Arnold Schwarzenegger
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COOL-COLOR ROOFING MATERIAL ATTACHMENT 2: TASK 2.4.2 REPORTS - DEVELOP A COMPUTER PROGRAM FOR OPTIMAL DESIGN OF COOL COATINGS

PIER FINAL PROJECT REPORT

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Pinwheel (version 0.1.1): a tool for the design of color-matched coatings with high solar reflectance

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1 Introduction

Slightly over half of the power in ground-level solar radiation arrives in the invisible "near-infrared" spectrum (700 to 2500 nm). Pinwheel is an application for the design of color-matched coatings with high near-infrared reflectance. Surfaces with such coatings will stay cooler in the sun than conventionally colored surfaces, which is advantageous in warm climates.

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We model a coated surface with two or three layers: an opaque substrate, an optional basecoat, and a topcoat. The solar spectral reflectance of the substrate; the thickness and colorant composition of the optional basecoat; and the thickness of the topcoat are specified by the coating designer. Pinwheel then seeks the topcoat colorant composition that maximizes the solar reflectance of the coated surface while acceptably matching a target visible spectral reflectance. Since the visible spectral reflectance is fixed (to within a tolerance), this process is essentially equivalent to maximizing near-infrared reflectance.[1]

The solar spectral reflectance of a coated surface, and hence its solar reflectance and visible spectral reflectance, are computed by applying to the solar spectral absorption and backscattering coefficients of colorants (a) a two-flux, two-constant model of light propagation through a film and (b) a colorant mixture model. Pinwheel has a large library of over 80 colorants (i.e., pigments and dyes) whose solar spectral properties have been characterized by LBNL.

Our tool differs in three major respects from conventional coating formulation software. First, it predicts solar spectral reflectance (300 - 2500 nm), rather than just visible spectral reflectance (400 - 700 nm). Second, it does not require that coatings be opaque. This permits design of thin coatings that transmit both visible and near-infrared light, as well as thicker coatings that stop visible light but transmit near-infrared light. Third, it contains the solar (and not just visible) spectral properties of many colorants.

2 Installation

Pinwheel executes in R, an interpreted programming environment available as free software for the Windows, Mac OS X, and Unix platforms. It has not yet been tested on non-Windows platforms.

2.1 Windows

1. Download the R base-package installer (version 2.1.0 or later; current name `rw2010.exe`) from `http://r-project.org`. Install R to its default directory (`C:\\Program Files\R`).

2. Download `Pinwheel-installer.exe` from `http://CoolColors.LBL.gov/pinwheel`, then run (i.e., double-click) the installer to create the folder `Pinwheel` (Table 1). Note that a password (available from the author) is required to install Pinwheel.

3. If R was installed in a directory other than `C:\\Program Files\R`, or if its version number exceeds 2.1.0, modify the target of the shortcut `Pinwheel/Launch Pinwheel` (original value: '`"C:\\Program Files\R\rw2010\bin\Rgui.exe" --no-restore --no-save`)' to point to the installed executable `RGui.exe`.

[1]In North America, 43% of ground-level global (direct + diffuse) solar radiation arrives in the visible spectrum (400 - 700 nm); 52% arrives in the near-infrared spectrum (700 - 2500 nm), and 5% in the ultraviolet spectrum (300 - 400 nm).

Table 1: Contents of the top-level folder `Pinwheel`.

item	type	contents
`Application Code`	folder	the Pinwheel application R code file
`Colorant Data`	folder	tab-delimited text files detailing the solar spectral radiative properties of 87 colorants
`Documentation`	folder	user's manual (this document)
`Reports`	folder	tabular (tab-delimited text) and graphical (PDF) solution reports generated by Pinwheel
`Substrate Reflectances`	folder	tab-delimited text files specifying the solar spectral reflectances (300 - 2500 nm @ 5-nm intervals) of several substrates
`Target Reflectances`	folder	user-defined, tab-delimited text files specifying the visible spectral reflectances (400 - 700 nm @ 20-nm intervals) of the design targets
`User Code`	folder	user-defined R code files that call the Pinwheel routines
`Launch Pinwheel`	file	shortcut that launches the R environment and sets the R working directory to the folder `Pinwheel`
`.RProfile`	file	R code that is automatically loaded when the R environment is launched via the `Launch Pinwheel` shortcut; `.RProfile` code loads the actual Pinwheel code in the subfolder `Application Code`
`ReadMe.txt`	file	Release notes (text).
`License.pdf`	file	License document (PDF).

2.2 Other platforms

To be written after testing.

3 Operation

The Pinwheel function `design()` inputs the specifications of the coated surface, such its desired visible spectral reflectance and a list of possible colorants, and outputs visually acceptable coating designs sorted in order of descending solar reflectance. There are five steps to this process.

1. Prepare a tabular datafile specifying the desired ("target") visible spectral reflectance of the coated surface.

2. Compose an R-code file consisting of a single `design()` function call whose arguments specify the coating system, the target reflectance datafile, and the colorants to try.

3. Launch Pinwheel.

4. Execute your design code within R after Pinwheel has loaded.

5. Review the solutions.

Table 2: Format of visible spectral reflectance table. Note that each reflectance r is a value between 0 and 1, and that the header row is required.

wavelength (nm)	reflectance
400	r_{400}
420	r_{420}
440	r_{440}
460	r_{460}
480	r_{480}
500	r_{500}
520	r_{520}
540	r_{540}
560	r_{560}
580	r_{580}
600	r_{600}
620	r_{620}
640	r_{640}
660	r_{660}
680	r_{680}
700	r_{700}

3.1 Preparing a visible spectral reflectance file

The target visible spectral reflectance of the coated surface is specified by reflectances (values 0 to 1) at 16 wavelengths from 400 to 700 nm at 20-nm intervals. Use a text editor or spreadsheet application to create a 17-row, two-column table of the form shown in Table 2. Save the table to the folder `Pinwheel/Target Reflectances` as a tab-delimited text file with a descriptive name of the form *`color`*`.txt`, such as `emerald-green.txt`.

3.2 Composing a `design()` call

The `design()` call arguments specify several physical characteristics of the coating system, including

- the candidate colorants for the topcoat (*required*)
- the desired visible spectral reflectance of the coated surface (*required*)
- the thickness of the topcoat (*optional*—defaults to 25 μm)
- the colorants to use in the basecoat (if present), and their volume concentrations (*optional*—defaults to no basecoat)
- the thickness of the basecoat, if present (*optional*—defaults to no basecoat)
- the substrate (*optional*—defaults to opaque white paint)

The arguments also specify several parameters for the coating design algorithm and its output, including

- the volume concentration levels at which to try each topcoat colorant (*optional*—defaults to 0%, 1%, 2%, 3%, 5%, 10%, 15%, 20%, 25%, and 30%)
- the metric used to measure the error in the match of visible spectral reflectance (*optional*—defaults to root mean square of the difference)
- the tolerance (i.e., allowable error) in the match of visible spectral reflectance (*optional*—defaults to 0.05)
- categories of colorants to exclude from the topcoat, such as those that are organic (*optional*—defaults to none)
- whether to simplify the candidate colorants for the topcoats by removing redundant colorants (*optional*—defaults to yes)
- whether to compute colorant absorption coefficients from tints (mixtures of colorants with white), rather than from masstones (pure colorants) (*optional*—defaults to yes)
- a limit to the number of solutions to retain for each topcoat colorant combination (*optional*—defaults to no limit)
- whether to output tabular and/or graphical solution reports (*optional*—each defaults to yes)
- whether to return the solutions for use in R code that calls `design()` (*optional*—defaults to no)
- whether to skip confirmation of the design parameters (*optional*—defaults to no)
- level of on-screen charting to occur during the design process (*optional*—defaults to high)

The syntax of a `design()` function call is

```
design(arg1=val1, arg2=val2, ...)
```

where each *`arg`* is a named argument, and *`val`* is its value.

3.2.1 Required `design()` arguments

The value of `topcoat.colorants` must be specified. Also note that either `target` or `target.mixture`, but not both, must be specified.

`topcoat.colorants` The candidate colorants for the topcoat, specified as a list of colorant vectors. A colorant vector is a set of one or more colorants, of which only one member will appear in the topcoat. If given a list of n colorant vectors, the design function will specify a topcoat with n colorants, one from each colorant vector.

A colorant vector may take the conventional R form `c("col1", "col2", ...)`, or the convenience form `"col1, col2, ..."`. The list of colorant vectors takes the conventional R form `list(vect1, vect2, ...)`, and must contain at least colorant vector. A colorant *col* is specified by its three-character code of the form *Fnn* (e.g., `G03`, representing Ferro Camouflage Green V-12650 {modified chromium oxide green in paint Chromium Green-Black Modified}. All 87 colorants are listed in Appendix A. The convenience form *F* represents all members of color family *F*; for example, `"W, G03"` is equivalent to `"W01, W02, W03, W04, G03"`).

Example: `topcoat.colorants=list("U01, U02, U03", "Y03, Y06", "R")` specifies that the topcoat will have three colorants, of which the first will be one of three blues (U01, U02, U03); the second will be one of two yellows (Y03, Y06); and the third will be one of the nine members of the red color family (R01, R02, ..., R09).

3.2.2 Optional `design()` arguments

The following arguments have default values (shown) which may be overridden by specifying *arg=val* in the function call. Note that either `target` or `target.mixture`, but not both, must be specified by the user; the other should be left NULL.

`target=NULL` The name of a target visible spectral reflectance file whose path is `Pinwheel/Target Reflectances/target.txt`. The default value of NULL indicates that the target visible spectral reflectances is to be obtained instead from a target mixture specified by the argument `target.mixture`. Note that the ".txt" suffix is omitted when defining `target`.

Example: `target="emerald-green"` specifies that the target visible spectral reflectance file is `Pinwheel/Target Reflectances/emerald-green.txt`.

`target.mixture=NULL` The name of an LBNL-prepared mixture from which to obtain the target visible spectral reflectance.[2] The default value of NULL indicates that the target visible spectral reflectance is to be obtained instead from the target spectral reflectance file specified by the argument `target`. Note: if a target mixture is used, the argument `target.mixture.background` must also be specified.

Example: `target.mixture="U11+G03[1:1]"` specifies that the target visible spectral reflectance should be obtained from mixture U11+G03[1:1].

`target.mixture.background=NULL` If `"white"`, use for the target visible spectral reflectance that of mixture *target.mixture* measured over a background of clear polyester + opaque white paint. If `"black"`, use that measured over a background of clear polyester + opaque black

[2]These mixtures are useful targets for testing Pinwheel because their compositions are known to and reported by `design()`. Enter '`mixtures`' at the R prompt to see the names of all LBNL-prepared mixtures.

paint. Note this argument is relevant only when a target mixture is specified.

Example: `target.mixture.background="white"` sets the background of the target mixture to clear polyester + opaque white paint.

`topcoat.thickness=25` Thickness of the topcoat in microns.

Example: `topcoat.thickness=15` specifies that the topcoat is 15 μm thick.

`basecoat.colorants=NULL` Colorants and their volume concentrations in the basecoat, if one exists. These are specified as a list of colorant-named concentrations of the form `list(`*`col1`*`=`*`c1`*`,` *`col2`*`=`*`c2`*`, ...)`, where *`c1`* is the concentration (value 0-1) of colorant *`col1`*. The default value of NULL indicates the absence of a basecoat.

Example: `basecoat.colorants=list("Y01"=0.15, "P04"=0.05)` specifies that the basecoat will contain yellow Y01 (concentration 15%) and pearlescent P04 (concentration 5%).

`basecoat.thickness=NULL` Thickness of the basecoat in microns. The default value of NULL indicates the absence of a basecoat.

Example: `basecoat.thickness=10` specifies that the basecoat is 10 μm thick.

`substrate="opaque white paint"` The name of the substrate, the solar spectral reflectance of which is stored in the file `Pinwheel/Substrate Reflectances/`*`substrate`*`.txt`. Measured solar spectral reflectances data is supplied for six substrates—`"opaque white paint"`, `"opaque black paint"`, `"aluminum foil"`, `"bare zincalume"`, `"treated zincalume"`, `"bare HDG"`, and `"treated HDG"`. Also, a theoretical "gray" substrate having reflectance $R/100$ at all wavelengths in the solar spectrum may be specified as `"gray`*`R`*`"` for any integer value of R between 0 and 100. There are no actual spectral datafiles for the reflectances of the gray substrates.

Example 1 (real substrate): `substrate="aluminum foil"` specifies that the substrate solar spectral reflectance file is `Pinwheel/Substrate Reflectances/aluminum foil.txt`. *Example 2 (theoretical substrate)*: `substrate="gray7"` specifies a hypothetical gray substrate with a uniform 7% solar spectral reflectance.

`concentration.levels=c(0,1,2,3,5,10,15,20,25,30)/100` The volume concentrations at which to try each topcoat colorant. Note the division by 100, because concentrations are expressed on a scale of 0 to 1, not 0 to 100. Concentrations may also be specified in the convenience form `"`*`c1`*`,` *`c2`*`,` *`c3`*`, ..."`, but in this form the concentrations values must be written as decimals (e.g., `"0, 0.01, 0.02, ..."`).

Table 3: Categories of colorants that can be excluded from the topcoat design, and the codes and descriptions of the members of each category.

hot		toxic		organic	
code	*description*	*code*	*description*	*code*	*description*
B01	carbon black	R05	cadmium orange	B12	perylene black
B02	bone black	Y02	cadmium yellow	U12	phthalo blue
B03	copper chromite black			U13	phthalo blue
B04	synthetic iron oxide black			U14	dioxazine purple
U10	iron blue			G10	phthalocyanine green
R01	iron oxide red			G11	phthalocyanine green
P13	mica + titanium dioxide + iron oxide			R06	acra burnt orange
				R07	acra red
				R08	monastral red
				R09	napthol red light
				Y13	yellow medium azo
				Y14	yellow orange azo

Example: `concentration.levels=c(0,1,2,3,4,5,6,7,8,9,10)/100` specifies test concentrations of 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10%.

`match.metric="rms.absolute"` The metric used to measure the error in the match of visible spectral reflectance. `"rms.absolute"` is the root mean square of the absolute difference between the visible spectral reflectances of the trial mixture and the target; `"max.absolute"` is the maximum absolute difference between these two spectra. Other metrics may be implemented in future versions of Pinwheel.

Example: `match.metric="max.absolute"` specifies the match metric should be maximum absolute difference.

`match.tolerance=0.05` The maximum acceptable error in the match of visible spectral reflectance (value 0-1).

Example: `match.tolerance=0.03` specifies a match tolerance of 0.03.

`exclude=NULL` A vector of the conventional R form `c(`*`cat1`*`, `*`cat2`*`, `...`)` or the convenience form `"`*`cat1`*`, `*`cat2`*`, `..."` specifying the categories of colorants not to use in the topcoat. Excludable categories include `"hot"` (strongly NIR-absorbing), `"toxic"` (containing cadmium), and `"organic"` (Table 3). The default value of `NULL` indicates that no categories are to be excluded.

Example: `exclude="hot, toxic"` will exclude from the topcoat any hot or toxic colorants.

`compute.k.from.tint=TRUE` Whether to use, if available,[3] the solar spectral absorption coefficient

[3]Tint-based absorption coefficients are available for the 56 colorants that were characterized in acrylic films

Table 4: Sets of similar colorants that can be represented in topcoat design by a single colorant.

similar colorants	representative colorant	colorant description
W01, W02, W03, W04	W03	titanium dioxide white
B08, B09	B08	Ferro Black V-799
B10, B11	B11	Shepherd Black 411
U12, U13	U13	phthalocyanine blue
G10, G11	G10	phthalocyanine green

K of a colorant computed from its tint, rather than from its masstone. Tint-based absorption coefficients are more accurate at wavelengths where the masstone is strongly absorbing and the masstone-based absorption coefficient is likely to be underestimated.

Example: `compute.k.from.tint=FALSE` prevents the use of tint-based absorption coefficients.

`simplify=TRUE` Whether to simplify (when possible) the candidate colorants for the topcoat by reducing similar colorants in a colorant vector to a single representative colorant (Table 4).

Example: `simplify=FALSE` turns off simplification.

`solutions.per.combination=NULL` The (integer) limit to the number of solutions to retain for each topcoat colorant combination. The default value of NULL indicates that all solutions will be retained. When a limit is specified, the solutions with the highest solar reflectance are retained.

Example: `solutions.per.combination=5` will limit to five the number of solutions retained for each topcoat colorant combination.

`verbosity="high"` The level of on-screen charting to take place during the design process. When `"high"`, three charts will be shown: (a) the visible spectral reflectance of the current trial; (b) the visible spectral reflectance of all solutions (current colorant combination); and (c) the solar reflectance vs. visible match error for all solutions (all colorant combinations). When `"medium"`, graph (a) is omitted; when `"low"`, all three graphs are omitted. Mode `"medium"` is much faster than mode `"high"`, while mode `"low"` is slightly faster than mode `"medium"`.

Example: `verbosity="medium"` displays only charts (b) and (c) during the design process.

`output.graphical.report=TRUE` Whether to generate a graphical report charting and describing each solution.

Example: `output.graphical.report=FALSE` prevents the generation of a graphical report.

prepared by LBNL, but not for the 31 colorants that were characterized in PVDF films prepared by one of LBNL's industrial partners.

`output.tabular.report=TRUE` Whether to generate a tabular report detailing each solution.
Example: `output.tabular.report=FALSE` prevents the generation of a tabular report.

`return.solutions=FALSE` Whether to return the `design()` solutions to R at the conclusion of the function call. This is not necessary if tabular and/or graphic reports are generated, but may be useful if `design()` is called within another algorithm. For example, the R code `x <- design(`*`arg1=val1`*`,` *`arg2=val2`*`, return.solutions=TRUE,` ...`)` would assign the solutions to the variable `x`. The default value of FALSE causes no value to be returned. textitExample: `return.solutions=TRUE` causes `design()` to return its solutions to R at the conclusion of the function call.

`confirm.parameters=TRUE` Whether to display and confirm the coating system parameters [i.e., the values of the arguments to `design()`] before designing a topcoat. Confirmation is useful when running Pinwheel interactively, but should be turned off for unattended operation.

Example: `confirm.parameters=FALSE` turns off parameter confirmation.

3.2.3 `design()` call examples

1. Using default physical and process parameters.

```
design(
    target="emerald-green",
    topcoat.colorants=list("U08, G", "W", "Y01, Y10, Y14"),
)
```

   This minimalist call designs a system that has the substrate `"opaque white paint"`, no basecoat, and a topcoat of thickness 25 μm that contains three colorants: the first, either cobalt chromite blue U08 or a member of the green color family (G); the second, a member of the white color family (W); and the third, either iron oxide yellow Y01, nickel titanate yellow Y10, or diarylide yellow Y14. The colorants will be simplified by eliminating four redundant colorants: titanium dioxide whites W01, W02, and W04 (similar to titanium dioxide white W03); and phthalo green G11 (similar to phthalo green G10). It will try to match the target visible spectral reflectance specified by the file `Pinwheel/Target Reflectances/emerald-green.txt` to within an RMS absolute difference of 0.05. Each colorant will be considered at volume concentrations of 0%, 1%, 2%, 3%, 5%, 10%, 15%, 20%, 25%, and 30%. All solutions will be retained, and both tabular and graphical reports will be generated. The input parameters will be confirmed before the design begins, and many details of the design process will be charted on-screen. No value will be returned as a result of this call.

2. Changing physical parameters.

```
design(
    target="emerald-green",
    topcoat.colorants=list("U08, G", "W", "Y01, Y10, Y14"),
    exclude="organic, hot",
    topcoat.thickness=20,
    basecoat.colorants=list("Y01"=0.15, "P04"=0.05),
    basecoat.thickness=15,
    substrate="treated zincalume"
)
```

This call reduces the topcoat thickness to 20 μm; changes the substrate to treated zincalume; adds a 15-μm basecoat composed of 15% iron oxide yellow Y01 and 5% interference gold pearlescent P04; and excludes from consideration in the topcoat any organic or hot colorants.

3. Changing physical and process parameters.

```
design(
    target="emerald-green",
    topcoat.colorants=list("U08, G", "W", "Y01, Y10, Y14"),
    topcoat.thickness=20,
    basecoat.colorants=list("Y01"=0.15, "P04"=0.05),
    basecoat.thickness=15,
    substrate="treated zincalume",
    concentration.levels=c(0,1,2,3,4,5,6,7,8,9,10)/100,
    match.metric="max.absolute",
    match.tolerance=0.03,
    verbosity="low"
)
```

This call uses topcoat colorant concentration levels of 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, and 10%, and accepts trial mixtures whose visible spectral reflectances matches that of the target to within a maximum absolute difference of 0.03. It does not generate any on-screen charts during the design processes, greatly reducing the time needed to complete the design. This call reduces the topcoat thickness to 20 μm, changes the substrate to treated zincalume, and adds a 15-μm basecoat composed of 15% iron oxide yellow Y01 and 5% interference gold pearlescent P04.

4. Calibrating `design()` using a mixture of known composition.

```
design(
    target.mixture="U14+Y01[1:1]",
    target.mixture.background="white",
```

```
        topcoat.colorants=list("U14", "Y01"),
        topcoat.thickness=22,
        substrate="opaque white paint",
        match.tolerance=0.04
    )
```

This call tests `design()` on an LBNL-prepared mixture of two paints—one colored with dioxazine purple U14, and the other colored with iron oxide yellow Y01. The goal is to find among the solutions one in which the concentrations of colorants U14 and Y01 approximately match their known concentrations in the mixture (which is reported).

3.2.4 Preparing design code

While a `design()` call may be entered at the R prompt, it is typically easier to compose the call in a text editor, such as EditPad Pro (`http://editpadpro.com`) or Notepad, and save it to the folder `Pinwheel/User Code`. It is helpful to give your file a meaningful name of the form *design*`.R`. For example, a call that will design an emerald green coated surface might be saved as `Pinwheel/User Code/emerald-green-design01.R`.

3.3 Launching Pinwheel

Open (double-click) the shortcut `Pinwheel/Launch Pinwheel` to launch R and load Pinwheel into the R environment. The startup process may take a few minutes as Pinwheel loads the colorant data and makes a series of one-time calculations.

3.4 Executing design code

Once Pinwheel has finished loading, it will display the message '`PINWHEEL is ready`'. Load and execute your design code either by entering

```
source("User Code/design.R")
```

at the R prompt or by using the menu command `File>Source R Code...` to select your code file. The Windows keyboard shortcut for the latter command is `ALT-f s`.

The `design()` call typically creates multiple windows within R. These windows, which tend to overlap, can be neatly placed side by side using the menu command `Windows>Tile` or keyboard shortcut `ALT-w t` (Figure 1). Note that a screen resolution of 1152 × 864 pixels or greater is required for proper rendering of the on-screen graphics.

When done, exit R by entering quit() or using the menu command `File>Exit`.

3.5 Reviewing solutions

Unless configured otherwise, `design()` will generate both tabular and graphical solution reports.

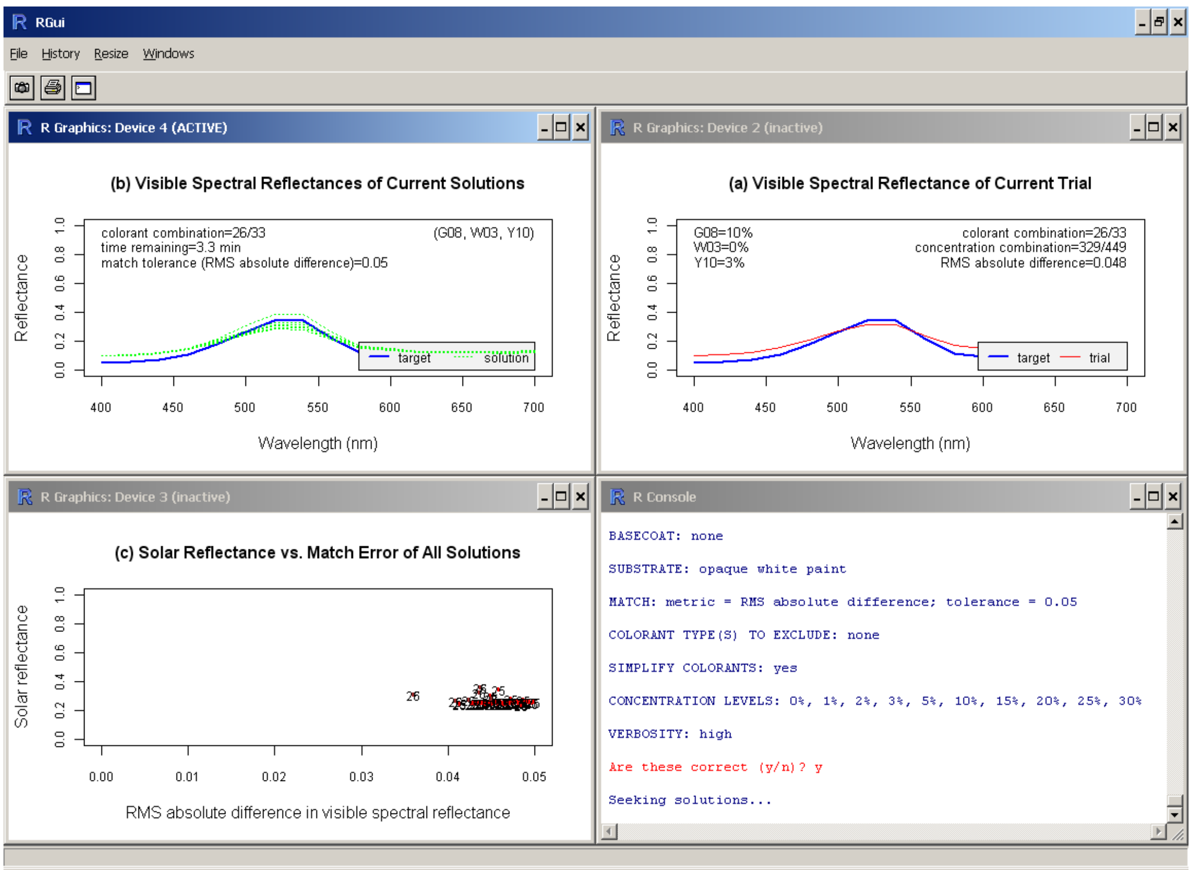


Figure 1: Pinwheel windows neatly tiled using the R menu command `Windows>Tile`.

The tabular report is a tab-delimited text file written to `Pinwheel/Reports/`*`target`*`-tabular-report.txt`. It will not load properly in Excel (at least not in Excel 2000) because the 441-element solar spectral reflectances in the report require more than 256 columns. However, you can view it in any text editor, or parse it with any programming language.

The graphical report is a PDF file written to `Pinwheel/Reports/`*`target`*`-graphical-report.pdf`. It shows one solution per page in order of descending solar reflectance (Figure 2). It is best to view this file in a standalone version of Acrobat or Acrobat Reader, rather than with the Acrobat Reader browser plug-in. Set the View options to Fit in Window and Single Page, then use the Page Up/Down keys to flip through the solutions.

4 Expandability

Substrate solar spectral reflectances files named *`substrate`*`.txt` can be added to the folder `Pinwheel/Substrate Reflectances`. Quit and restart Pinwheel after adding a new substrate reflectance file.

References

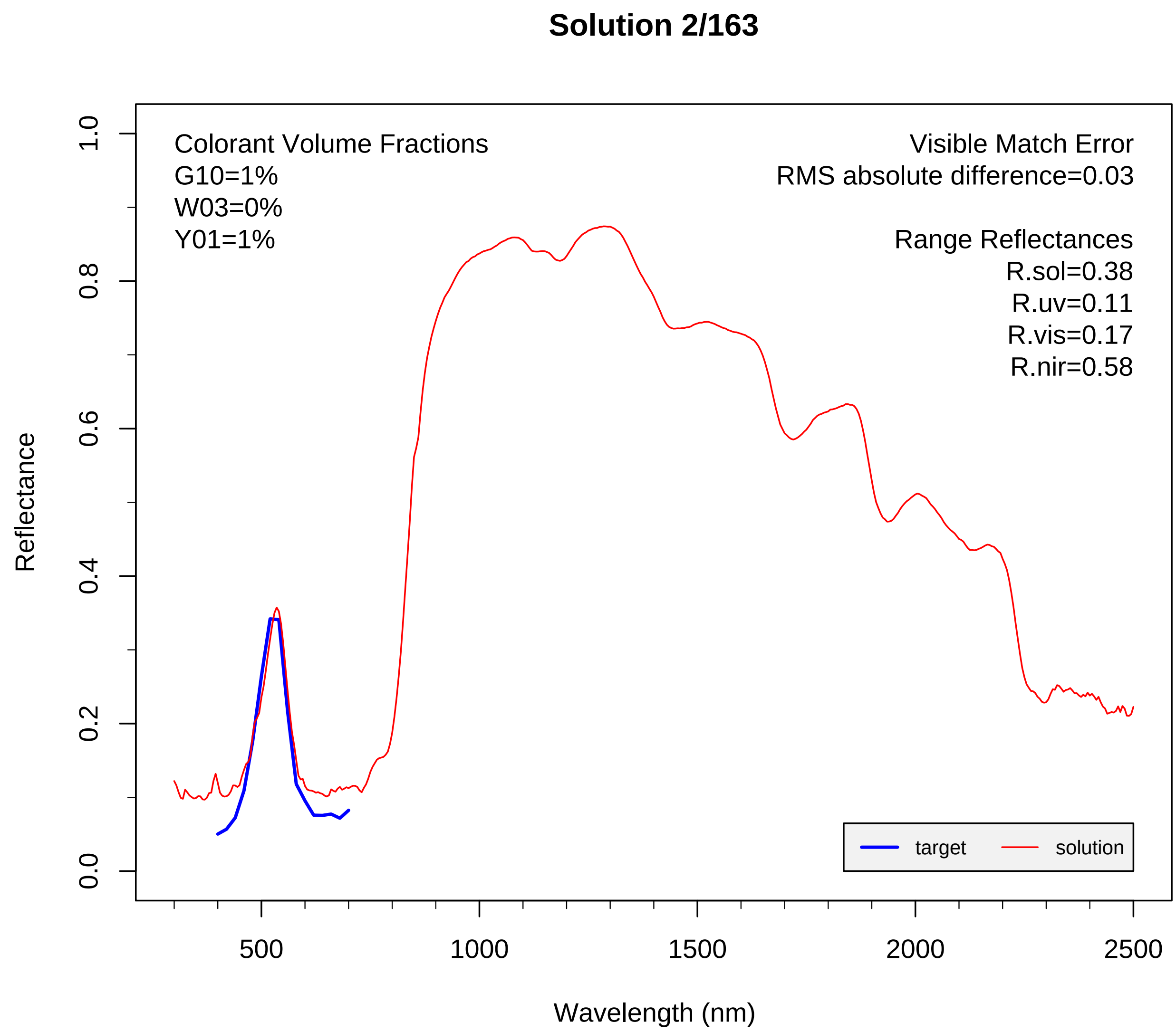
[1] Ronnen Levinson, Paul Berdahl, and Hashem Akbari. Lawrence Berkeley National Laboratory Pigment Database. `http://CoolColors.LBL.gov/LBNL-Pigment-Database/database.html`.

[2] Ronnen Levinson, Paul Berdahl, and Hashem Akbari. Solar spectral optical properties of pigments, Part I: model for deriving scattering and absorption coefficients from transmittance and reflectance measurements. *Solar Energy Materials & Solar Cells*, (in press), 2005.

[3] Ronnen Levinson, Paul Berdahl, and Hashem Akbari. Solar spectral optical properties of pigments, Part II: survey of common colorants. *Solar Energy Materials & Solar Cells*, (in press), 2005.

A Colorants

Tables A-1 through A-7 list the 87 colorants grouped into the white, black/brown, blue/purple, green, red/orange, yellow, and pearlescent families. The colorants are fully described in LBNL's pigment database [1] and articles [2, 3].



TARGET: emerald−green

TOPCOAT: thickness = 25 μm; colorants = G10 (1%), W03 (0%), Y01 (1%)

BASECOAT: none

SUBSTRATE: opaque white paint

G10 = Chlorinated Copper Phthalocyanine (PG 7) {phthalocyanine green in paint Phthalo Green (i)}
W03 = Titanium Dioxide (PW 6) {titanium dioxide white in paint Titanium White (i)}
Y01 = Synthetic Hydrated Iron Oxide (PY 42) {iron oxide yellow in paint Yellow Oxide}

Figure 2: A solution shown in a graphical report.

Table A-1: White colorants

code	description
W01	Ishihara Tipaque CR-90 (PW 6) {titanium dioxide white in paint Inorganic Oxide White}
W02	Titanium Dioxide (PW 6) {titanium dioxide white in paint Titanium Dioxide White}
W03	Titanium Dioxide (PW 6) {titanium dioxide white in paint Titanium White (i)}
W04	Titanium Dioxide (PW 6) {titanium dioxide white in paint Titanium White (ii)}

Table A-2: Black/brown colorants

code	description
B01	Amorphous Carbon Black (PBk 7) {carbon black in paint Carbon Black}
B02	Amorphous Charred-Bone Carbon (PBk 9) {carbon black in paint Ivory Black}
B03	Shepherd Black 1D (PBk 28) {other non-selective black in paint Copper Chromite Black}
B04	Synthetic Black Iron Oxide (PBk 11) {other non-selective black in paint Mars Black}
B05	Shepherd Black 376 (PBk 30) {chromium iron oxide selective black in paint Chrome Iron Nickel Black Spinel}
B06	Shepherd Black 10C909 (PG 17) {chromium iron oxide selective black in paint Chromium Green-Black Hematite}
B07	Ferro Black V-797 {chromium iron oxide selective black in paint Chromium Green-Black Hematite Modified (i)}
B08	Ferro Black V-799 {chromium iron oxide selective black in paint Chromium Green-Black Hematite Modified (ii)}
B09	Ferro Black V-799 (PBr 29) {chromium iron oxide selective black in paint Chromium Green-Black Hematite Modified (iii)}
B10	Shepherd Black 411 (PBr 29) {chromium iron oxide selective black in paint Chromium Iron Oxide (i)}
B11	Shepherd Black 411 (PBr 29) {chromium iron oxide selective black in paint Chromium Iron Oxide (ii)}
B12	BASF Paliogen Black L0086 (PB 32) {organic selective black in paint Perylene Black}
B13	Calcined Natural Iron Oxide (PBr 7) {iron oxide brown in paint Burnt Sienna}
B14	Natural Iron Oxide (PBr 7) {iron oxide brown in paint Raw Sienna}
B15	Natural Iron Oxide w/Manganese (PBr 7) {iron oxide brown in paint Raw Umber}
B16	Shepherd Brown 156 (PBk 12) {other brown in paint Iron Titanium Brown Spinel (i)}
B17	Shepherd Brown 8 (PBk 12) {other brown in paint Iron Titanium Brown Spinel (ii)}
B18	Shepherd Golden Brown 19 (PBk 12) {other brown in paint Iron Titanium Brown Spinel (iii)}
B19	Ferro Chestnut Brown V-10364 (PY 164) {other brown in paint Manganese Antimony Titanium Buff Rutile}
B20	Shepherd Brown 12 (PBr 33) {other brown in paint Zinc Iron Chromite Brown Spinel (i)}
B21	Shepherd Brown 157 (PBr 33) {other brown in paint Zinc Iron Chromite Brown Spinel (ii)}

Table A-3: Blue/purple colorants

code	description
U01	Ferro Blue V-9250 (PB 28) {cobalt aluminate blue in paint Cobalt Aluminate Blue Spinel (i)}
U02	Shepherd Blue 385 (PB 28) {cobalt aluminate blue in paint Cobalt Aluminate Blue Spinel (ii)}
U03	Shepherd Blue 424 (PB 28) {cobalt aluminate blue in paint Cobalt Aluminate Blue Spinel (iii)}
U04	Shepherd Artic Blue 3A (PB 28) {cobalt aluminate blue in paint Cobalt Aluminum Blue}
U05	Oxides of Cobalt and Aluminum (PB 28) {cobalt aluminate blue in paint Cobalt Blue}
U06	Cobalt Chromite (PB 36) {cobalt chromite blue in paint Cerulean Blue}
U07	Shepherd Blue 190-A (PB 36) {cobalt chromite blue in paint Cobalt Chromite Blue}
U08	Ferro Blue V-9248 (PB 36) {cobalt chromite blue in paint Cobalt Chromite Blue-Green Spinel (i)}
U09	Shepherd Blue 212 (PB 36) {cobalt chromite blue in paint Cobalt Chromite Blue-Green Spinel (ii)}
U10	Milori Blue (PB 27) {iron blue in paint Prussian Blue}
U11	Complex Silicate of Na and Al with S (PB 29) {ultramarine blue in paint French Ultramarine Blue}
U12	Copper Phthalocyanine (PB 15) {phthalocyanine blue in paint Phthalo Blue (i)}
U13	Toyo Lionel BF-28201 (PB 15) {phthalocyanine blue in paint Phthalo Blue (ii)}
U14	Carbazole Dioxazine (PV 23 RS) {dioxazine purple in paint Dioxazine Purple}

Table A-4: Green colorants

code	description
G01	Bayer GN-M Chrome Oxide Green (PG 17) {chromium oxide green in paint Chrome Green}
G02	Anhydrous Chromium Sesquioxide (PG 17) {chromium oxide green in paint Chromium Oxide Green}
G03	Ferro Camouflage Green V-12650 {modified chromium oxide green in paint Chromium Green-Black Modified}
G04	Shepherd Green 187B (PB 36) {cobalt chromite green in paint Cobalt Chromite Blue-Green Spinel (iii)}
G05	Ferro Camouflage Green V-12600 (PG 26) {cobalt chromite green in paint Cobalt Chromite Green Spinel (i)}
G06	Shepherd Green 179 (PG 26) {cobalt chromite green in paint Cobalt Chromite Green Spinel (ii)}
G07	Light Green Oxide (PG 50) {cobalt titanate green in paint Cobalt Teal}
G08	Shepherd Green 223 (PG 50) {cobalt titanate green in paint Cobalt Titanate Green Spinel (i)}
G09	Shepherd Sherwood Green 5 (PG 50) {cobalt titanate green in paint Cobalt Titanate Green Spinel (ii)}
G10	Chlorinated Copper Phthalocyanine (PG 7) {phthalocyanine green in paint Phthalo Green (i)}
G11	Clariant GT-674-D Endurophthal Green B (PG 7) {phthalocyanine green in paint Phthalo Green (ii)}

Table A-5: Red/orange colorants

code	description
R01	Bayer Bayferrox 6622 Iron Oxide (PR 101) {iron oxide red in paint Red Iron Oxide (i)}
R02	Elementis RO-3097 (PR 101) {iron oxide red in paint Red Iron Oxide (ii)}
R03	Ferro Red V-13810 (PR 101) {iron oxide red in paint Red Iron Oxide (iii)}
R04	Synthetic Red Iron Oxide (PR 101) {iron oxide red in paint Red Oxide}
R05	Cadmium Orange (PO 20) {cadmium orange in paint Cadmium Orange}
R06	Quinacridone (PR 206) {organic red in paint Acra Burnt Orange}
R07	Quinacridone Red Gamma (PR 209) {organic red in paint Acra Red}
R08	Ciba Geigy Monastral NRT-742-D Scarlet (PV 19) {organic red in paint Monastral Red}
R09	Naphthol AS-OL (PR 9) {organic red in paint Naphthol Red Light}

Table A-6: Yellow colorants

code	description
Y01	Synthetic Hydrated Iron Oxide (PY 42) {iron oxide yellow in paint Yellow Oxide}
Y02	Cadmium Yellow (PY 35) {cadmium yellow in paint Cadmium Yellow Light}
Y03	Dominion Color Krolor KY-781-D (PY 34) {chrome yellow in paint Chrome Yellow}
Y04	Ferro Autumn Gold V-10415 (PBr 24) {chrome titanate yellow in paint Chrome Antimony Titanium Buff Rutile (i)}
Y05	Ferro Bright Golden Yellow V-10411 (PBr 24) {chrome titanate yellow in paint Chrome Antimony Titanium Buff Rutile (ii)}
Y06	Shepherd Yellow 193 (PBr 24) {chrome titanate yellow in paint Chrome Antimony Titanium Buff Rutile (iii)}
Y07	Ishihara Tipaque TY-300 (PBr 24) {chrome titanate yellow in paint Chrome Titanate Yellow}
Y08	Ferro Yellow V-9415 (PY 42) {nickel titanate yellow in paint Nickel Antimony Titanium Yellow Rutile (i)}
Y09	Ferro Yellow V-9416 (PY 53) {nickel titanate yellow in paint Nickel Antimony Titanium Yellow Rutile (ii)}
Y10	Shepherd Yellow 195 (PY 53) {nickel titanate yellow in paint Nickel Antimony Titanium Yellow Rutile (iii)}
Y11	Ishihara Tipaque TY-50 (PY 53) {nickel titanate yellow in paint Nickel Titanate Yellow}
Y12	Strontium Chromate Yellow + Titanium Dioxide {strontium chromate yellow + titanium dioxide in paint Primer}
Y13	Arylide Yellow 5GX (PY 74 LF) {Hansa yellow in paint Yellow Medium Azo}
Y14	Diarylide Yellow (PY 83 HR70) {diarylide yellow in paint Yellow Orange Azo}

Table A-7: Pearlescent colorants

code	description
P01	Engelhard Exterior Mearlin 239X Bright Gold {mica + titanium dioxide in paint Bright Gold (Pearlescent)}
P02	Engelhard Exterior Mearlin 139X Bright White {mica + titanium dioxide in paint Bright White (Pearlescent)}
P03	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Blue}
P04	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Gold}
P05	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Green}
P06	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Orange}
P07	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Red}
P08	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Interference Violet}
P09	Mica Coated w/Titanium Dioxide {mica + titanium dioxide in paint Iridescent White}
P10	Engelhard Exterior Mearlin 2329X Brass {mica + titanium dioxide + iron oxide in paint Brass (Pearlescent)}
P11	Engelhard Exterior Mearlin 249X Bright Bronze {mica + titanium dioxide + iron oxide in paint Bright Bronze (Pearlescent)}
P12	Engelhard Exterior Mearlin 349X Bright Copper {mica + titanium dioxide + iron oxide in paint Bright Copper (Pearlescent)}
P13	Mica Coated w/Titanium Dioxide and Iron Oxide {mica + titanium dioxide + iron oxide in paint Rich Bronze}
P14	Engelhard Exterior Mearlin 449X Russet {mica + titanium dioxide + iron oxide in paint Russet (Pearlescent)}