White Paper #4

Level: Intermediate

Date: Dec 2004

Color Management - Conceptual Overview, Evolution, Structure & Color Rendering Options

Color Management
(digital imaging)

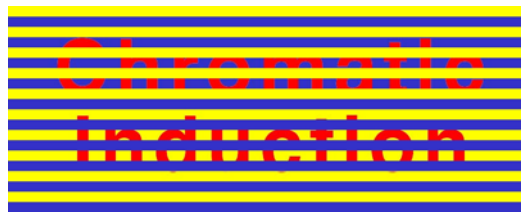
communication of the associated data required for unambiguous interpretation of color content data, and application of color data conversions as required to produce the intended reproductions

Note 1: Color content may consist of text, line art, graphics, and pictorial images, in raster or vector form, all of which may be color managed.

Note 2: Color management considers the characteristics of input and output devices in determining color data conversions for these devices.

Evolution of Understanding

- Digital color mode
  - RGB, CMYK, YCC, etc. (typically device values)
- Colorimetry
  - Works for fixed output device (TV model with source color rendering)
  - Device independent image concept?
- Appearance
  - Viewing conditions affect desired colorimetry
    - But HVS not well understood - research topic
    - No published models available that describe appearance robustly



- Image state and reference medium
  - Desired image appearance depends on output medium
    - Color rendering, as opposed to gamut mapping
  - Need to know image state to unambiguously interpret color data
    - Implicit in traditional photography & graphic arts

Color Management Tasks

- Fixed output device characteristics
  - Viewing conditions and mode, dynamic range and color gamut, medium (substrate & surface)
  - Ship desired image colorimetry to output device
    - Generally, using some device-ready color encoding
- Variable output device characteristics
  - Optimal image appearance may be device dependent
  - Cross device/media color transforms include color rendering

Color Appearance Models

- Appearance models are useful for imaging applications.
  - Chromatic adaptation; spaces for gamut mapping; dependence of colorfulness on absolute luminance; error minimization
- However, since the cross media objective is often NOT to reproduce appearance, color rendering approaches that independently use appearance models to deal with viewing condition differences, and gamut mapping to deal with gamut differences, may not be optimal.
  - The primary color rendering job may be to alter appearance to produce a pleasing reproduction on different media.
  - The changes in colorimetry driven by the appearance model may be counter to those driven by gamut mapping, making independent optimization ineffective.
  - We don’t have appearance models that robustly describe appearance, particularly for images.

Reproduction Models

- Simultaneously consider viewing condition effects, media limitations, user preferences, and potentially image characteristics in developing color rendering transforms
- Can be based on analysis of what is done to image colorimetry by experts in achieving excellent cross media reproductions
- At least partially empirical
  - But so are appearance models and gamut mapping
  - Can add components based on HVS understanding, as it increases
  - Simultaneous optimization is the key

Color Imaging Architecture

- Unambiguous exchange of color image data
  - ISO 22028-1 specifies:
    - Color space encoding, viewing conditions, image state and reference medium
- Organized application of color rendering
  - Proprietary or standardized
- Implementation mechanisms:
    - Produce standard color encodings - encodings of the colorimetry of an image on a reference medium (including viewing conditions).
      - Writers/readers color render to/from standard color encoding
    - Attach color profiles - provide transforms to be applied to the encoded image data to produce image colorimetry in a Profile Connection Space (PCS) describing a specified medium (including viewing conditions).
      - Appropriate transforms to/from PCS are linked by Color Management Module (CMM)

Color Rendering Options

- Intermediate reproduction description
  - Provide input-side color re-rendering to some well-defined real or virtual reference medium
  - Exchange image data
  - Output-side color re-rendering is performed from reference medium to actual output medium
- Deferred color rendering
  - Encode source colorimetry with medium characteristics and viewing conditions information
  - Make color re-rendering capability available on output
  - When final output is selected, perform color re-rendering directly from source to actual output

Early and Late Binding

- Terms used in graphic arts to designate when in the workflow the conversion/separation to CMYK takes place
  - Usually start with an intermediate reproduction description created on a computer or produced by a capture device (typically RGB), but can capture directly to CMYK
- Early binding produces an intermediate reproduction description, based on some assumed output device
  - This (second) intermediate image may need to be color re-rendered to different output devices
  - It is helpful if early binding images are in some “standard” CMYK
- Late binding defers conversion/separation to device values until the actual output device is known
  - Multiple files may be produced for multiple devices

Intermediate Reproduction Description

- Advantages
  - More consistent output than with scene-referred exchange
    - The desired artistic intent can be communicated in the intermediate image
  - Proven in practice by photographers & graphic artists
  - Commonly used bridging transforms for color re-rendering can be highly tuned and made widely available
  - Requires less sophisticated processing capability at output
- Disadvantages
  - Color re-rendering to actual output may be necessary
    - May not produce optimal results, particularly if intermediate image reference medium is very different from actual output medium
  - Less output-side control of scene-to-picture color rendering
  - In the early binding case, assumptions that device values and GCR will or should be maintained when re-purposing may be incorrect

Deferred Color Rendering

- Advantages
  - Increases output-side control of color rendering and re-rendering
  - The color rendering or re-rendering is direct to the actual output
    - No worries that intermediate image is too different from actual output
  - In the late binding case, decisions involving device value selection (spot color substitution and solids) are deferred until actual device is known
- Disadvantages
  - Less consistent output due to greater color rendering freedom
    - Need mechanism for preview/proof of color rendering
    - Image creator's artistic intent may not be maintained
    - Image data after processing for output is device specific and can cause difficulties if fed back into open workflows
  - Capability to perform color rendering or re-rendering from source must be available at output
  - May require more hand tuning, if more aggressive automated color rendering and re-rendering algorithms do not produce the desired result

Current Status: Color Rendering (scene to picture)

- Intermediate reproduction description approach dominates today
  - Standard output-referred exchange
- Manually guided deferred color rendering (e.g. camera raw) is becoming more popular
  - Although color rendering is typically to a standard output-referred color image encoding for exchange
    - Digital negative and positive concepts

Current Status: Color Re-rendering (early and late binding)

- Both early and late binding are used
  - But the image state is not always communicated
- Both profile-based (perceptual intent) and CMM-based MRC+BPC (media relative colorimetric plus black point compensation) color re-rendering are used
  - ICC v2 issues limit perceptual intent performance and reliability
    - ICC v4 addresses these, but profiles are not available
      - Not yet proven to users
  - MRC+BPC deals with first order dependency of desired appearance on media characteristics, but is not optimal
    - Advanced CMM-based color re-rendering not yet standard
      - Color re-rendering algorithms are proprietary, and are rapidly evolving
      - Difficult transforms frequently require hand-tuning for optimization

Current Status: Implementations

- **sRGB uses intermediate reproduction description based on reference CRT display and viewing conditions**
  - Quality of implementations continues to increase as understanding and color rendering capability increase.
- **ICC profiles offer several rendering intents, enabling both color rendering options**
  - Perceptual intent uses reference print intermediate
  - Measurement based colorimetric intents enable deferred color rendering by smart (proprietary) CMM, and also colorimetric proofing
    - Limited standardized color rendering capability in CMM (MRC+BPC)
  - Saturation intent enables proprietary workflows
- **Both sRGB and ICC color management are evolving as understanding increases**

ICC version 2 Issues

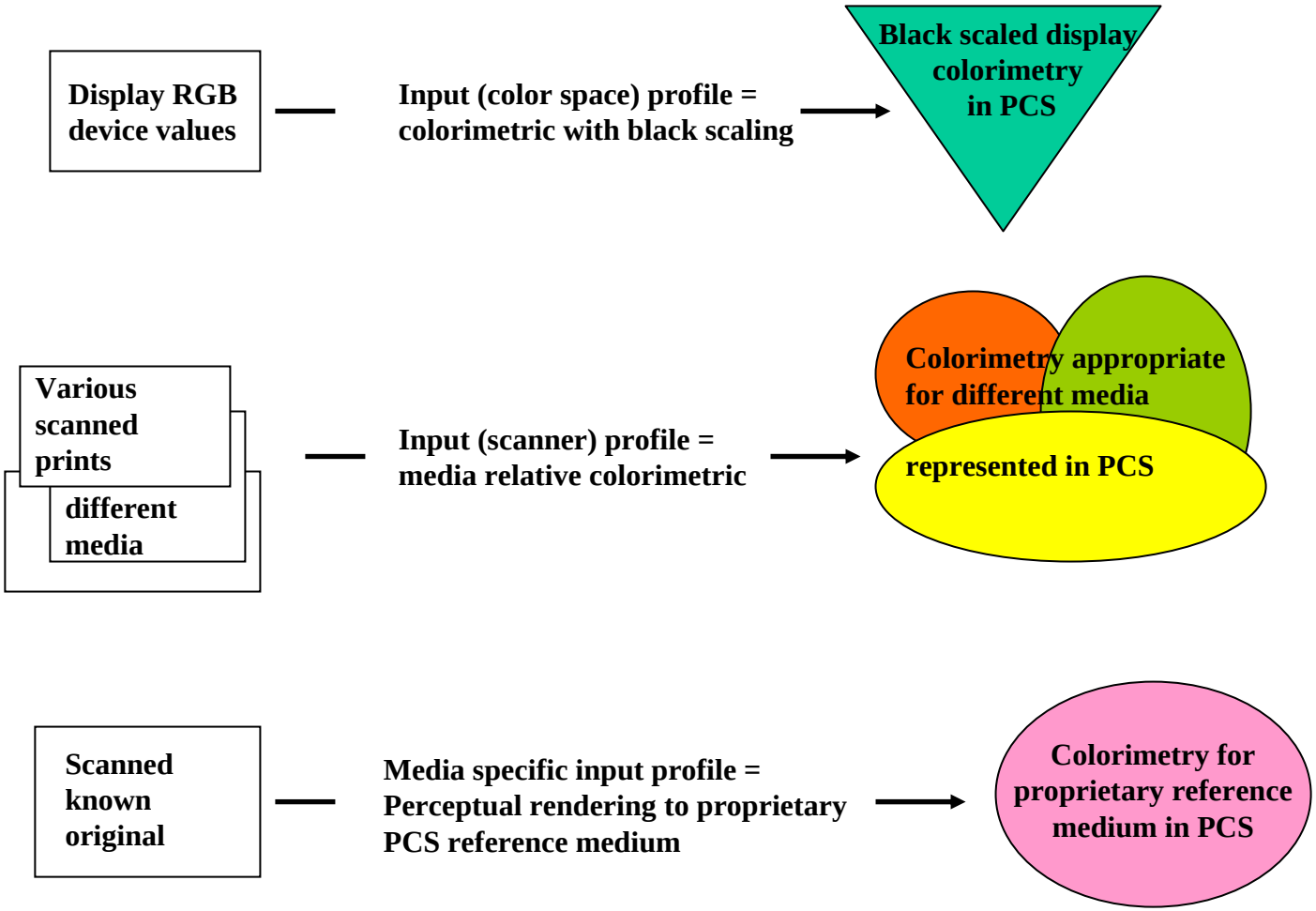
- Ambiguous media white point chromatic adaptation state
- Ambiguous input side color re-rendering
- Colorimetric intents not required to be measurement based
  - Measurement methods not always well defined
- No standard perceptual intent reference medium
- Insufficient flexibility in transform forms

Capability limitations and interoperability problems result

v2 Input-side Color Re-rendering

- At least three possibilities:
  - unidentified in profile
    - Colorimetric with no black scaling
    - Colorimetric with black scaling
    - Perceptual
      - to some arbitrary reference medium
- Depending on the source image, and the input profile re-rendering, the PCS colorimetry could be appropriate for a variety of media and viewing conditions

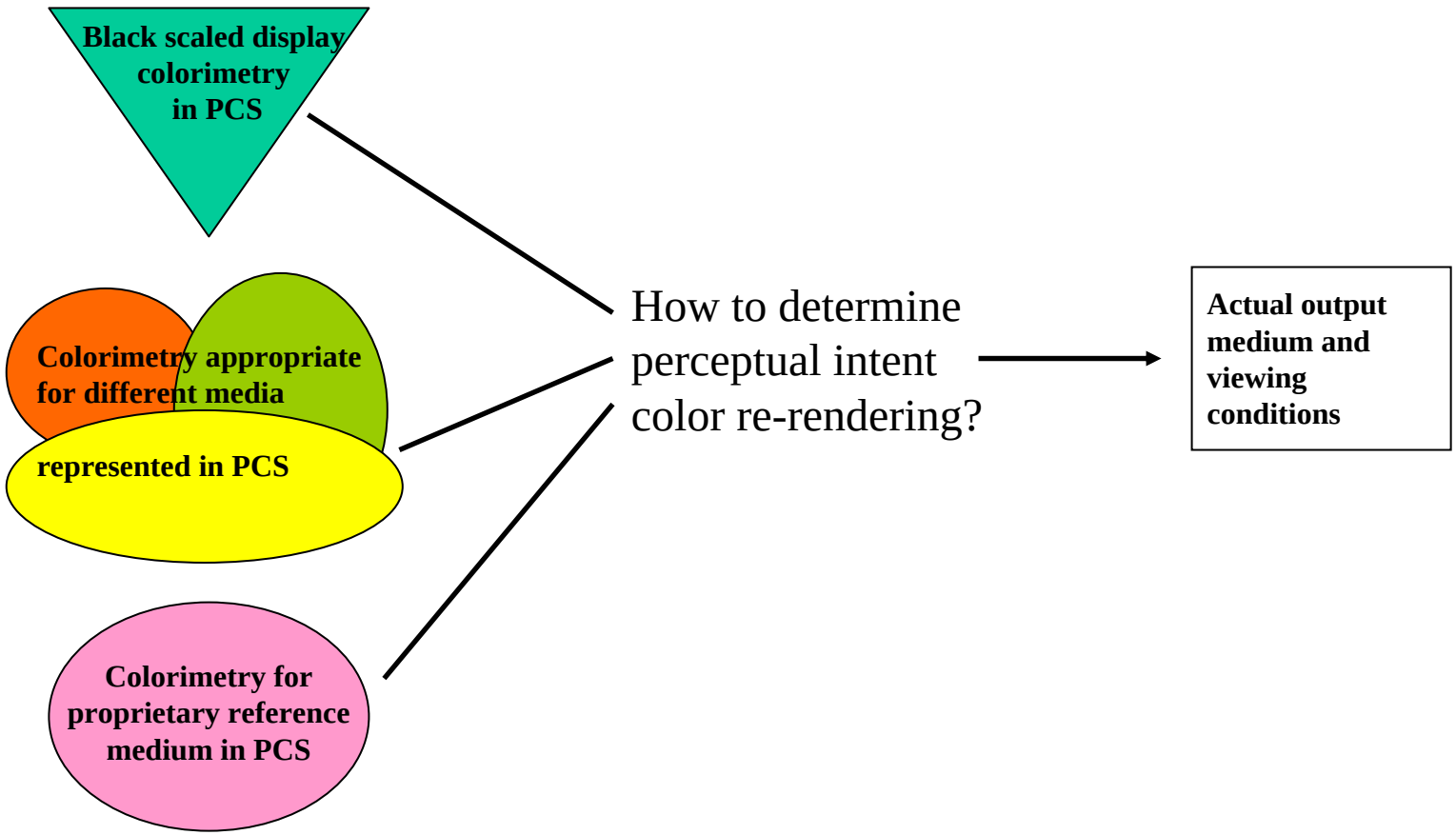
v2 Input Color Re-rendering Possibilities



v2 Output-side Perceptual Intent Dilemma

- The perceptual intent of a v2 output profile is supposed to perform a pleasing re-rendering of the PCS image colorimetry to the actual output medium and viewing conditions
- ***But the output profile creator has no knowledge of the medium and viewing conditions for which the PCS colorimetry is appropriate!***
  - It is impossible to create an optimal perceptual rendering without this knowledge
  - Precludes optimal cross-vendor interoperability

The output profile knows the end result, but there are many possible starting points in the PCS



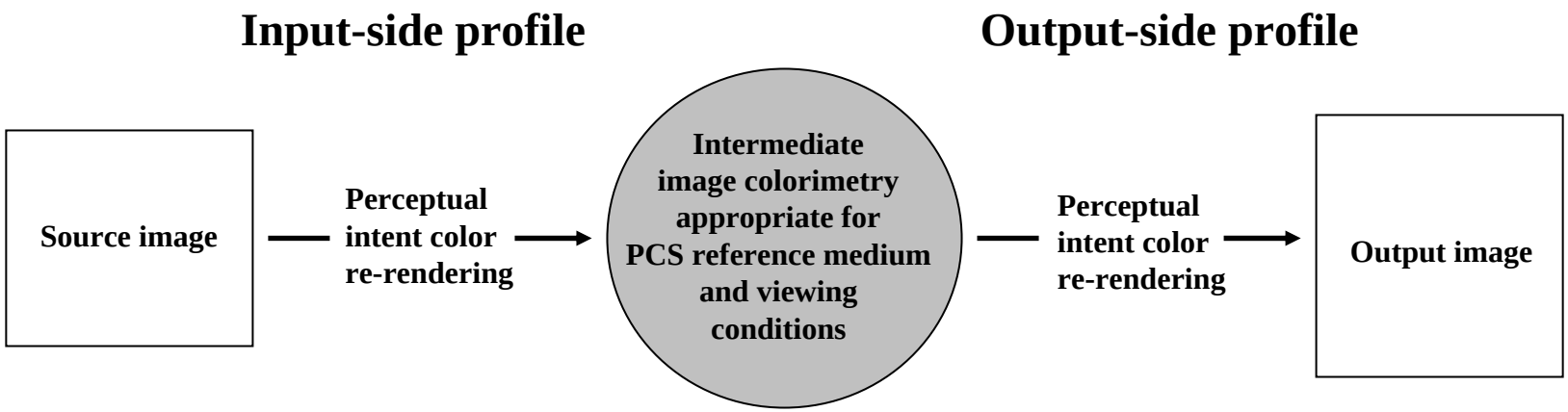
v2 Colorimetric Rendering Intent Issues

- Source colorimetry may be black scaled or color re-rendered to a proprietary reference medium, to enable improved single vendor interoperability
- Because PCS colorimetry may not be accurate relative to the original, v2 profiles will not support advanced CMM color rendering
  - The CMM cannot rely on the source colorimetry, as represented in the PCS
- Other issues exist with v2 profiles because of specification ambiguity and incorrect construction

The ICC v4 Solution

- **Colorimetric rendering intents are measurement based**
  - Can be relied on for proofing
  - Provide accurate colorimetry for CMM color re-rendering
- **Specification ambiguities are resolved and text clarified to reduce incorrect implementations**
- **Well-defined reference medium for perceptual intent insures cross-vendor interoperability**
  - But need to formalize reference medium gamut specification
- **Greatly increased transform capability through extended forms**
  - lutAtoBtype

The ICC v4 Perceptual Path



CMM connects profiles with similar PCS gamuts

- **minimal gamut mapping needed because image colorimetry in PCS is matched for input and output**
- **source and output media (and viewing condition) differences are dealt with in perceptual intent color maps**

Perceptual Transform Includes

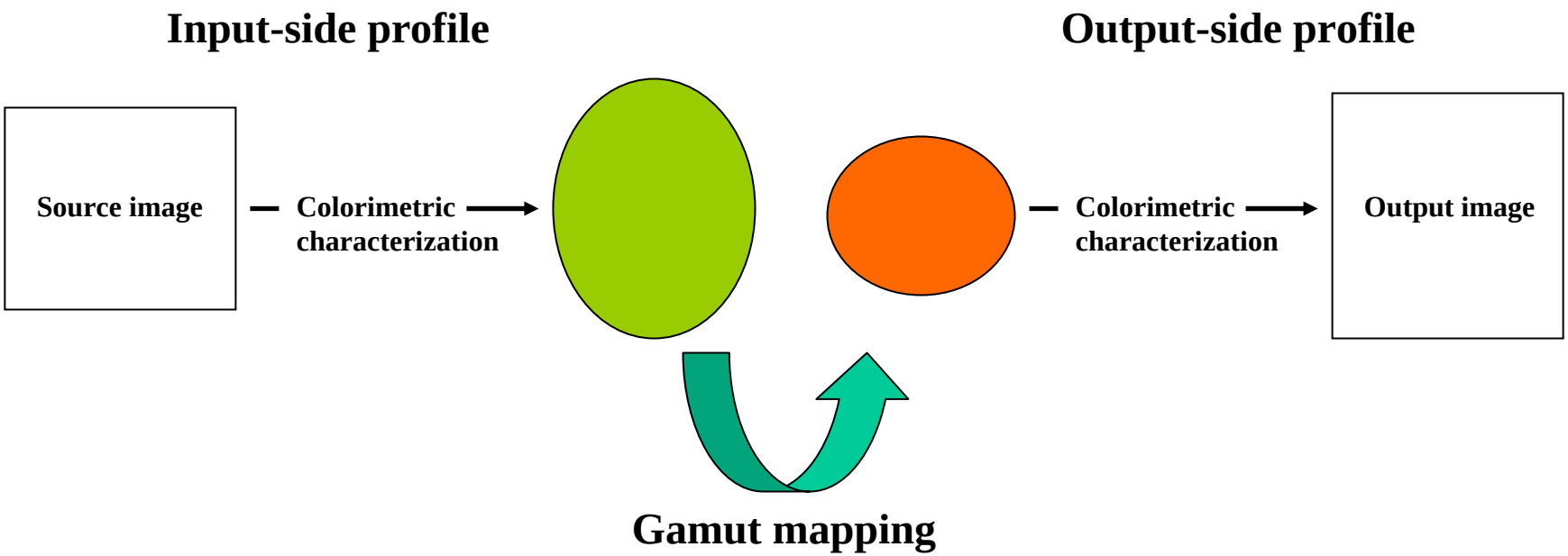
- Device value to colorimetry transform
- Color re-rendering to/from reference medium in PCS, includes:
  - Consideration of viewing condition differences
    - Appearance effects
  - Consideration of media characteristics & image state
  - Consideration of color rendering preferences
    - Preferred reproduction

CMM just connects profiles together to create device-to-device transform

Perceptual Transform Characteristics

- **Useful for general image reproduction across devices/media**
- **Color re-rendering typically proprietary, so profiles from different sources may produce different “looks”.**
  - Users select profiles based on color re-rendering preferences
    - However, this is currently difficult due to v2 issues and lack of coordinated color management (OS, App, Driver/RIP).
  - As differences between actual and reference media decrease, perceptual and colorimetric intents should converge.
- **Currently, users are cautious about the perceptual intent because of v2 experience**
  - Need availability of good v4 profiles and coordinated color management to restore confidence.

The ICC v4 Colorimetric Path



- no change in colorimetry within gamut intersection
- colors out of source image gamut not produced in output image
- colors in source image that are out of output image gamut are clipped

Colorimetric Transform Includes

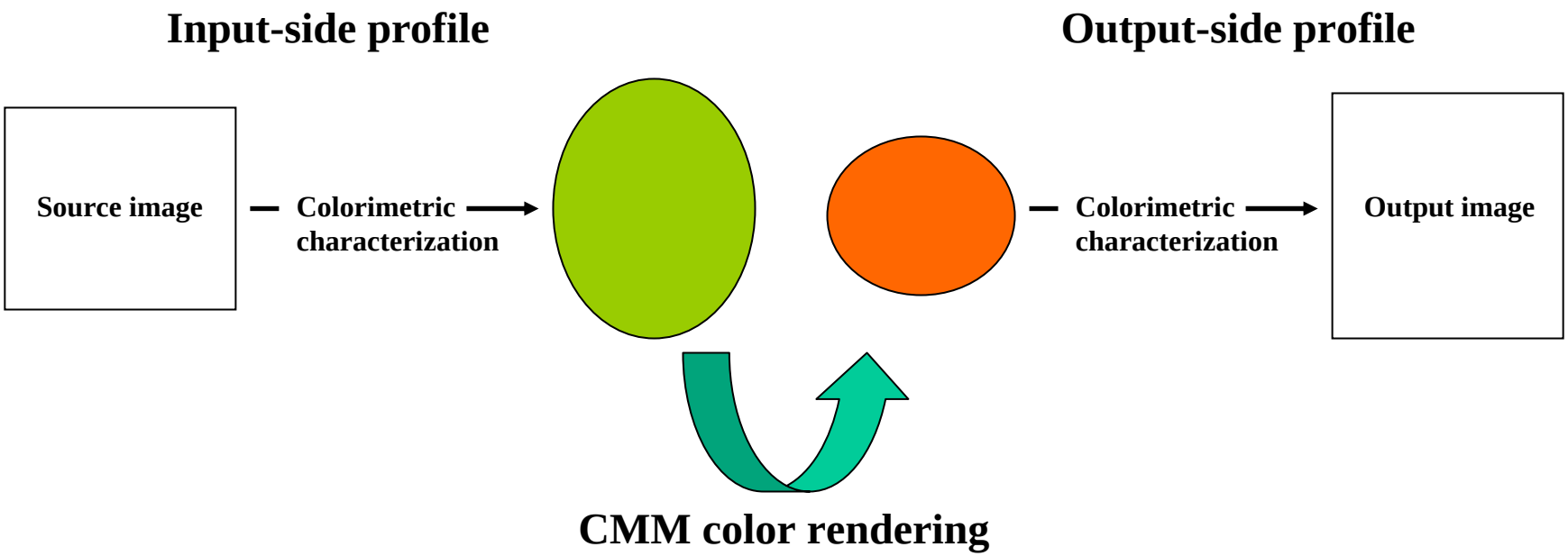
- Device value to colorimetry transform
  - Based on measurements made using standard methods
- Chromatic adaptation to/from D50 PCS white point
  - Allows gamut mapping to be performed directly, if desired
    - In proofing situations, gamut mapping is best minimized by choice of proofing media
  - Chromatic adaptation matrix is included in profile, and therefore invertable if CMM-based chromatic adaptation is desired

Does not include other appearance transforms, to avoid unnecessary color appearance model complexity, instability, and other issues mentioned earlier.

Colorimetric Transform Characteristics

- **Useful for preview/proofing applications, and in support of CMM color rendering.**
- **Media Relative Colorimetric + Black Point Compensation (MRC+BPC) provides standard baseline CMM color rendering that is adequate when media substrate and gamut shape differences are not large.**
  - Baseline reproduction model includes:
    - Chromatic adaptation
    - Media white relative colorimetry with black point (XYZ) scaling
      - Performs gamut expansion & compression
  - Current widespread use of MRC+BPC demonstrates importance of media considerations.

ICC v4 CMM Color Rendering



- CMM algorithms color re-render source image colorimetry to be appropriate for actual output medium
  - considers source and output medium gamuts and viewing conditions
  - supports color appearance model based color re-rendering
  - can take advantage of full output medium gamut
  - facilitates user adjustment of color re-rendering at time of output

Moving Forward

- Color rendering research supports both automated perceptual intent transform generation and increased CMM color rendering capability.
- High quality ICC v4 tools and profiles need to become widespread to move away from v2 issues.
- Considerable work is needed to coordinate color management across OS, applications and devices.
- User interfaces also need considerable work, but not codifying current problems.
  - Advance both color management and UI effectiveness.
- We need to work in a coordinated way to advance all of the above.
  - Build on solid understanding & communication, e.g. ISO 22028-1.