Astronomical data analysis with computers

Hard X-/Soft Gamma-Ray Telescopes

Sergey Tsygankov

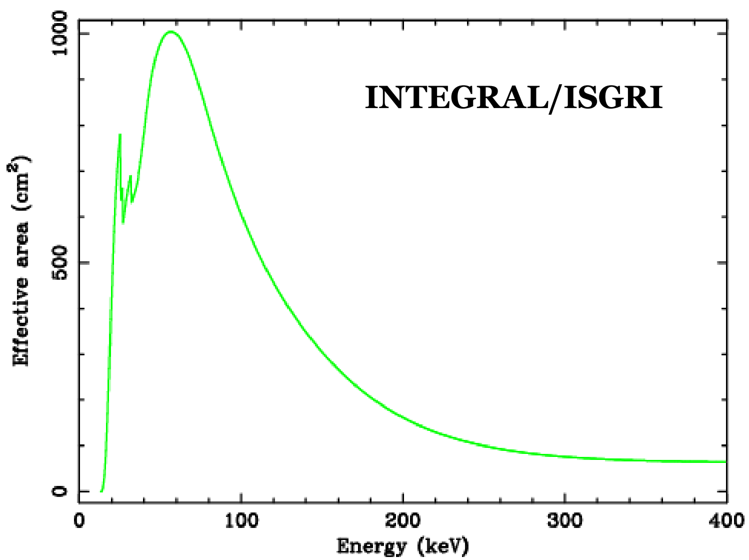
UNIVERSITY of OULU
OULUN YLIOPISTO

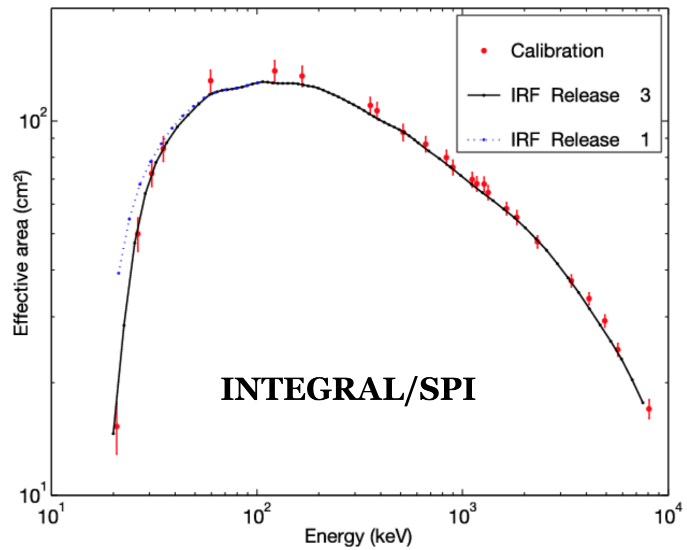
Efficiency and off-diagonal response

In the hard X-ray range, often only a correction of efficiency (effective area) versus energy is necessary:

(counts/s/keV seen at E) / (effective area at E in cm^2) = photons/cm^2/s/keV

A(E) – Ancillary Response Function (ARF)



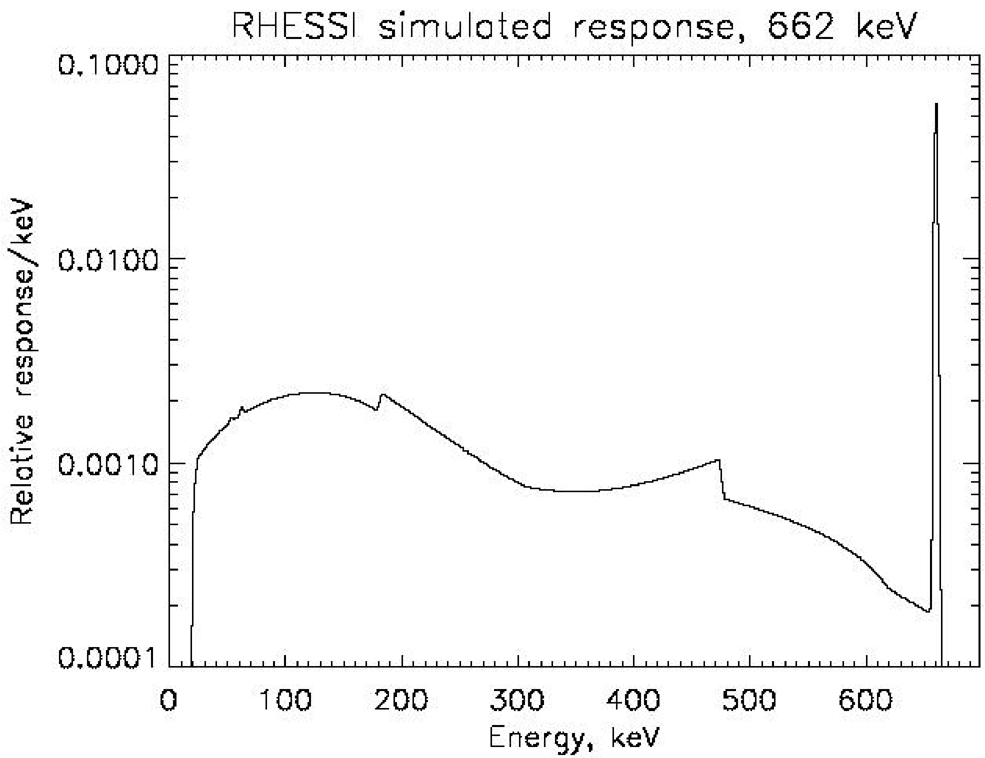


At high energies, many counts are often shifted to low energies instead of just lost, and this simple division becomes a matrix inversion instead.

Off-diagonal response

Spectrographs do not measure the true, or intrinsic, spectrum of a source, but instead measure the number of photons that are recorded in individual energy channels in the instrument. A photon entering the spectrograph with an input energy of E can be recorded as having a different energy E', which can be different from the input energy.

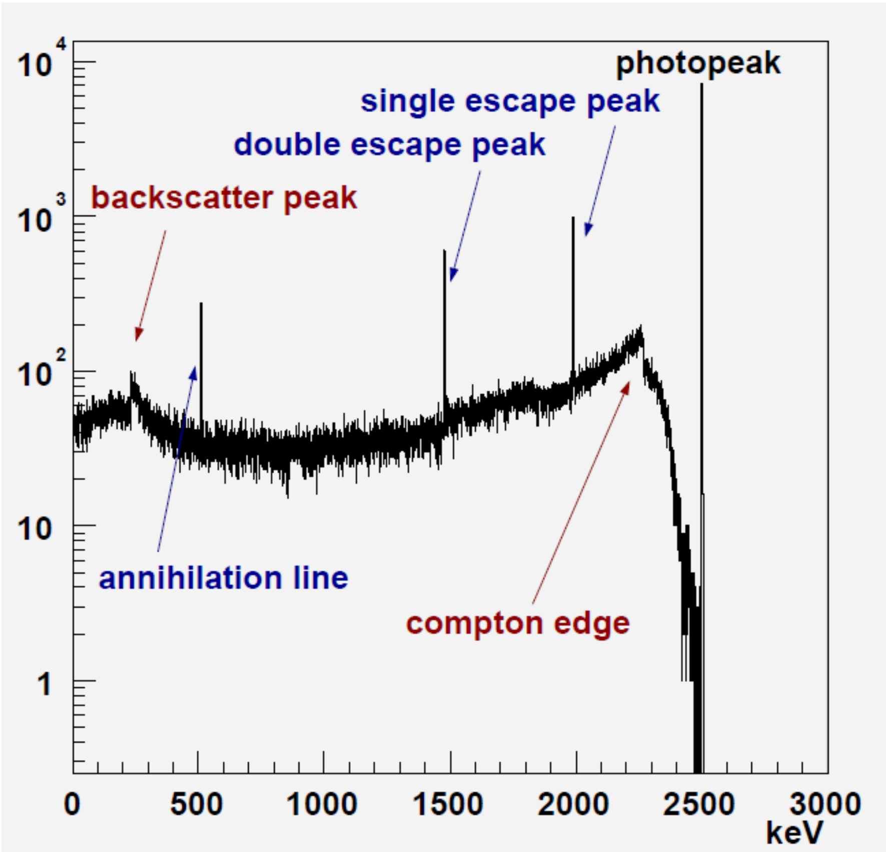
Therefore, the spectrum that we measure is actually the convolution of the intrinsic spectrum with the response function of the instrument. The response function characterizes how the instrument changes the intrinsic spectrum during the process of recording the spectrum.



Off-diagonal response

(1) Photoeffect. All of the photon's energy is transferred to the "photoelectron" in the detector volume; such events contribute to the photopeak. (2) Compton scatter event. It contributes to the photopeak if the scattered photon's energy is also absorbed by the crystal. (3) This Compton scatter event contributes to the Compton continuum (CC). After scattering off an electron, the deflected photon leaves the detector volume. If the energy transferred to the electron is (almost) maximal, i.e. the photon is deflected by 180^{o}, the event contributes to the Compton edge (CE).

(4) If multiple Compton scatters take place prior to the scattered photon's leaving the detector, energy deposits in the region between CE and photopeak are possible. (5) When a photon traverses the Ge detector only to Compton-scatter in passive material behind the crystal, the scattered photon can be absorbed in the Ge detector on the 'return trip'. Such backscattered photons have energies around 200 keV due to their large scattering angles. Such events make up the backscatter peak.



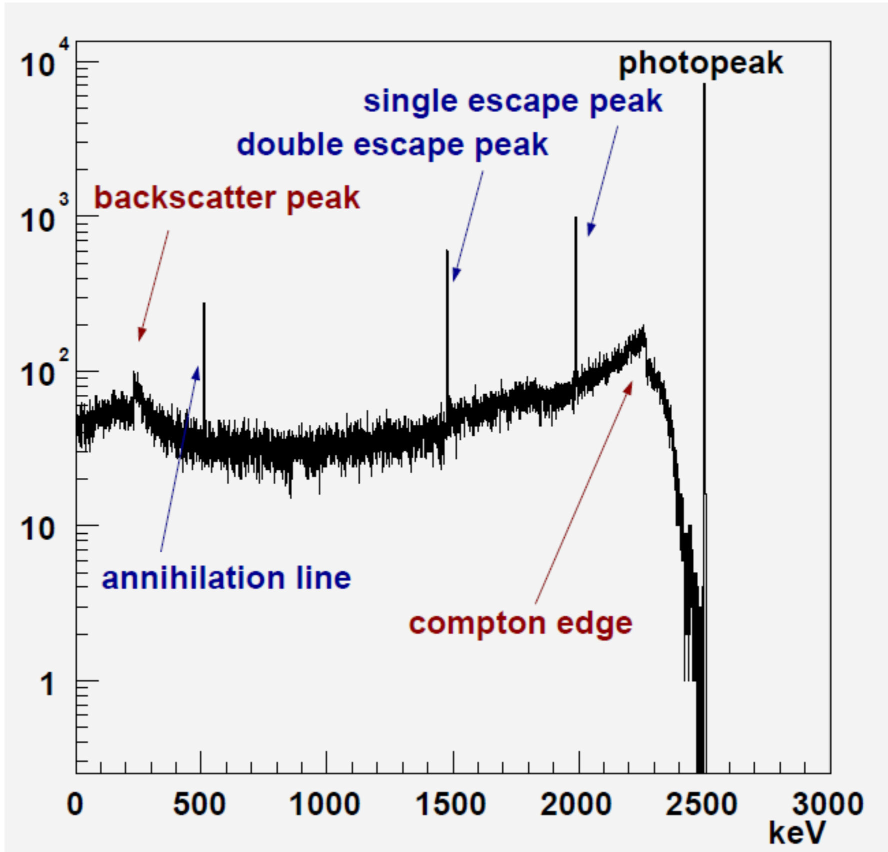
Ge detector response to a monoenergetic 2.5 MeV beam.

Off-diagonal response

(6) If the incoming photon's energy is > 1.022 MeV, pair production is possible. The resulting e− and e+ are decelerated in the crystal. When the e+ is sufficiently slowed down it interacts with an e− in the detector, yielding two 511 keV photons. If these are both fully absorbed in the detector, the event contributes to the photopeak.

(7) Here, an event is shown where both 511 keV photons escape the Ge detector without further interactions. Such events contribute to the double escape peak (DE). It is also possible for only one 511 keV photon to escape. The event then contributes to the single escape peak (SE).

Any of the effects listed above can also appear in other combinations, yielding events contributing to either photopeak or continuum.



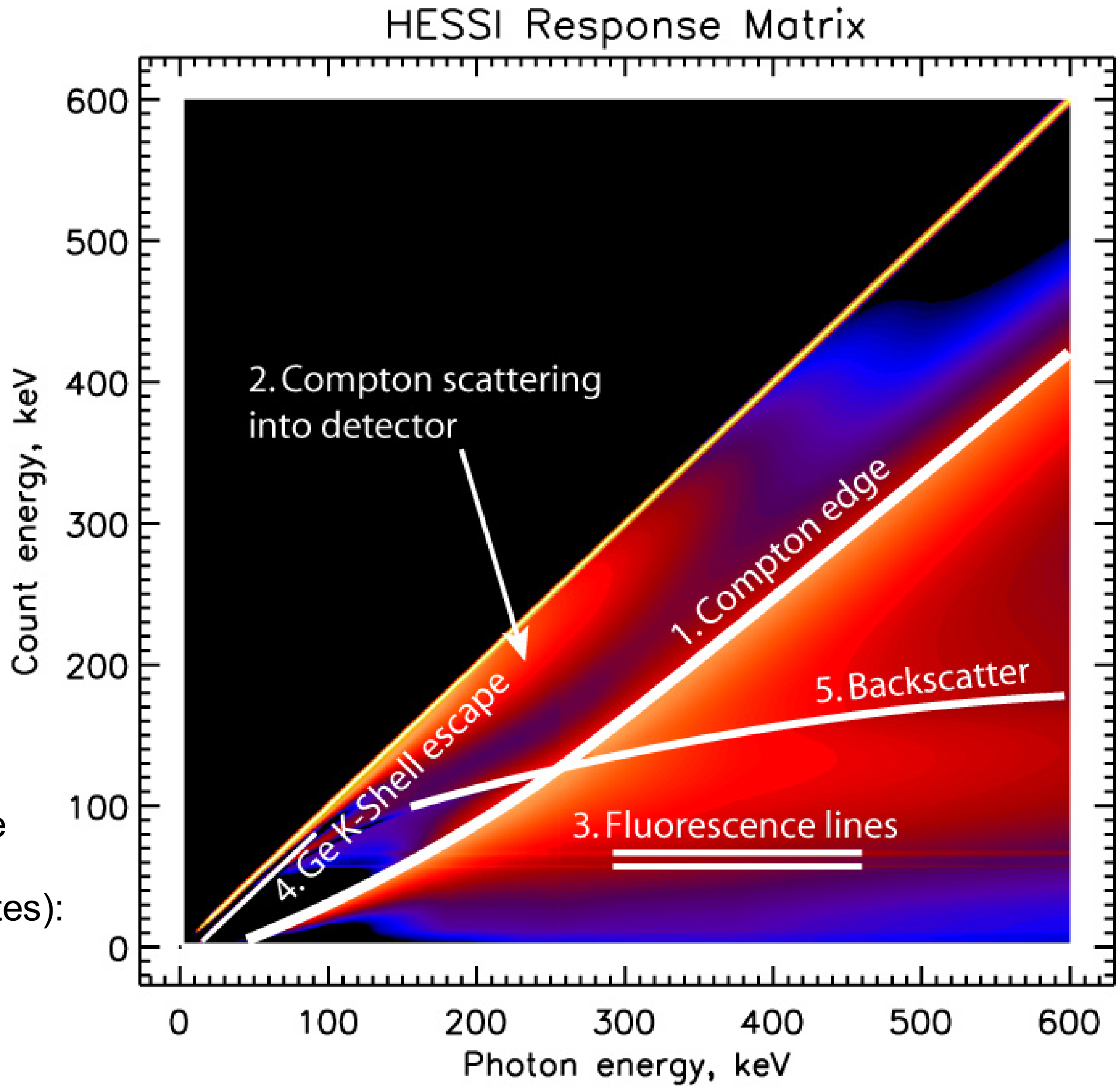
Ge detector response to a monoenergetic 2.5 MeV beam.

Off-diagonal response

Redistribution: Probability that a photon of incident energy E is recorded at energy E’

Usually contained in the Redistribution Matrix File (RMF)

Time variable (detectors are damaged by high energy particles and micro-meteorites): RMF and ARF should be updated through the Guest Observer Facilities



Spectral analysis

Suppose we observe D(I) counts in channel I (of N) from some source. Then :

$$D(I) = T \int R(I,E)\, A(E)\, S(E)\, dE$$

- T is the observation length (in seconds)
- R(I,E) is the probability of an incoming photon of energy E being registered in channel I (dimensionless)

$$\int R(I,E)\, dI = 1$$

- A(E) is the energy-dependent effective area of the telescope and detector system (in cm^2)
- S(E) is the source flux at the front of the telescope (in photons/cm^2/s/keV)

Spectral analysis

$$D(I) = T \int R(I,E)\, A(E)\, S(E)\, dE$$

We assume that T, A(E) and R(I,E) are known and want to solve this integral equation for S(E). We can divide the energy range of interest into M bins and turn this into a matrix equation :

$$D_i = T \sum R_{ij} A_j S_j$$

where S_j is now the flux in photons/cm^2/s in energy bin j.
We want to find $S_{j.}$

Spectral analysis

$$D_i = T \sum R_{ij} A_j S_j$$

The obvious tempting solution is to calculate the inverse of R_{ij}, premultiply both sides and rearrange :

$$(1/T A_j) \sum (R_{ij})^{-1} D_i = S_j$$

This does not work! The S_j derived in this way are very sensitive to slight changes in the data D_i. This is a great method for amplifying noise.

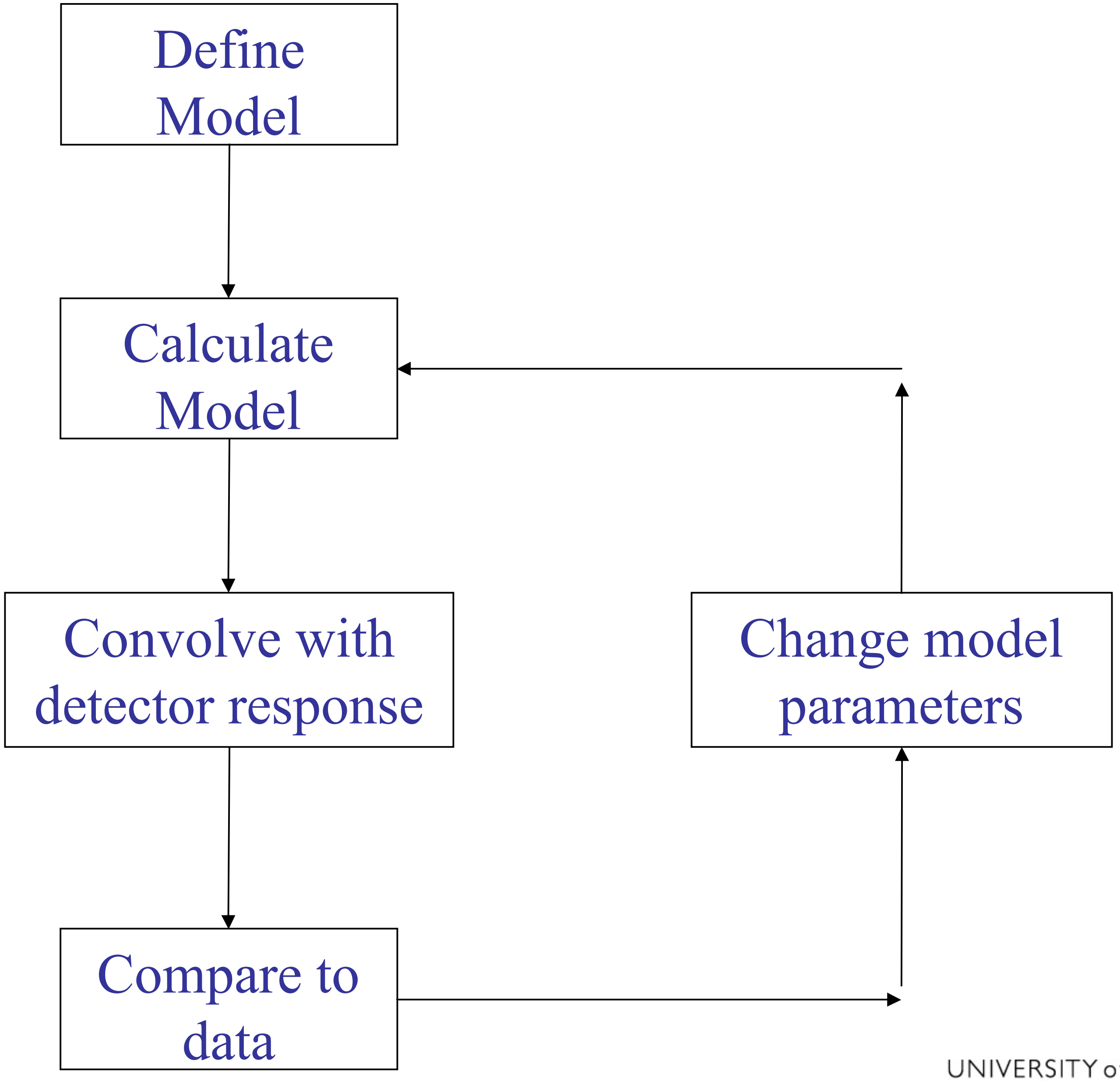
Spectral analysis: Forward-fitting

The standard method of analyzing X-ray spectra is "forward-fitting". This comprises the following steps:

- Calculate a model spectrum.
- Multiply the result by an instrumental response matrix.
- Compare the result with the actual observed data by calculating some statistic.
- Modify the model spectrum and repeat till the best value of the statistic is obtained.

The solution is NOT unique. Only some extra physical knowledge helps to get an answer.

Forward-fitting algorithm



Spectral analysis: Error propagation

For gamma-ray energies, Poisson statistics are the dominant error. Limitations on using sqrt(N) for error:

You must do this in units of **raw counts only**, not counts/s, not background subtracted counts

It's inaccurate for N<10 or so. sqrt(N+1) is slightly better but still no good for N<3. Binning counts to broader energy channels to get N ~ 10 is one of the possible solutions.