Perfecting Global Search Methods in Lens Design

Modern lens design software makes it easy.

Donald C. Dilworth, President, Optical Systems Design, Inc.

1965 “It would be wonderful if we could just start with plane-parallel plates and the computer would turn it into a great lens design.”

1975 To find a good lens design you have to start close to a good design.

1990 We can find a great lens design by trying 200,000 random configurations.

2008 Lens design is like climbing a mountain. DSEARCH is born.

2010 Man Versus Machine: a contest between DSEARCH and David Shafer.

2013 A Zoom lens from scratch: the case for number crunching.

Why is lens design hard?

Like a mountain range. You want the lowest valley

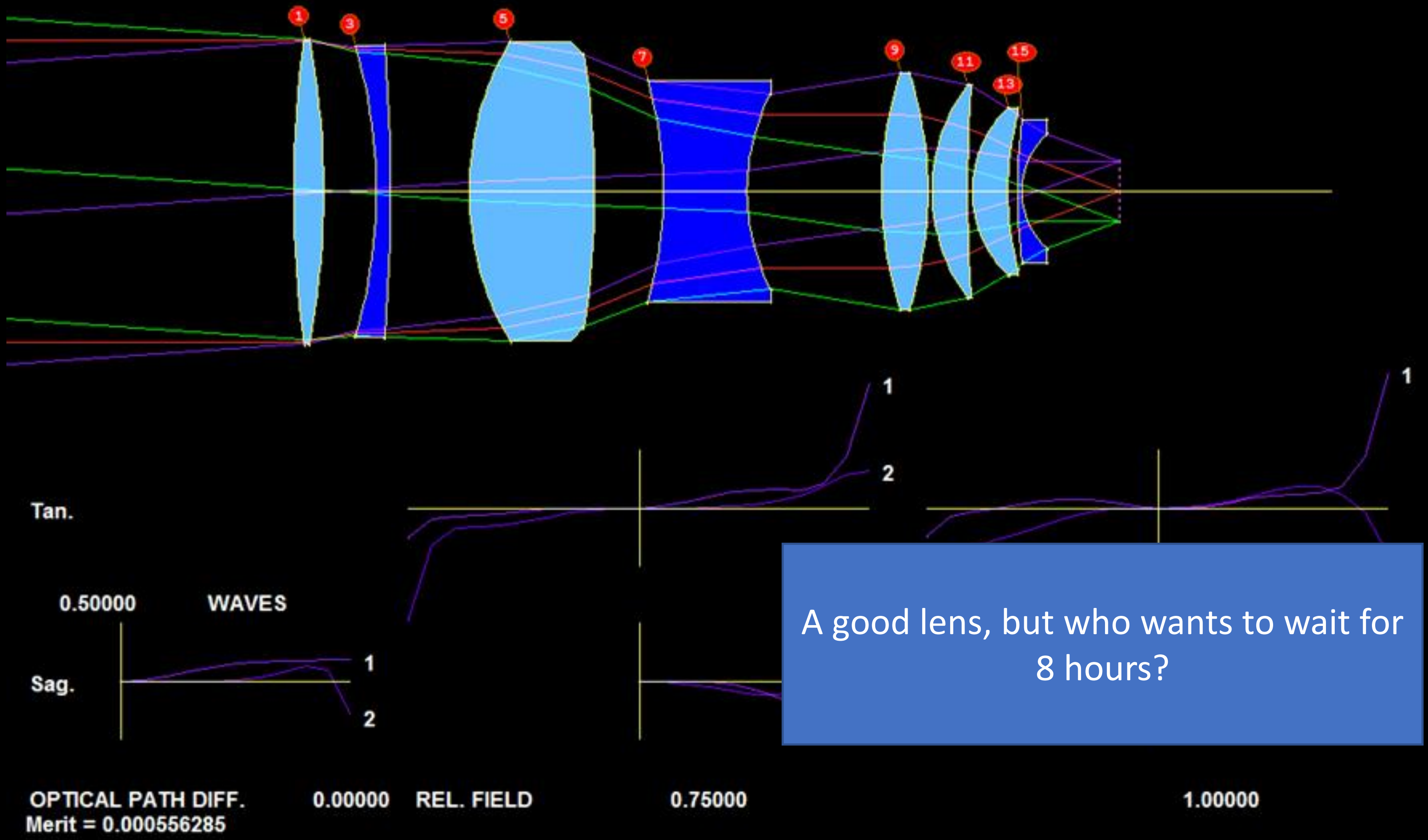
Here’s a sample problem: an 8-element lens. We want a good design – with no starting point.

That’s hard to do.

Let’s try 5000 random configurations.

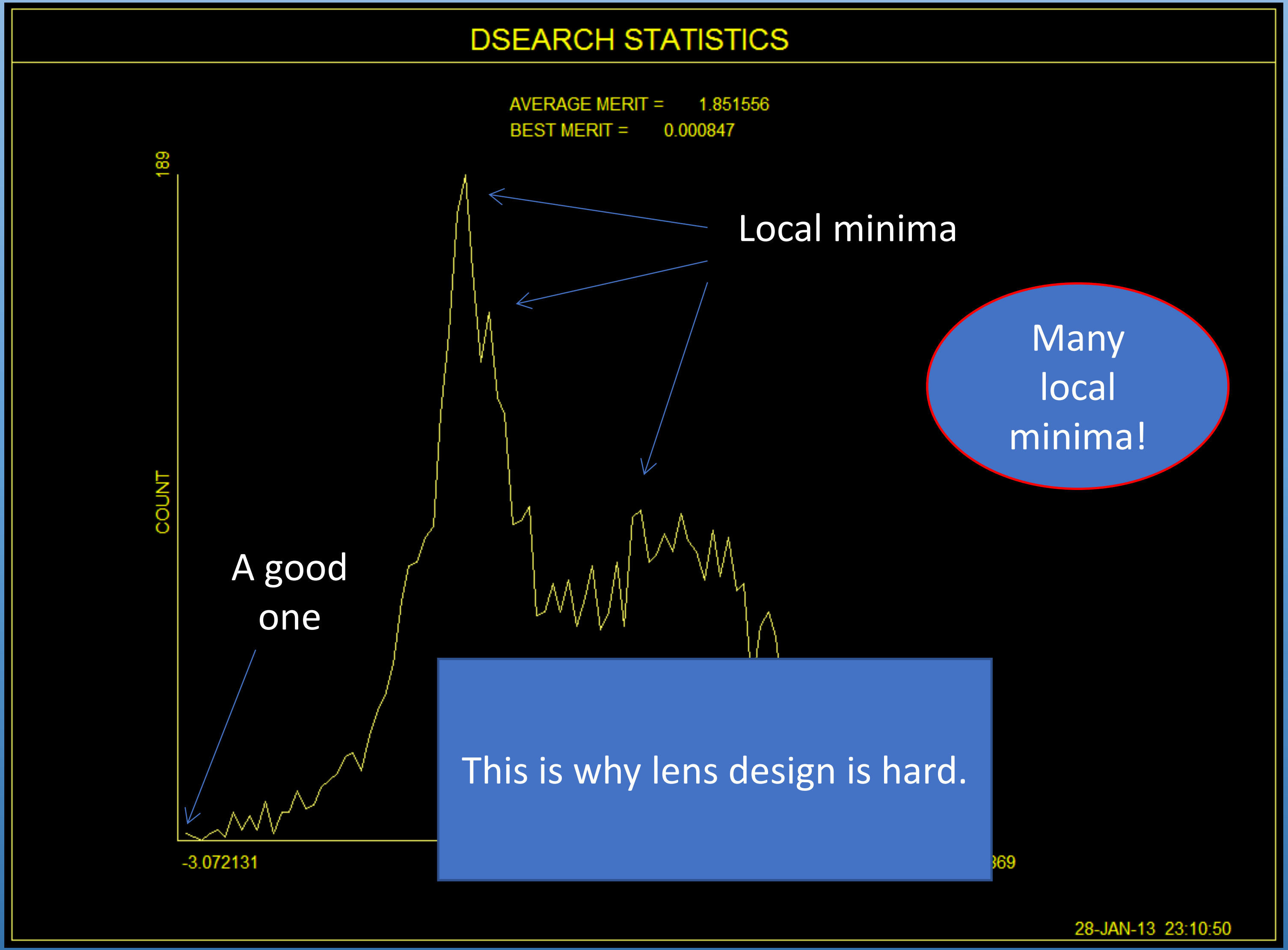
Let it run for 8 hours.

And here is the result:



A good lens, but who wants to wait for 8 hours?

Look at the statistics of those 5000 cases:



How to make it faster?

Try fewer cases

How to select them?

Make a binary number!

- Binary number determines the direction you head down from the top of the hill.
  - Initial radii set by user input.
  - All radii equal +/- that value. (Bending = 0).

00000000, 00000001, 00000010, 00000011, …

Still not fast enough. How long does it take to design a lens with other programs?

Seven-element lens, starting with plane-parallel plates:

Program 1: Two hours
Program 2: 40 minutes

A 7-element lens needs 128 directions.

A 12-element lens needs 4096 directions.

If each case takes 40 minutes, you need 2730 hours!

I'm not going to wait that long.

The key is to find a *very fast* optimization algorithm.

The PSD III algorithm can design the 7-element lens in less than one second.

What is PSD III?

A way to account for the effects of higher-order derivatives.

Comparison of PSD III and DLS

- Other programs use DLS or something derived from it.
- Ran test job on two other commercial programs.
- Seven elements, all flat.
- Equal thicknesses, airspaces.
- Model glass in center of glass map.
- Goal: close to 6 microns average RMS spot size over field.

One program: two hours

Other program: 40 minutes

PSD III? Watch the next video.

Second-Derivative Optimization

This approximation leads immediately to

$$\frac{\partial^2 f_i}{\partial x_j^2} \approx \frac{\left.\frac{\partial f_i}{\partial x_j}\right|_{\Delta x_j} - \frac{\partial f_i}{\partial x_j}}{|\Delta x_j| + \left.\sqrt{\sum_k \Delta x_k^2 \frac{SEC_k}{SEC_j}}\,\right|_{k \neq j}}$$

These values often differ, between variables, by 14 orders of magnitude.

DLS wants the second derivative. “Damping” is a crude approximation

Influence of *all* higher-order derivatives is accounted for, statistically.

This is the PSD III method.

1986

Comparison: convergence rates for several algorithms

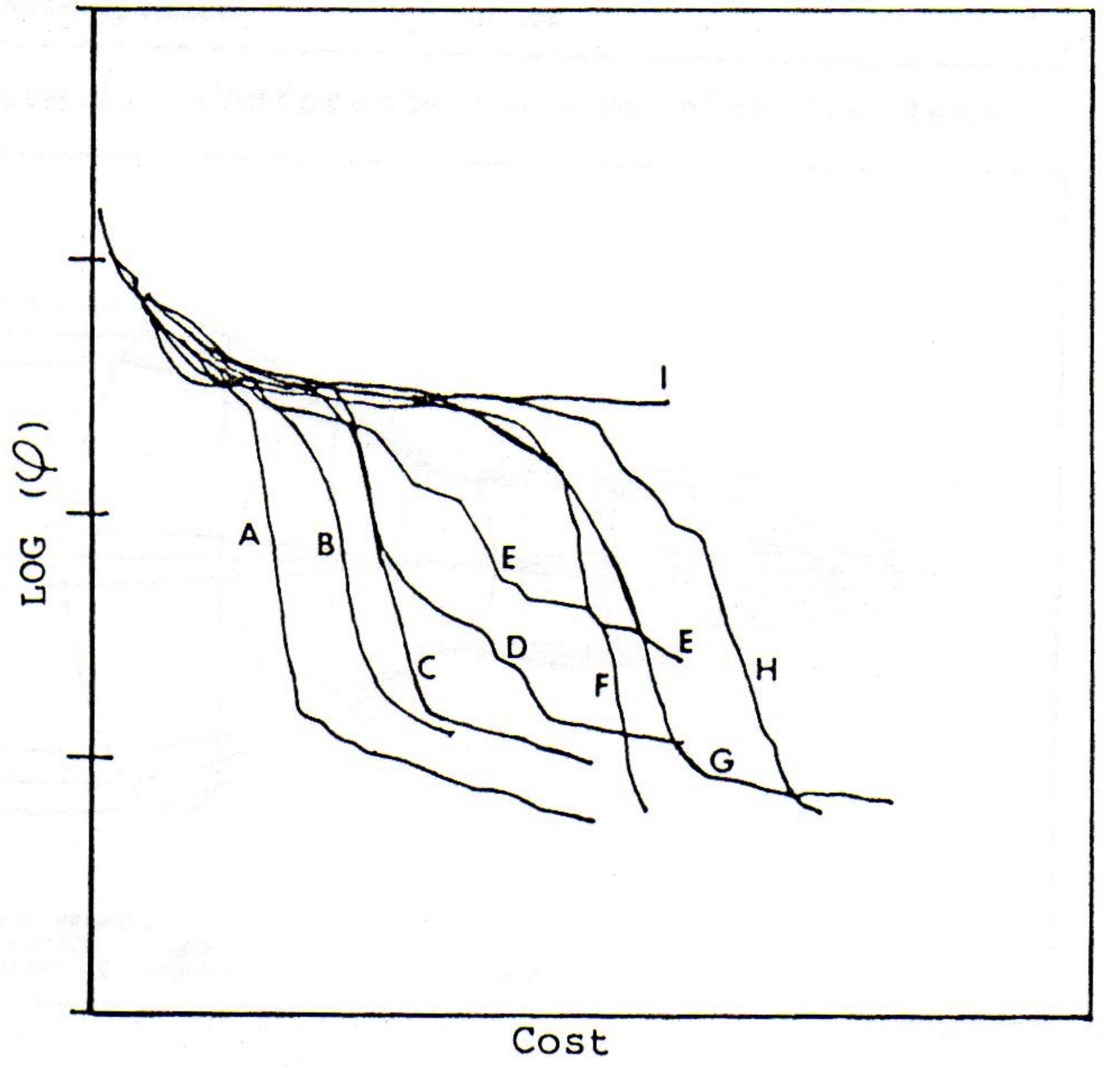


Figure 2. Convergence curves for triplet lens. Curves are as follows: A = PSD III, B = PSD I-FM, C = PSD I, D = DLS-FM, E = PSD III-FM, F = PSD III with damping search (OD), G = PSD I(OD), H = PSD I-FM-(OD), I = DLS.

Optimizing a triplet should be easy. Not all algorithms can do it efficiently.

With this kind of speed the search methods become practical.

With this kind of speed, you can search 4096 cases in 68 minutes.

That’s still too slow!

Multicore processing can do it faster: 10 cores in 6.8 minutes.

Still too slow!

Quick mode for faster results

Screening pass, merit function has only 3rd and 5th order aberrations (plus 3 real rays)

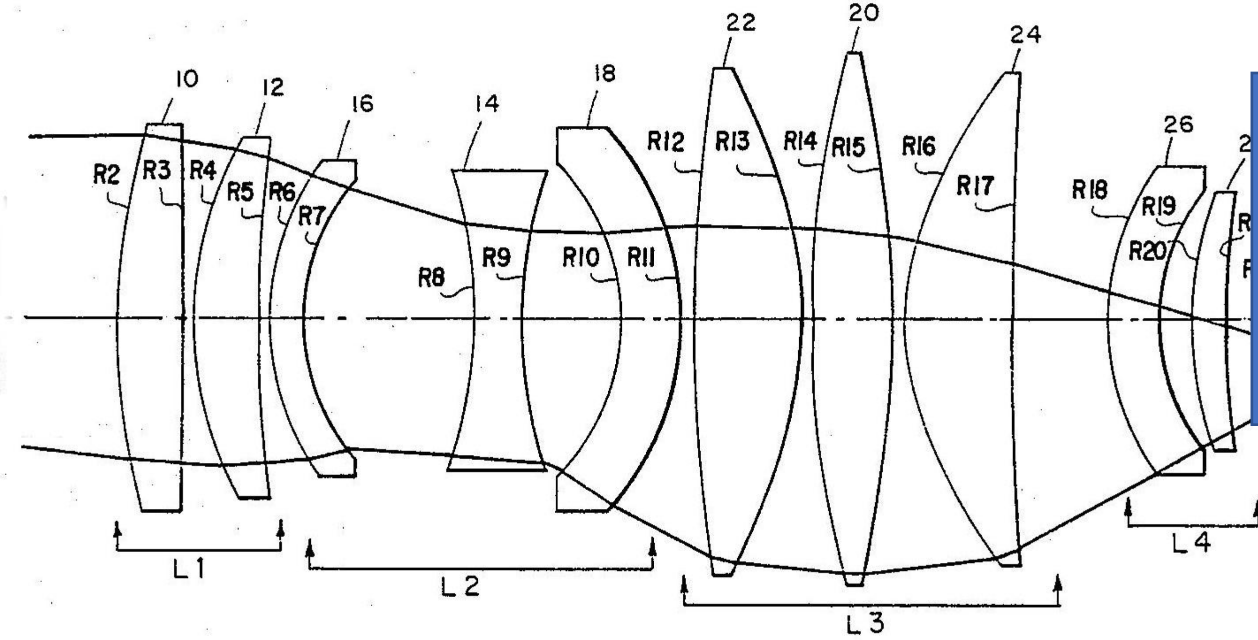
Select the 10 best results…

… and optimize those with a large grid of rays.

Just how good is DSEARCH?

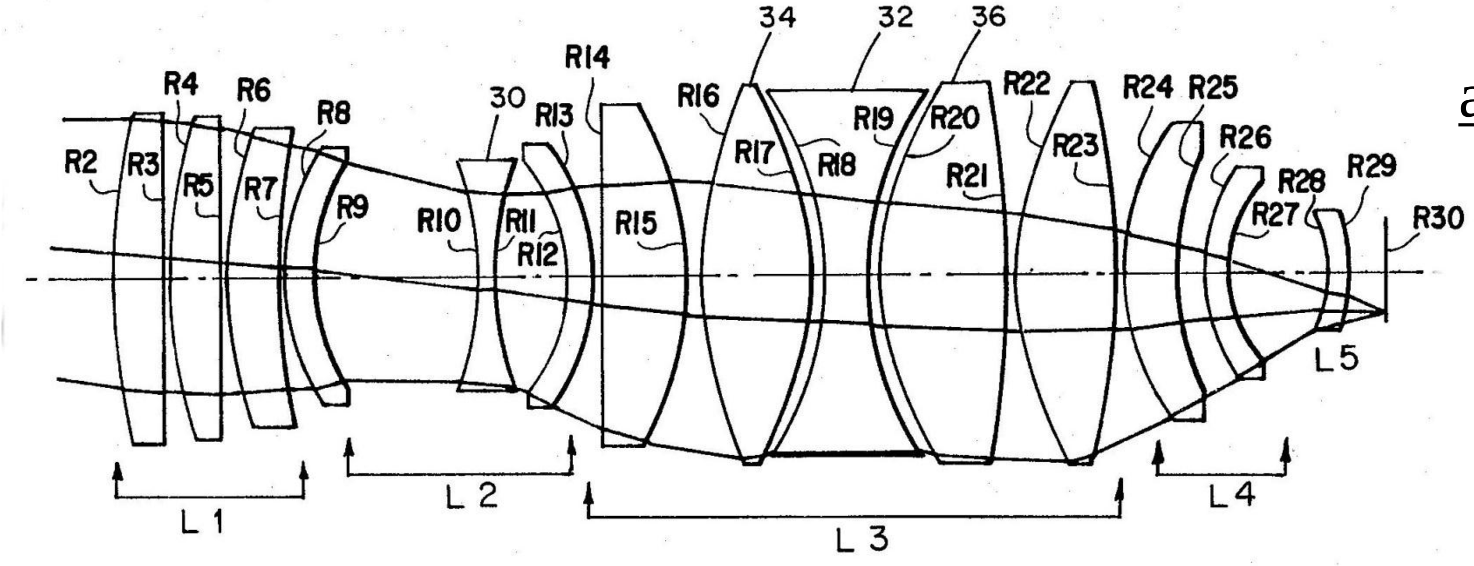
How does DSEARCH compare with an expert human designer?

We had a contest.



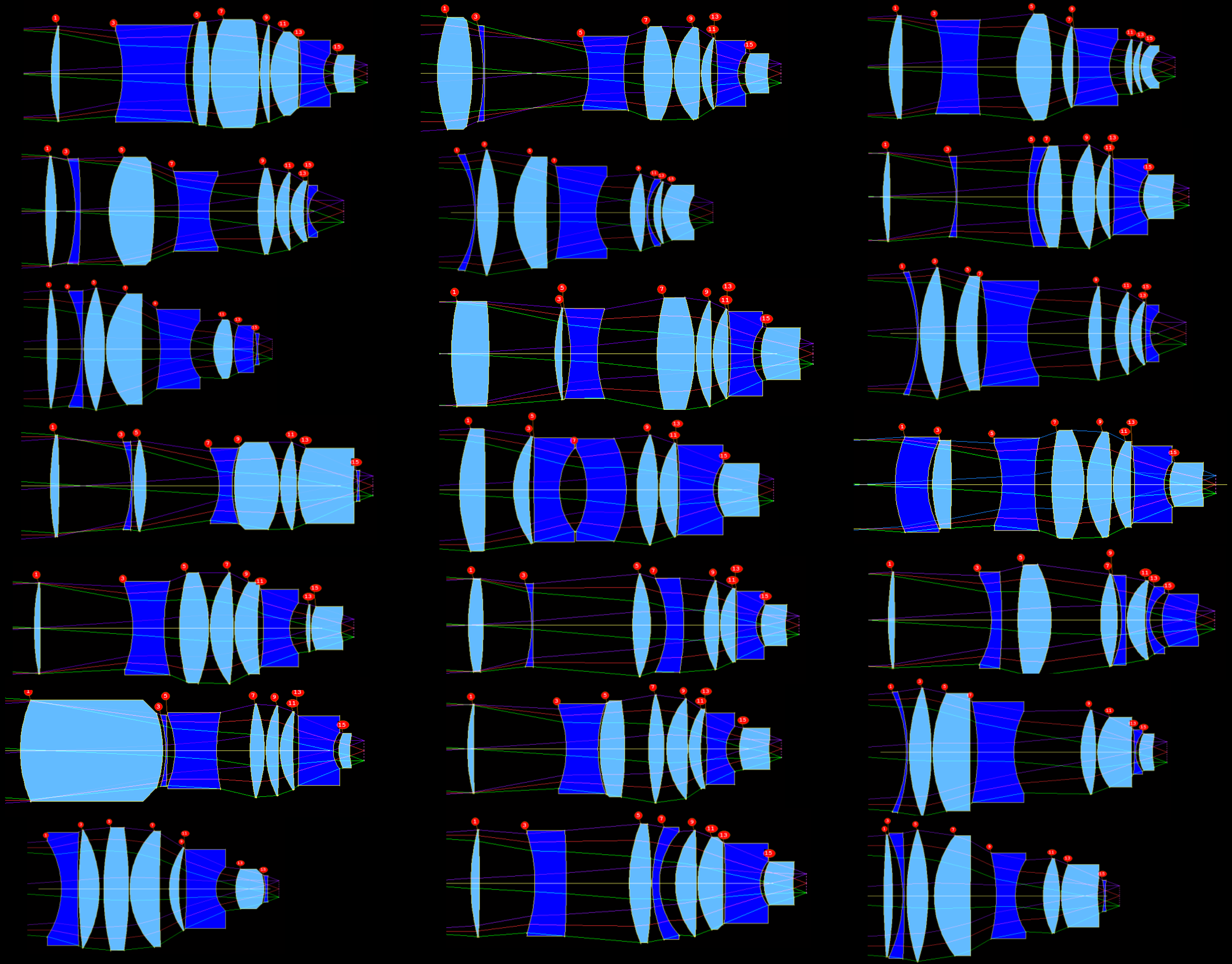
This lens was designed by David Shafer, one of the world's best.

<u>unachromatized</u>



<u>achromatized</u>

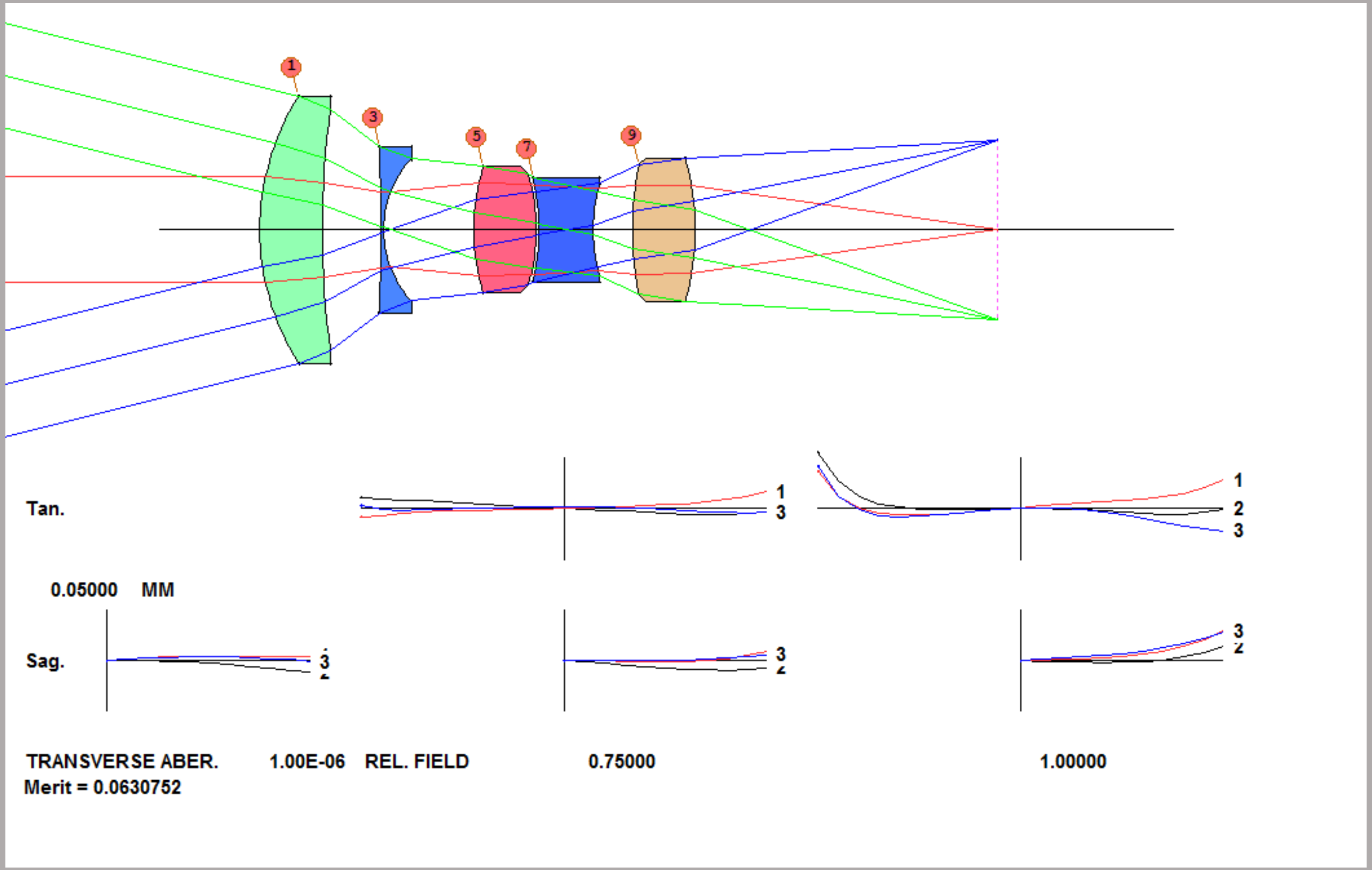
My US patent #4,770,477



DSEARCH found 23 configurations as good as or better than the lens designed by a human expert.

DSEARCH wins.

How fast is DSEARCH? Here's an example:
5-element lens
F/3.5
Semi field 14 degrees
Semi aperture 21.42 mm.

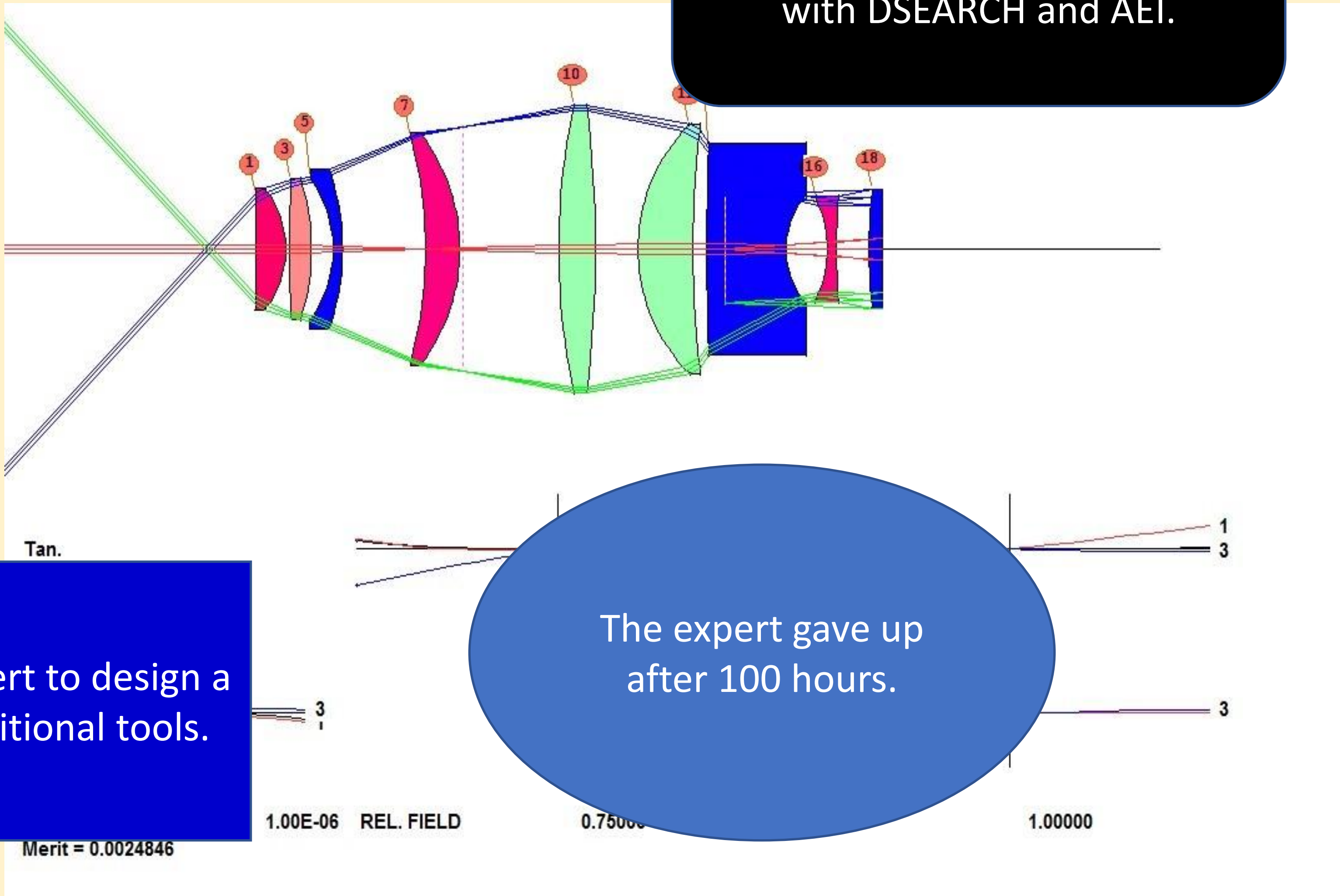


DSEARCH found this lens in 28.78 seconds.

Here’s a more difficult problem:

90-degree eyepiece
Perfect wavefront
Perfect distortion
Perfect pupil aberration
Perfect field stop blur.

This design was done in 15 minutes, from start to finish, with DSEARCH and AEI.



I challenged a human expert to design a lens this good, using traditional tools.

The expert gave up after 100 hours.

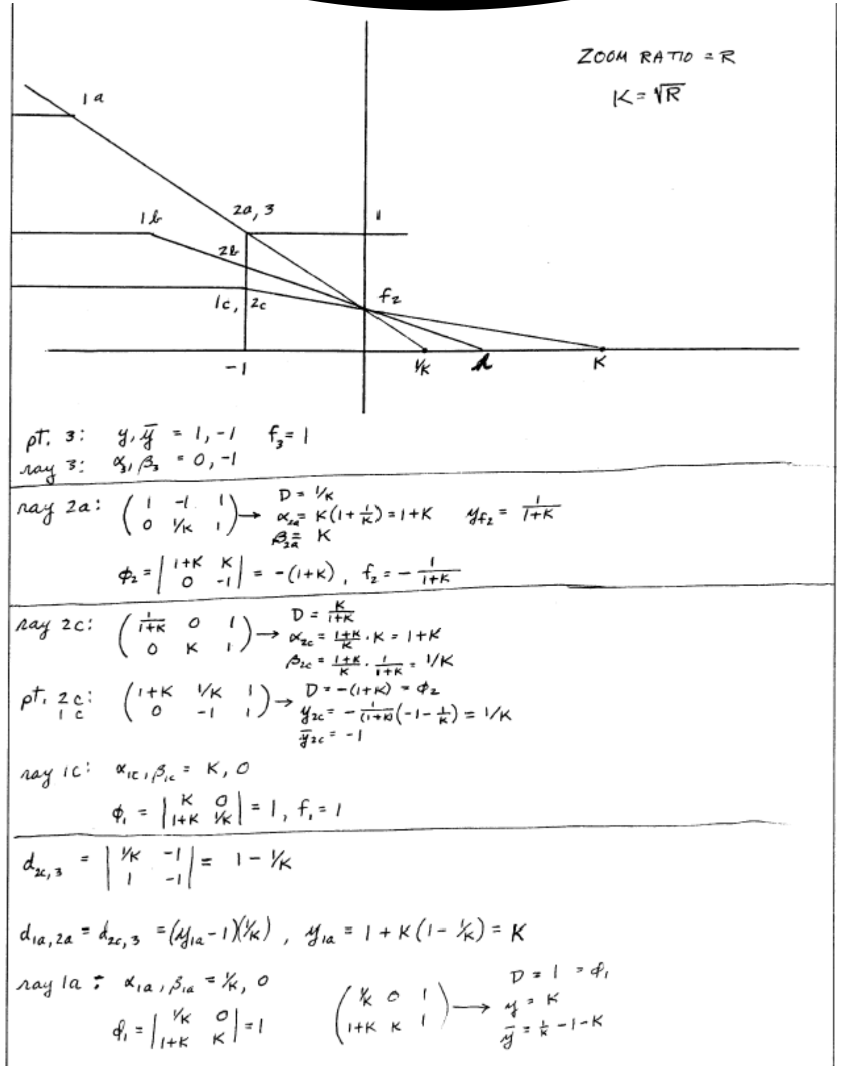
DSEARCH makes that problem look easy.

We need a harder problem.

Let's do a ZOOM lens!

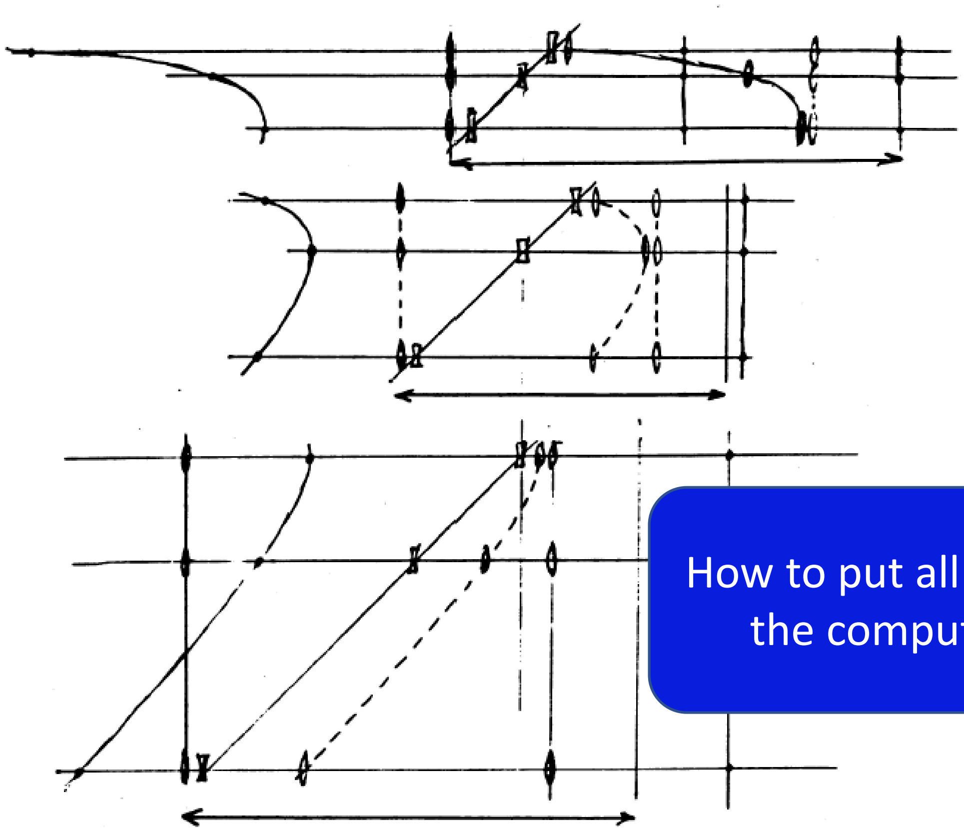
Try to guess how long that will take.

Recently, a customer sent me 10 pages of hand calculations for a zoom lens.



This is an example of the *designer* doing most of the work.

This is not *modern*.

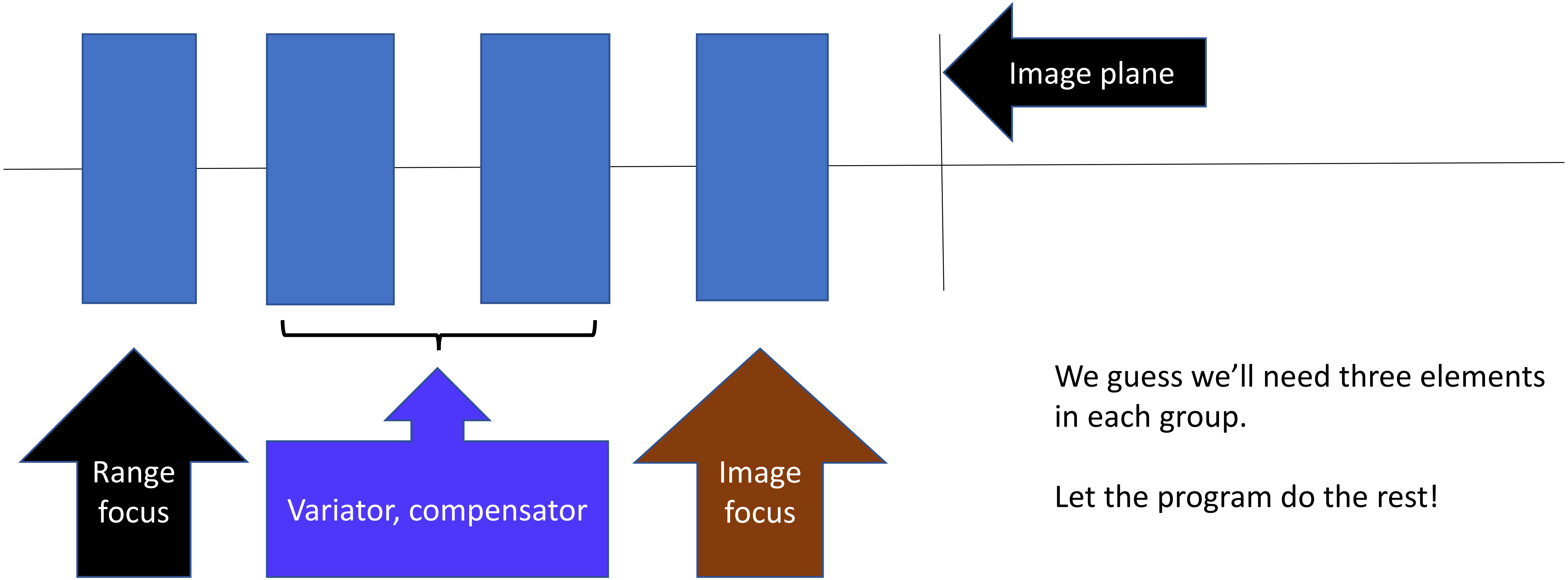


How to put all this on the computer?

Some assembly required….

Zoom lenses are more difficult.

Theory tells us we need four groups.



We guess we'll need three elements in each group.

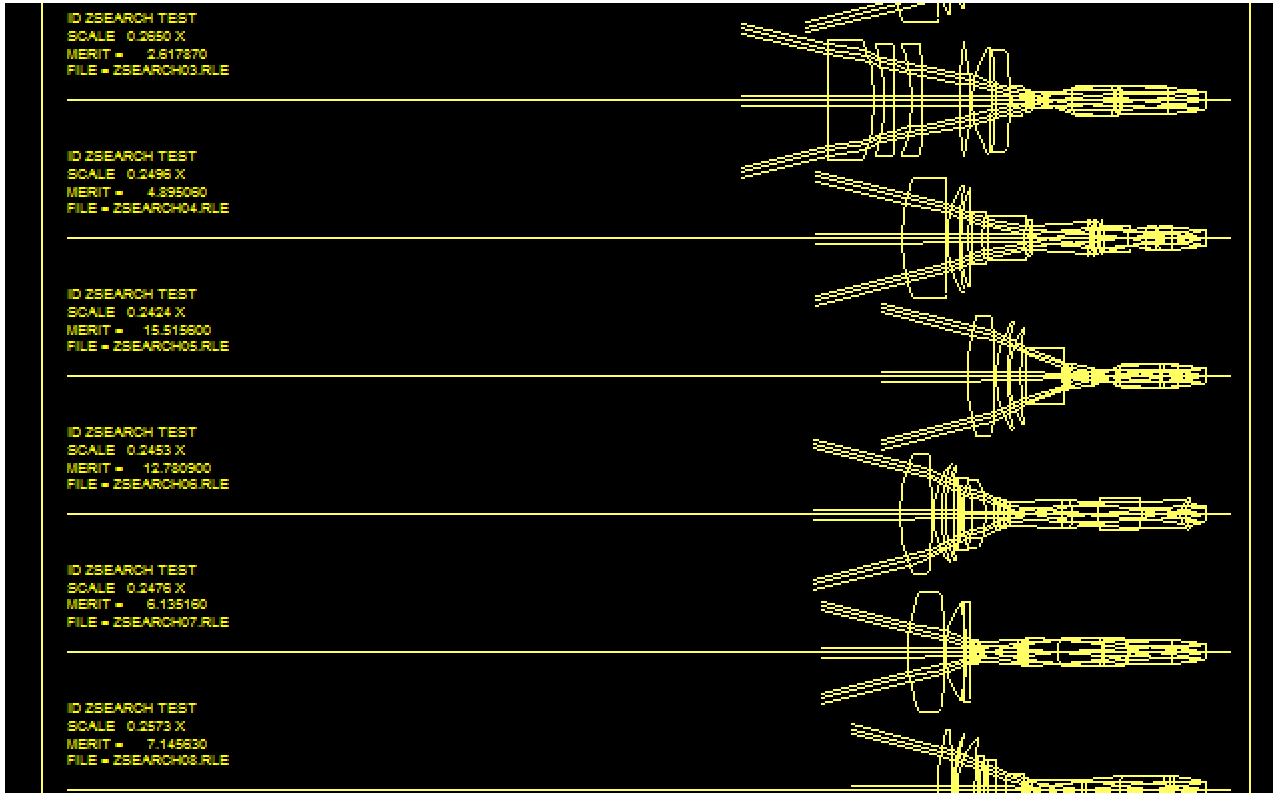
Let the program do the rest!

This will be the input to ZSEARCH™:

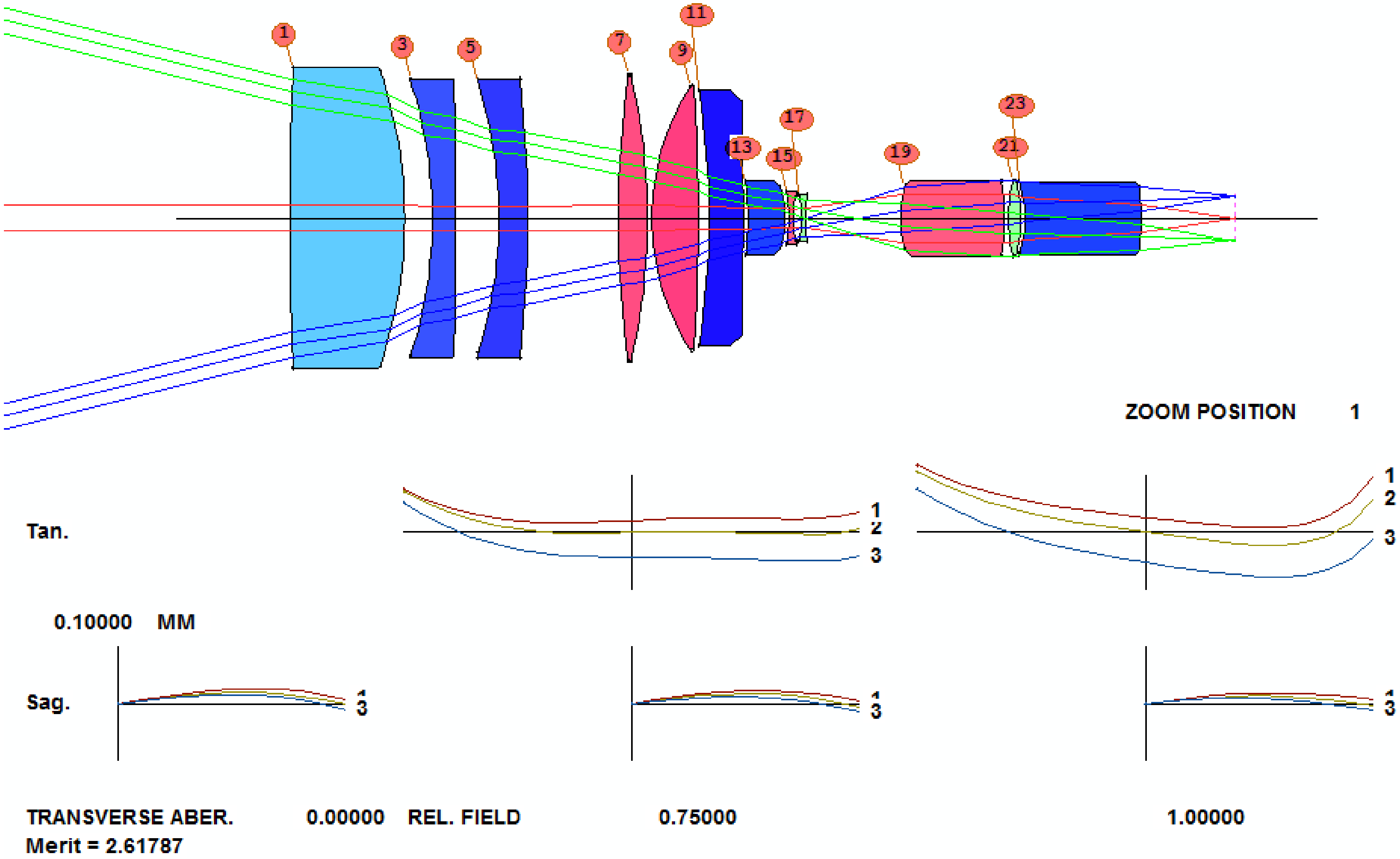
```
LOG                    ! to keep track of things later
PROJ                   ! to see how long this run took
CORE 12                ! it runs 12 times faster
ZSEARCH 3 QUIET        ! save results in library location 3

SYSTEM
ID ZSEARCH TEST
OBB 0 14 2.85         ! infinite object, 14 degrees semi field, 2.85 mm semi aperture.  This
                          defines the wide-field object
UNI MM
WAVL CDF
END

GOALS
ZOOMS 10                   ! request 10 zoom positions
GROUPS 3 3 3 3             ! lens has four groups with 12 elements altogether
ZGROUP 0 Z Z 0             ! and groups 2 and 3 will zoom
```

```
FINAL                  ! declare the desired object at the last zoom position, which is the narrow field
                           zoom
OBB 0 1.7545 22.8      ! object is 1.7545 degrees semi field and 22.8 mm semi aperture.  That implies an
                           8X zoom.

ZSPACE LIN             ! other zoom objects will be linearly spaced between the first and last
APS 19                 ! put the stop on the first side of the last group
GIHT 5 5 10            ! the image height is 5 mm for all zooms, with a weight of 10.
BACK 20 .01            ! the back focus is 20 mm and will vary.  A target will be added to the merit
                           function with a low weight.
COLOR M                ! correct all defined colors
ANNEAL 50 10           ! anneal the lens as it is optimized in real-ray mode
QUICK 15 40            ! 15 passes in quick mode, 40 in real-ray mode
END

SPECIAL AANT
AAC 30 1 5             ! request a maximum semi aperture on all elements of 30 mm
ACA 50 1 1             ! monitor rays to keep away from the critical angle.
END
GO                     ! start ZSEARCH
PROJ                   ! see how long the run took.
```

ZSEARCH comes back with the 10 best lenses it found.



This is the top lens returned by ZSEARCH:



Not good enough!

- Here is where *number crunching* comes to the rescue.
  - AEI (Automatic Element Insertion)
  - AED (Automatic Element Deletion)

Can go both ways.

Start with a simple ZSEARCH lens…

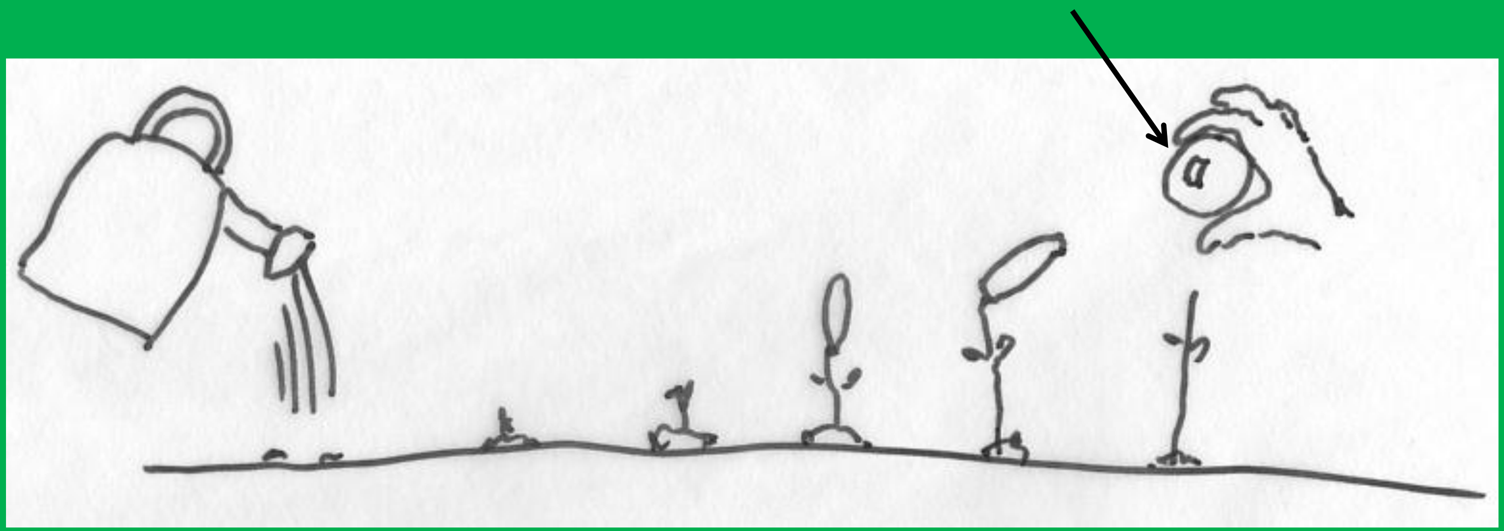
… and modify it as needed.

Runs faster

What can AEI do?

What is AEI?

AEI can *grow* new lens elements…



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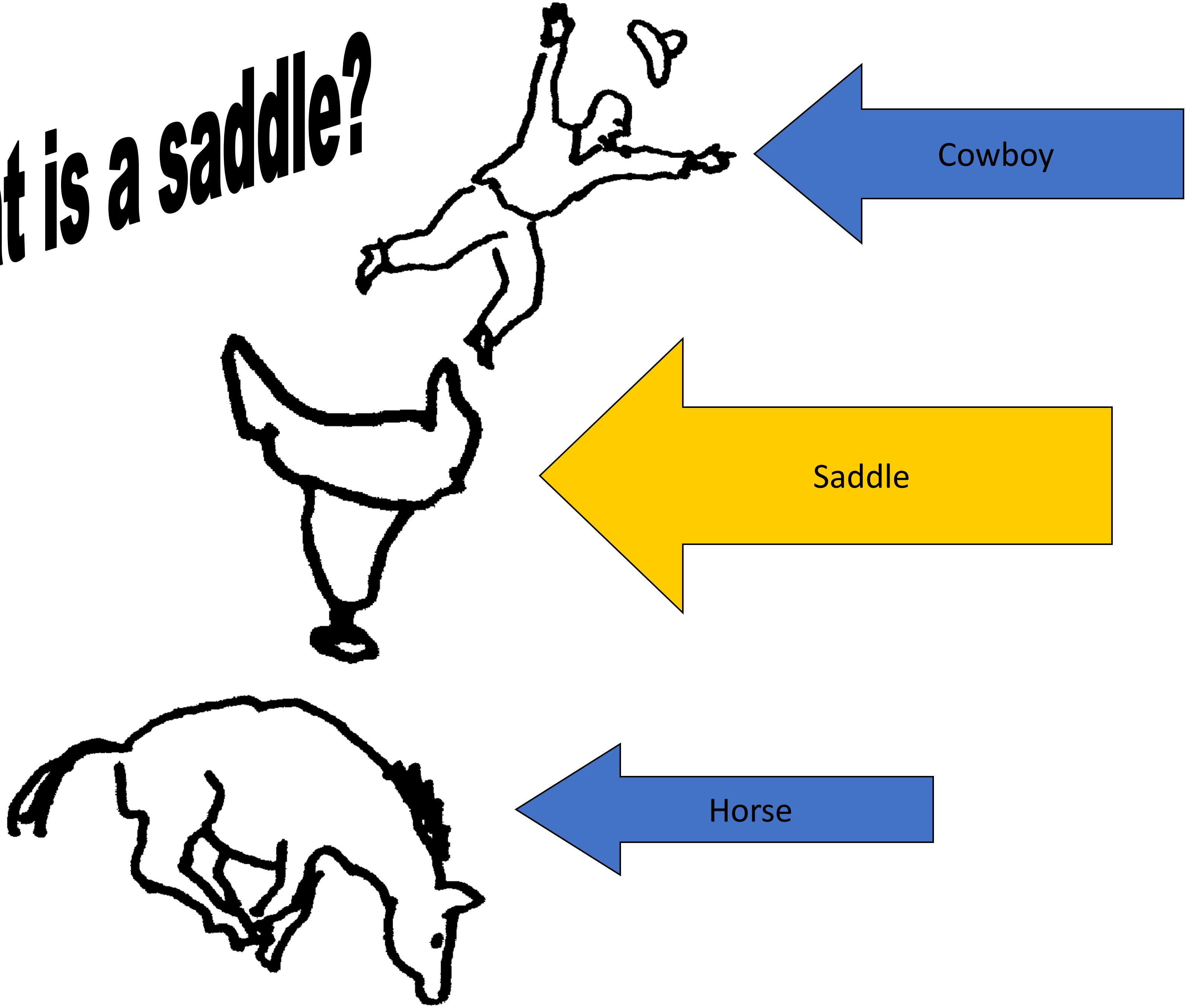
…with the **Saddle-Point** Build method

- Developed from ideas of Dr. Florian Bociort.

What is a saddle?



A Saddle

- Curves up in one dimension
- Curves down in others

Design is minimum with
respect to the variable in red.

Design can be improved
with the variable in green.

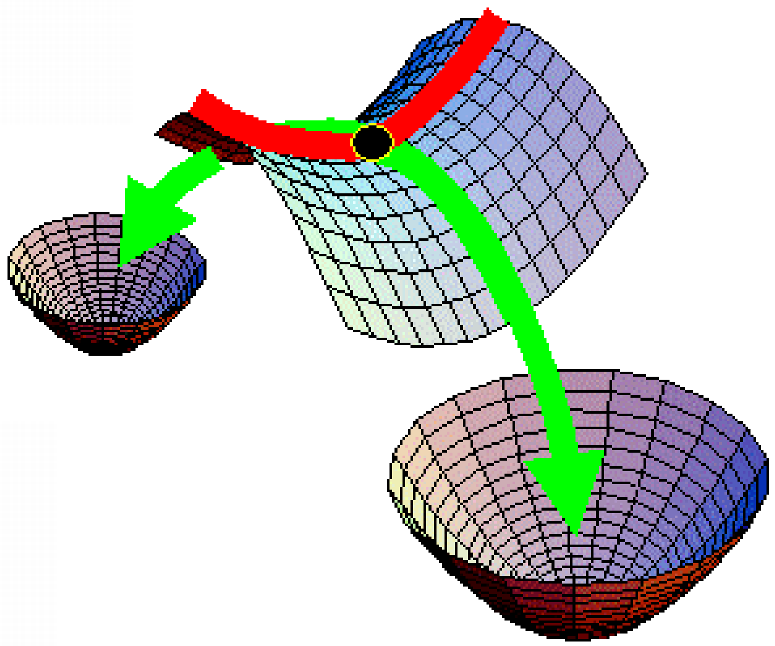


Illustration courtesy of F. Bociort

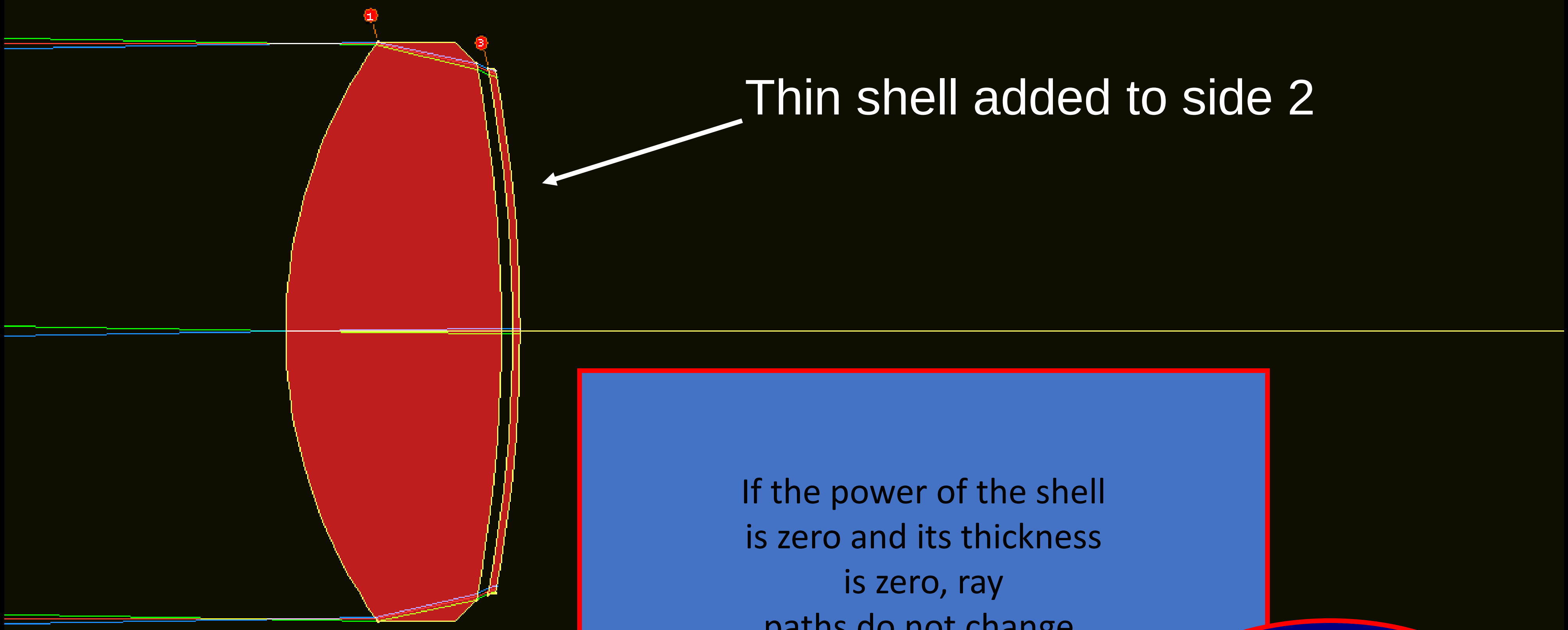
Central Idea:

- If a lens is at a local minimum, it is optimum with respect to all of the variables.

- With new variables, additional improvement may be possible.

- How to add variables?
  - Don’t disturb the merit function.
  - Add thin element of almost zero power.

Thin shell added to side 2



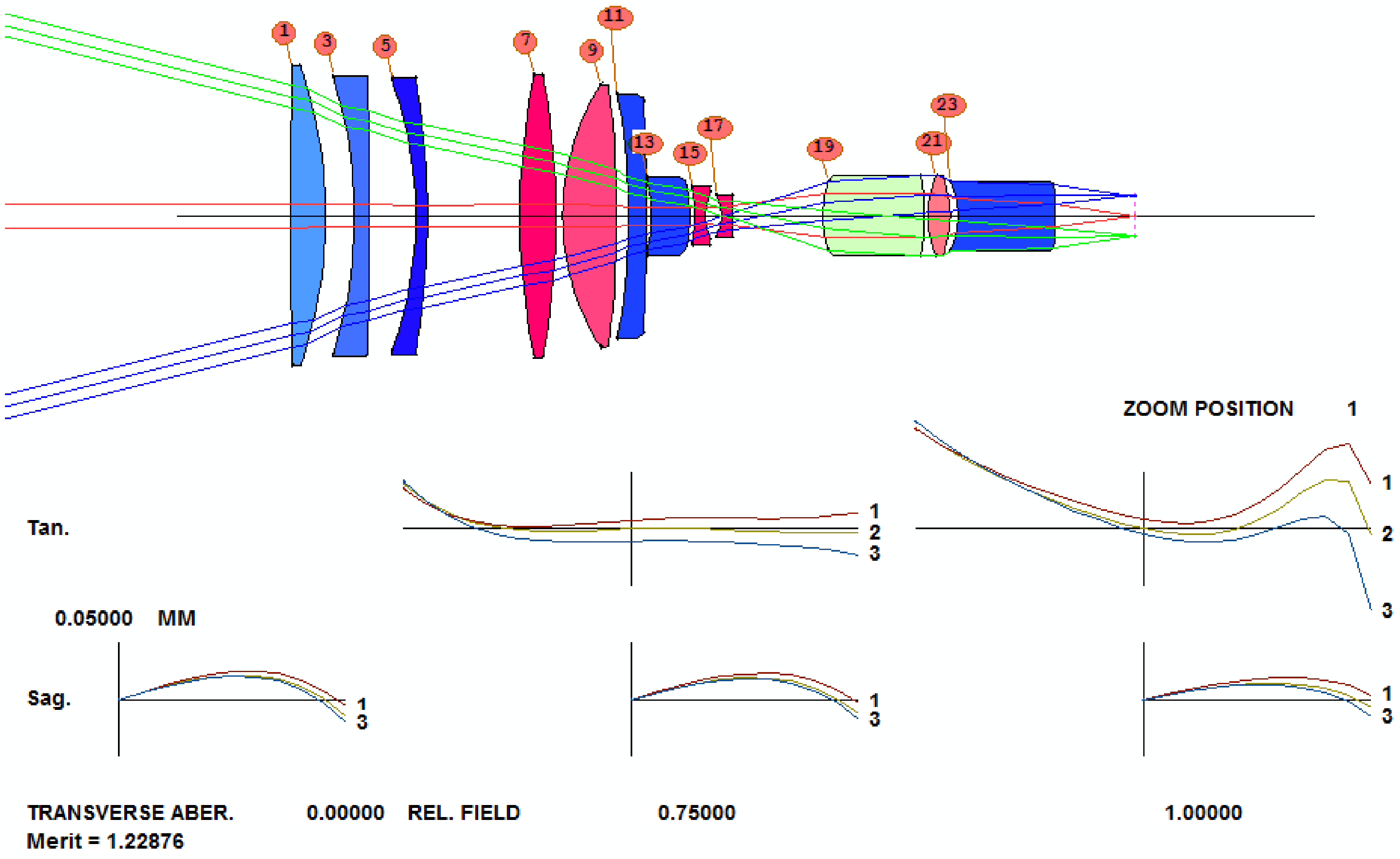
If the power of the shell is zero and its thickness is zero, ray paths do not change.

But now there are 6 new degrees of freedom.

Saddle-point method can build up a whole lens

- Add a thin shell to each side of current lens elements.
- Assign weak negative and then weak positive power to the shell.
- Assign small shell thickness, and small separation, to satisfy mechanical parts of merit function. (Departs from pure theory.)
- Optimize each case, select best one.
- Loop until desired number of elements are in place.

First we optimize the zoom lens in its current configuration.



Not good enough!

How to improve the lens?

We could try guessing.

This is an exercise in number crunching.

Let the computer do all the work.

Lens form after AEI has added two new elements

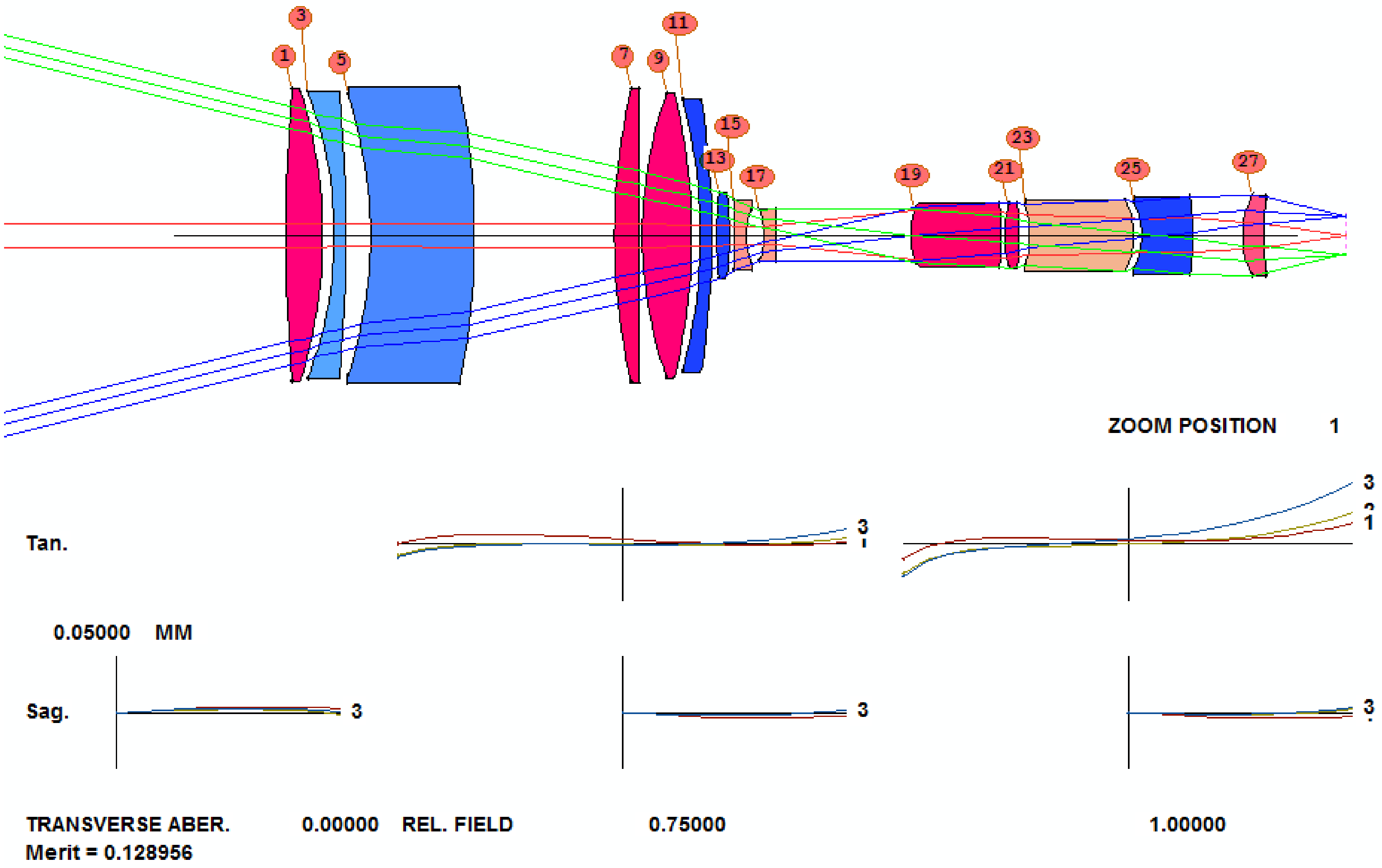
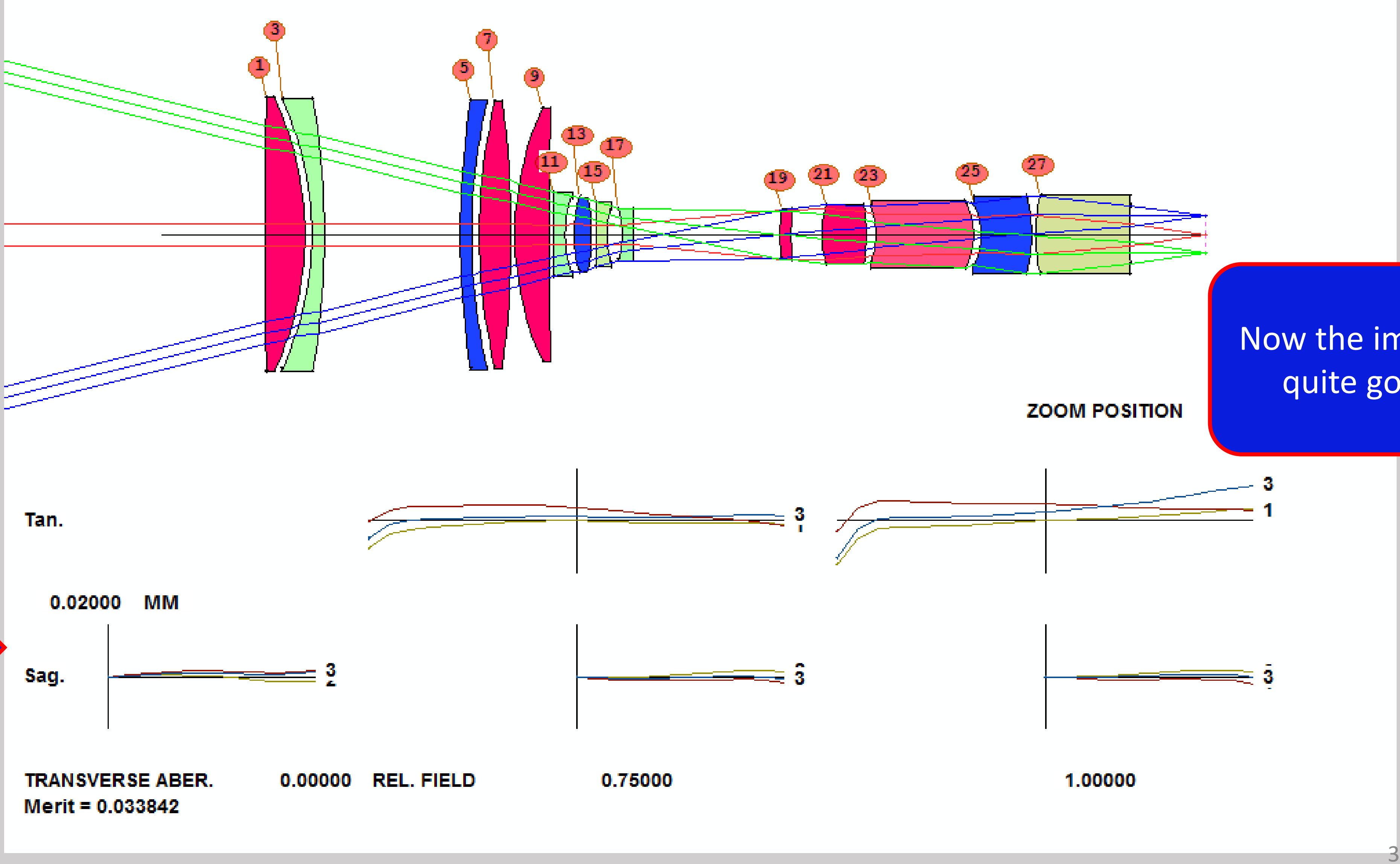


Image is better.

Lens form after running AED and then AEI twice more:



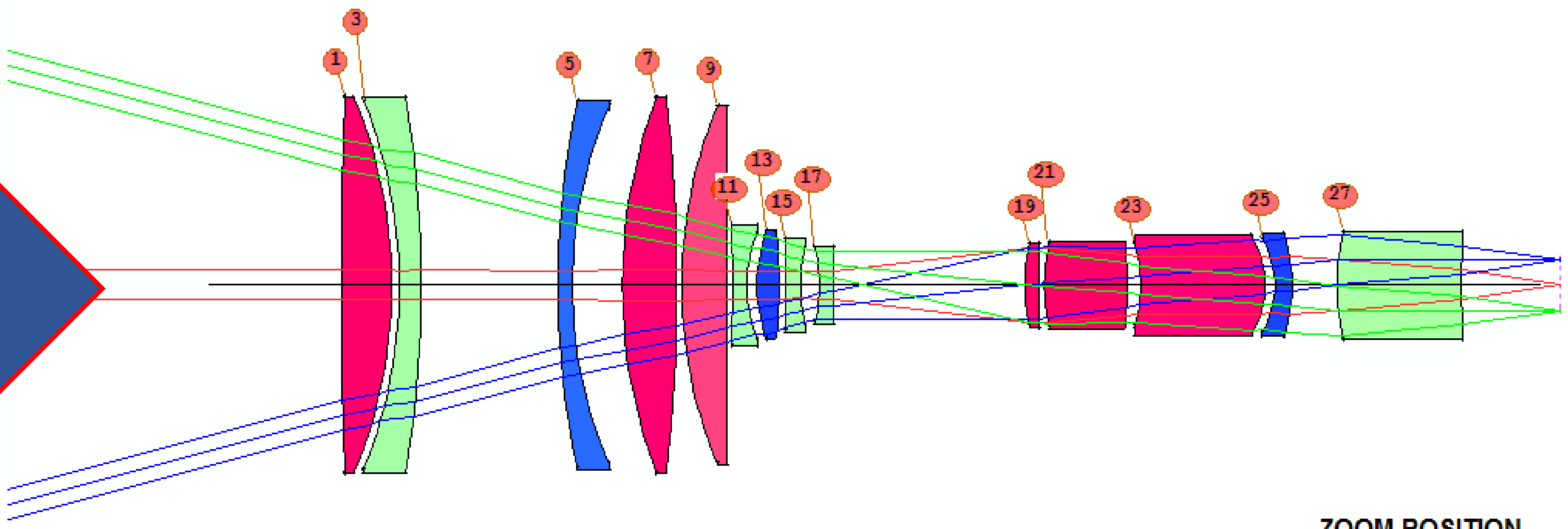
Now the image is quite good.

Note the scale change.

Now it's a pretty good lens, but ...

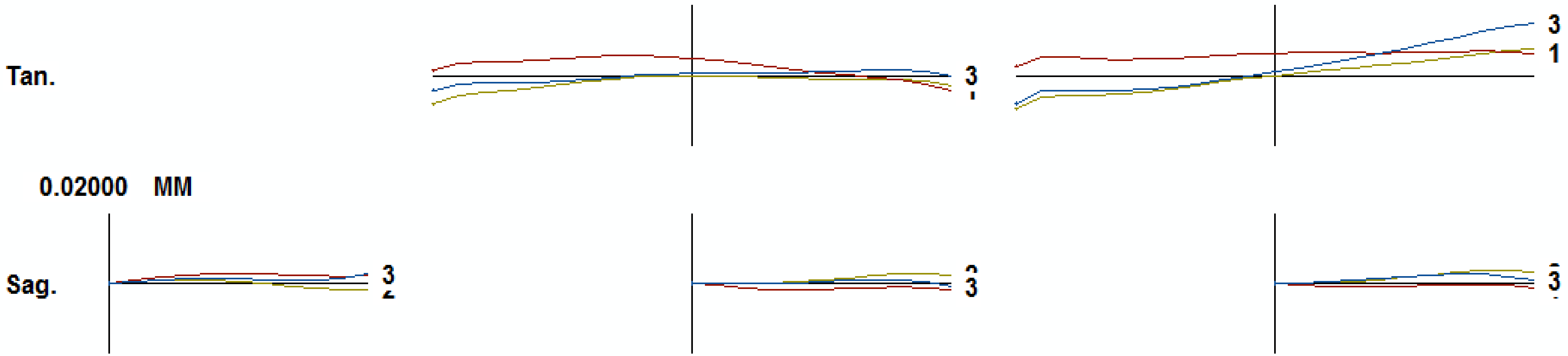
- It has model glass types.
  - More number crunching needed
    - Use ARGLASS™ to substitute real glass for the models
    - Sequential or sorted order.
    - Selected glass catalog, filtered.

Now the lens has real glass



ZOOM POSITION 1

Same quality



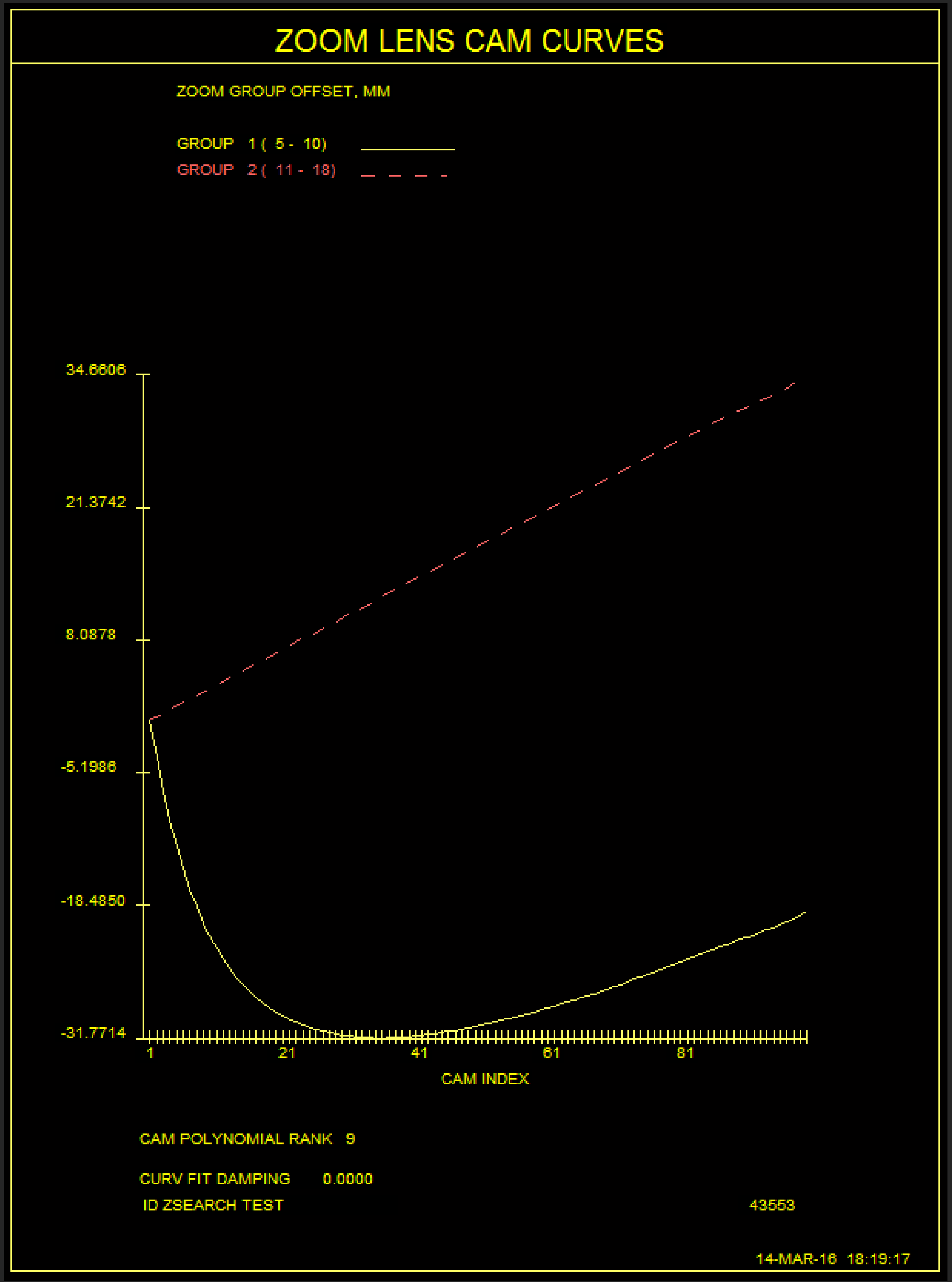
TRANSVERSE ABER. 0.00000 REL. FIELD 0.75000
Merit = 0.0691492

Now we need a CAM curve

What is a CAM curve?

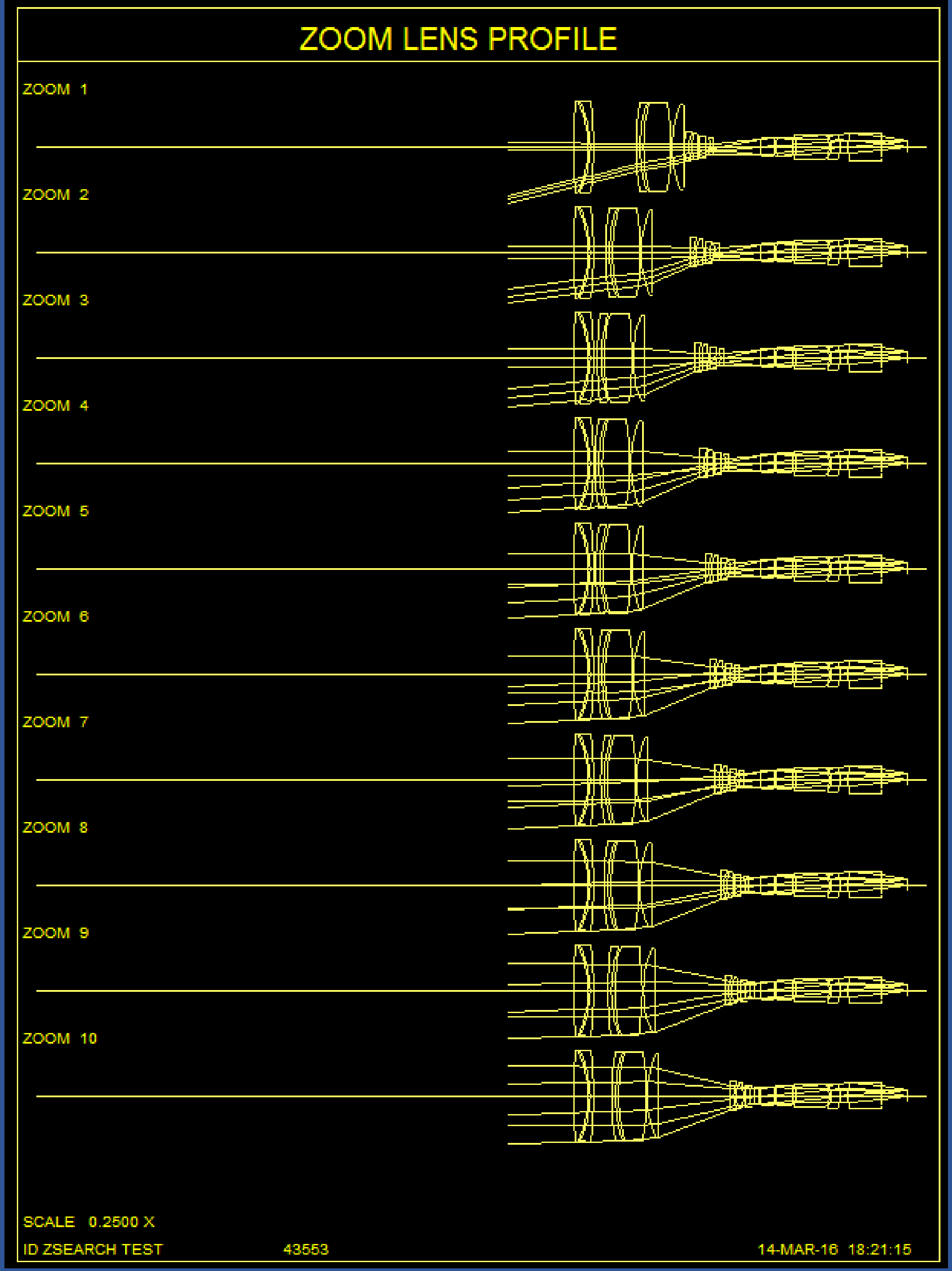
- Can interpolate in between zoom positions.
  - Image only corrected at the defined zooms
  - What happens in between?
- Fit all zooms to a polynomial.
  - Number of terms almost equal the number of zooms
  - Power-series polynomial.
- Or piecewise cubic interpolation.
  - Shows performance over zoom range.

Here are the cam curves.



Here is our zoom lens at 10 zooms.

ZSEARCH™ is successful!



We have learned:

1. Global search methods are a mature science.
2. Many lens problems can be solved more quickly with a computer than by a human designer.
3. Lens designers from 50 years ago would be astonished.

Optical Systems Design, Inc.
www.osdoptics.com