code>angle</code></td>
<td>Rotates the user space by <code>angle</code> degrees</td>
</tr>
<tr>
<td>Translate</td>
<td><code>translate</code></td>
<td><code>tx</code>, <code>ty</code></td>
<td>Translates the user space by <code>(tx, ty)</code></td>
</tr>
</tbody>
</table>

*gsave saves the current path, gray value, line width and user coordinate system*
The graphics state operators make it easy to work in a simple coordinate system, even if the target is scaled or rotated: instead of drawing a rotated square, you can draw a regular square in a rotated coordinate system.
A Fibonacci Graph

```latex
/fibInc { % m n -> n (m+n)
  exch % m n -> n m
  1 index % n m -> n m n
  add % m n -> n (m+n)
} def
/x 0 def /y 0 def /dx 10 def
newpath
100 100 translate % make (100, 100) the origin
x y moveto % i.e., relative to (100, 100)
0 1
25 {
  /x x dx add def % increment x
  dup /y exch 100 idiv def % set y to 1/100 last fib val
  x y lineto % draw segment
  fibInc
} repeat
2 setlinewidth
stroke
showpage
```
Numbers and Strings

Numbers and other objects must be converted to strings before they can be printed:

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Method</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>int</td>
<td><strong>string</strong></td>
<td>string</td>
</tr>
<tr>
<td></td>
<td></td>
<td>create string of capacity int</td>
</tr>
<tr>
<td>any string</td>
<td><strong>cvs</strong></td>
<td>substring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>convert to string</td>
</tr>
</tbody>
</table>
/LM 100 def % left margin
/FS 18 def % font size
/sBuf 20 string def % string buffer of length 20

/fact {
  dup 1 lt % n -> n bool
  { pop 1 }
  {
    dup % n -> n n
    1 % -> n n 1
    sub % -> n (n-1)
    fact % -> n (n-1)!NB: recursive lookup
    mul % n!
  }
  ifelse
} def

/showInt { % n -> __
  sBuf cvs show % convert an integer to a string and show it
} def
Factorial ...

/showFact { % n -> __
    dup showInt
    (! = ) show
    fact showInt
} def
/newline { % __ -> __
    currentpoint exch pop % get current y
    FS 2 add sub % subtract offset
    LM exch moveto % move to new x y
} def
/Times-Roman findfont FS scalefont setfont
LM 600 moveto
0 1 20 { showFact newline } for % do from 0 to 20
showpage

0! = 1
1! = 1
2! = 2
3! = 6
4! = 24
5! = 120
6! = 720
7! = 5040
8! = 40320
9! = 362880
10! = 3628800
11! = 39916800
12! = 479001600
13! = 6.22702e+09
14! = 8.71783e+10
15! = 1.30767e+12
16! = 2.09228e+13
17! = 3.55687e+14
18! = 6.40237e+15
19! = 1.21645e+17
20! = 2.4329e+18
# Boolean, control and string operators

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>eq</code> any1 any2</td>
<td>Test equal</td>
</tr>
<tr>
<td><code>ne</code> any1 any2</td>
<td>Test not equal</td>
</tr>
<tr>
<td><code>ge</code> any1 any2</td>
<td>Test greater or equal</td>
</tr>
<tr>
<td>true</td>
<td>Push boolean value true</td>
</tr>
<tr>
<td>false</td>
<td>Push boolean value false</td>
</tr>
<tr>
<td><code>if</code> bool proc</td>
<td>Execute proc if bool is true</td>
</tr>
<tr>
<td><code>ifelse</code> proc1 proc2</td>
<td>Execute proc1 if bool is true else proc2</td>
</tr>
<tr>
<td><code>for</code> init incr limit proc</td>
<td>Execute proc with values init to limit by steps of incr</td>
</tr>
<tr>
<td><code>repeat</code> int proc</td>
<td>Execute proc int times</td>
</tr>
<tr>
<td><code>length</code> string</td>
<td>Number of elements in string</td>
</tr>
<tr>
<td><code>get</code> string index</td>
<td>Get element at position index</td>
</tr>
<tr>
<td><code>put</code> string index int</td>
<td>Put int into string at position index</td>
</tr>
<tr>
<td><code>forall</code> string proc</td>
<td>Execute proc for each element of string</td>
</tr>
</tbody>
</table>
A simple formatter

/LM 100 def
/RM 250 def
/FS 18 def
/showStr { 
  dup stringwidth pop
  currentpoint pop
  add
  RM gt { newline } if
  show
} def
/newline { 
  currentpoint exch pop
  FS 2 add sub
  LM exch moveto
} def
/format { { showStr ( ) show } forall } def
/Times-Roman findfont FS scalefont setfont
LM 600 moveto
A simple formatter ...

[ (Now) (is) (the) (time) (for) (all) (good) (men) (to) 
(come) (to) (the) (aid) (of) (the) (party.) ] format 
showpage

Now is the time for all good men to come to the aid of the party.
Roadmap

- PostScript objects, types and stacks
- Arithmetic operators
- Graphics operators
- Procedures and variables
- Arrays and dictionaries
# Array and dictionary operators

<table>
<thead>
<tr>
<th>-</th>
<th>[</th>
<th>mark</th>
<th>start array construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>mark obj0 ... objn-1</td>
<td>]</td>
<td>array</td>
<td>end array construction</td>
</tr>
<tr>
<td>int array</td>
<td>array</td>
<td>array</td>
<td>create array of length n</td>
</tr>
<tr>
<td>array length</td>
<td>int</td>
<td>number of elements in array</td>
<td></td>
</tr>
<tr>
<td>array index get</td>
<td>any</td>
<td>get element at index position</td>
<td></td>
</tr>
<tr>
<td>array index any put</td>
<td>-</td>
<td>put element at index position</td>
<td></td>
</tr>
<tr>
<td>array proc forall</td>
<td>-</td>
<td>execute proc for each array element</td>
<td></td>
</tr>
<tr>
<td>int dict</td>
<td>dict</td>
<td>create dictionary of capacity int</td>
<td></td>
</tr>
<tr>
<td>dict length</td>
<td>int</td>
<td>number of key-value pairs</td>
<td></td>
</tr>
<tr>
<td>dict maxlength</td>
<td>int</td>
<td>capacity</td>
<td></td>
</tr>
<tr>
<td>dict begin</td>
<td>-</td>
<td>push dict on dict stack</td>
<td></td>
</tr>
<tr>
<td>- end</td>
<td>-</td>
<td>pop dict stack</td>
<td></td>
</tr>
</tbody>
</table>
Using Dictionaries — Arrowheads

```
/arrowdict 14 dict def % make a new dictionary
arrowdict begin
  /mtrx matrix def % allocate space for a matrix
end
/arrow { % open the dictionary
  arrowdict begin
    /headlength exch def % grab args
    /halfheadthickness exch 2 div def
    /halfthickness exch 2 div def
    /tipy exch def
    /tipx exch def
    /taily exch def
    /tailx exch def
    /dx tipx tailx sub def
    /dy tipy taily sub def
    /arrowlength dx dx mul dy dy mul add sqrt def
    /angle dy dx atan def
    /base arrowlength headlength sub def
    /savematrix mtrx currentmatrix def % save the coordinate system
  }
Usage: tailx taily tipx tipy thickness headthickness headlength arrow
```
mtrx currentmatrix
pop
tailx taily translate
angle rotate
0 halfthick neg moveto
base halfthick neg lineto
base halfheadthick neg lineto
arrowlength 0 lineto
base halfheadthick lineto
base halfthick lineto
0 halfthick lineto
closepath
savematrix setmatrix
end}
def

% save the coordinate system
% translate to start of arrow
% rotate coordinates
% draw as if starting from (0,0)

% restore coordinate system
Notice how a dictionary is used to allocate space for all the “local” variables of the arrow procedure. We need 14 slots for 14 key-value pairs (7 parameters plus another 7 “local variables”). By defining our own dictionary, and pushing it to the dictionary stack, we make sure that the names we use do not conflict with any other similar names used by other procedures.

The dictionary stack therefore serves the same purpose as the runtime stack in most programming languages.
Instantiating Arrows

Usage: tailx taily tipx tipy thickness headthickness headlength arrow

```
newpath
    318 340 72 340 10 30 72 arrow
fill
newpath
    382 400 542 560 72 232 116 arrow
3 setlinewidth stroke
newpath
    400 300 400 90 90 200 200 3 sqrt mul 2 div arrow
.65 setgray fill
showpage
```
NB: arrow does not do a newpath, so arrows can be added to existing paths
What you should know!

- What kinds of stacks does PostScript manage?
- When does PostScript push values on the operand stack?
- What is a path, and how can it be displayed?
- How do you manipulate the coordinate system?
- Why would you define your own dictionaries?
- How do you compute a bounding box for your PostScript graphic?
Can you answer these questions?

- How would you implement a while procedure?
- When should you use translate instead of moveto?
- How could you use dictionaries to simulate object-oriented programming?
- How would you program this graphic?
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