The Visual Computer

Visualization of eclipses and planetary conjunction events. The interplay between model coherence, scaling and animation

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The problem of an instructive and realistic animation and visualization of the shadow- and color-conditions during conjunctions of actively and passively illuminated cosmic objects has found only particularly satisfying solutions so far. As an example we study a total solar eclipse. There are didactic shortcomings of specialized astronomical software, even though solutions have been given, which are very impressive for experts.
Using the possibilities of commercial 3D-animation software we give an object-oriented partial solution. In order to get correct astronomical representations we model – for different tasks – the object space under cinematic aspects with parameters for spatial and temporal scaling, for illumination and coloring under couplings of varying strength. The adaptation of the parameters to optimal acceptance of the spectator must be done a posteriori.

Key words: Animation of celestial conjunctions – Object oriented motion simulation – Illumination by bright sources – Weber-Fechner-perception – Solar eclipse

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1 Introduction

Extraordinary astronomic events like total solar eclipses, meteroite falls or supernovae are rare and not reproducible. The perception of human viewers highly depends on accidential weather circumstances and on the observation point. It is therefore desirable to produce artificial pictures and films, which give most realistic impressions of those situations.
In contrast to usual science fiction a serious approach has to give correct simulations of the complicated order of events for an earthbound spectator and for varying virtual positions in space as well. The responsible designer has to master the tradeoff between a conceivable illustration and the reality of the universe, which can be grasped – if at all – only via temporal and spatial zooming.
Common astronomic visualisation software gives very impressive solutions with respect to cinematic correctness. But it doesn't give satisfactory realistic impressions of those events, where the immense adaptive ability of the human eye needs to be modeled in a reasonable way.
The challenge of the great European solar eclipse of 1999 encouraged people to produce material of the required kind. We point out the main difficulties and suggest some solutions, which come from our own experience.

2 General issues

2.1 Model coherence as basis for correct representations of astronomic events

The representation of astronomic events like a solar eclipse requires a good astronomical know-how. The motions of the heavenly bodies are determined by physics – there are no degrees of freedom. Therefore, there is no reason to model an autonomous behavior of the objects, as it has to be done, e.g., in the animation of animals [7].
A non-astronomer might run into heavy mistakes unless his program is supported and controled by a coherent model. Therefore object-oriented programming in the version of using the object space, which starts from the geocentric or the heliocentric model of the solar system, is required. Only then visualization bears the guarantee for correctness!
Of course, the development of events cannot be simulated from the bottom of the basic physical laws:

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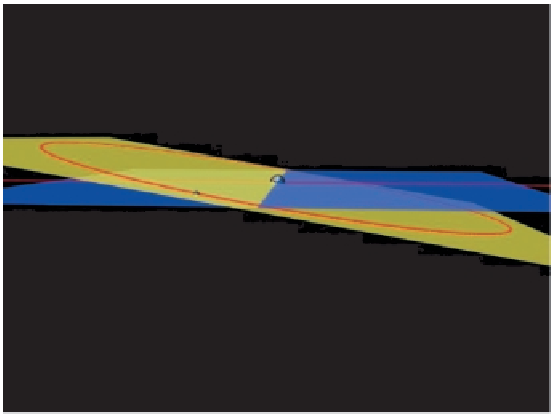


Fig. 1. Orbiting planes

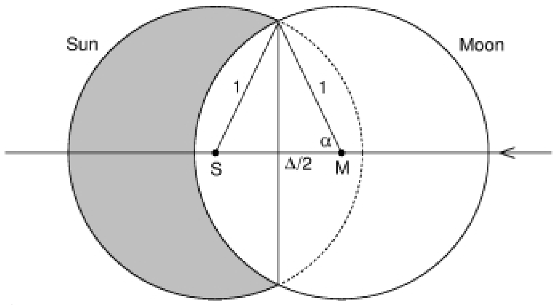
Newton's differential celestial mechanic is not trivial. We have to distinguish carefully between mathematical simulations, which are impossible for us, and animated visualization. For the latter only the well known cinematic consequences, which hide inertia and gravitation, can be used, i.e. we are working with Kepler's laws. The basic reason which causes the relatively rare solar eclipses is the fact, that earth and moon are orbiting in different planes (Fig. 1).
In order to demonstrate the really relevant features, we have to conceal those effects, which are not essential for the show. Thus, the fact, that earth- and lunar-orbit are elliptic and not circular, is only important for the distinction between total and annular eclipses. In such a case, it is more effective to regard the lunar orbit as elliptic and to keep the earth's orbit circular, even though the elliptic form of the earth orbit has also a slight influence on this distinction.

2.2 Space- and time-scaling for an appropriate visualisation of conjunction events

Within the astronomic context a strict object-orientation produces specific problems, which are in the center of our paper.
The main problem for the visualization of cosmic motion- and illumination-events is scaling. The differences in size between the objects sun, earth and moon are such big, that for a reasonable common representation of these three objects in one image, a radical and non-uniform reduction has to take place.
Programs like Redshift 3 [10] store all the data for planetary objects in a uniform size in the object space. All the data of this program result from physical simulations, which have been collected by NASA over a long time. The user can either see big portions of the sky with its stars. Or he can enlarge a scene with a single object, or two objects in conjunction, from a fixed viewpoint. Single isolated Objects can also be emphasized via specific filters.
In astro-software there are excellent facilities for time zooming and thus for animation from a fixed observation point in real time. On the other hand the choice of an appropriate observation position is rather difficult, and a convenient support for a dynamic change of the camera position is not always available. The manipulations with programs like Redshift require a lot of genuine own activity and of astronomic know how.
We have tried to produce a non-interactive video, and in doing so to optimize the change of size-relations in order to find a good compromise between an instructive animation and correct cinematics.
There remains a lot of basic psychological research to be done concerning the creation of attractive and comprehensible videos: How much of a complex causal chain can be grasped by a spectator? How fast has an animated motion to be, how often has a scene to be repeated in order to be understood? How can we simplify things without loosing essentials?
A general answer to all these question and the production of an instructive accompanying audio was beyond our purposes.

2.3 Substitutes for model coherent illumination- and shading-techniques

The illuminative power of the sun, which is an extended object and by no means dot-like, is so tremendous, that we have to replace it by a technique of imitating auxiliary constructions for an indirect illumination of the scene. Nobody should look directly into the sun without eye-protection – but this fact cannot be simulated on the screen.
As an actively illuminating object the sun should be a good candidate for applying the radiosity approach to outdoor scenes. But during a total solar eclipse there are big problems:
Consider two spheres like sun and moon (with same apparent radius $r = 1$ for simplicity). The moon



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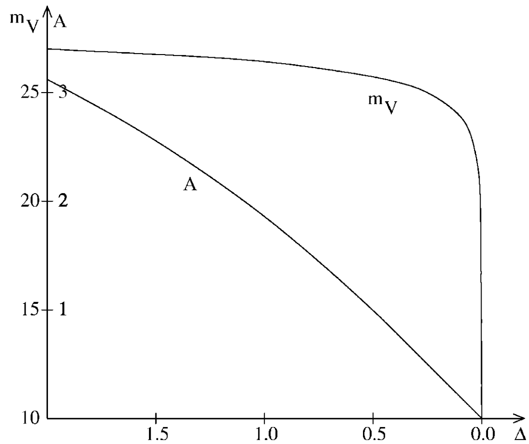

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Fig. 2. Development of a total solar eclipse
Fig. 3. Magnitude of the occluded sun

is gradually covering the sun moving on the central track from right to left with uniform velocity. Let Δ be the distance of the centers S and M of sun and moon, respectively. The time between the first contact ($\Delta = 2$) and totality ($\Delta = 0$) is about 80 minutes. Obviously, we have $\frac{\Delta}{2} = \cos\alpha$, and the uncovered area A of the sun, which is proportional to the absolute intensity and thus to the number of emitted photons, is $A = \pi(1 - \frac{2\alpha}{180}) + \sin(2\alpha)$ (Fig. 2).
Figure 3 shows the decrease of A dependent on Δ.
But the perception of the human eye follows Weber-Fechners logarithmic law [2]. The visual magnitude m_V has the value $m_V = 0$ for bright stars, goes down to $m_V = 23$ at the lower limits of observability and ends up at approximately $m_V = -27$ for the bright sun. The scale for m_V is adjusted by the convention, that a factor 100 in absolute intensity corresponds to 5 orders of visual magnitude for perception. Therefore one step on the m_V-scale corresponds to a factor $\sqrt[5]{100} = 2.51$, and the sun has $2.51^{27} = 6.3 \times 10^{10}$ more intensity than a star of visual magnitude $m_V = 0$. Since the corona of the sun – which is the visible part of the sun at totality – has approximately $m_V = -10$. which is roughly also the magnitude of the full moon, m_V for the sun is decreasing during a total solar eclipse from -27 to -10. Now m_V – this quantity is actually perceived by the human watcher – behaves quite different from A: By taking logarithms of A, we get the second curve of Fig. 3, which shows a dramatic decrease of brightness-perception within very few seconds before totality (see also Table 1), a fundamental difference to the situation at sunset. Since the reduction down to magnitude -10 does only happen in totality, an annular solar eclipse is by far less attractive: The most dramatic seconds are missing.
The geocentric features of illumination and shading (e.g. fluttering and sickle-shaped shadows and flying lines) near the totality are not yet completely understood, because there are rather few confirmed observations and fotos. Therefore a realistic visualization has to rely on fantasy from hearsay.

Table 1. Visual magnitude of sun between first and second contact

Δ	seconds to go	α	A	m_V
2.0	4800.0	0.0	3.1416	−27.0
1.5	3600.0	41.41	2.6883	−26.831
1.0	2400.0	60.0	1.9132	−26.462
0.5	1200.0	75.522	0.9895	−25.746
0.4	960.0	78.463	0.7946	−25.508
0.3	720.0	81.373	0.5979	−25.198
0.2	480.0	84.261	0.3993	−24.760
0.1	240.0	87.134	0.1999	−24.009
0.05	120.0	88.567	0.1	−23.257
0.01	24.0	89.714	0.02	−21.510
0.005	12.0	89.857	0.01	−20.757
0.001	2.4	89.971	0.002	−19.010
0.0005	1.2	89.986	0.001	−18.257
0.0001	0.24	89.997	0.0002	−16.510
0.00005	0.12	89.998	0.0001	−15.755
0.00001	0.024	89.999	0.00002	−14.004
0.0	0.0	90.0	0.0	−10.0

It seems to us, that in designing visualizations the difference between absolute and visual brightness is often neglected. At least for total solar eclipses the distinction is of vital importance.
There are consequences also for visualizations in heliocentric space: A realistic representation of the umbra and penumbra of a solar eclipse cannot be deduced automatically from the object model:
First: The umbra of the moon is sharp and parallel like a needle in space; the usual broad and conical representation of it in popular texts is more instructive, but false.
Second: The sudden change of color and brightness in the totality phase of an eclipse requires hand-controled techniques for interpolation and animation of colors and of illumination.
The common illumination-tools of 3D-visualization software are spotlights and parallel lights, but none of these correspond to the real illumination by the sun.
The first idea – to use parallel light in the earth-moon-system – fails, because the penumbra of the moon on earth (viewed from space) is not realizable.
As a substitute one can try to work with several spotlights which are placed at the circumference of the sun. The problem with this approach is – in addition to performance problems – ironically the exact rendering quality of 3D-visualization systems: For each light different sharp shadows are created and can easily be distinguished by the spectator.
While in reality the border between umbra and penumbra is quite sharp thanks to the missing atmosphere of the moon, the intensity of the penumbra is actually decreasing only slowly with the distance from the border.

3 Main tasks

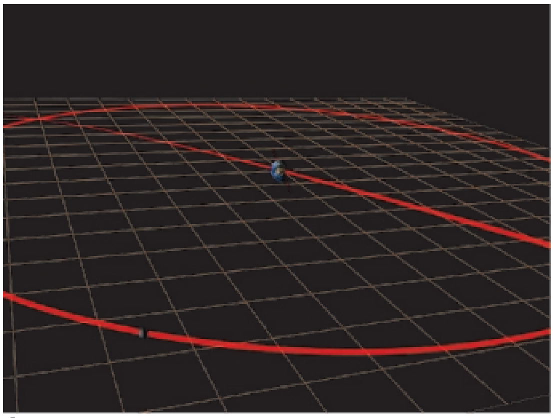
3.1 Geocentric presentation of a total solar eclipse

First, the normal course of the moon and of the sun over the sky is to visualize for one day or for one lunation (29 1/2 days) in medium northern latitudes at about the time of the equinoxes. The moon has to be made visible even at the time of the new moon, when he is running actually invisible near the sun. This can be achieved by a moderate self illumination of the moon.
Usually the new moon passes the sun from above or from beneath and doesn't hit the sun. The insertion of the annual orbit of the sun (ecliptic) and of the monthly orbit of the moon into the image shows, that a solar eclipse only happens, if the new moon is situated in the intersection of both orbits, which is called a knot or dragon-point. We have to illustrate, that a solar eclipse is a pure visiblity phenomeneon and that – contrary to a lunar eclipse – no objective darkening of the eclipsed object takes place. On the other hand, an illustration of the phases of the moon, of the rotation of the moon and of other features is possible, but not essential.
The model uses for the central earth two spheres with different distances from the spectator in the center. The near (metereological) sphere contains a cloud-texture, the far sphere consist of a texture for fixed stars on the firmament. Both spheres are moving with different speeds, no further animation is required. However, sun and moon are moving independently on their orbits between the two spheres, the moon being nearer and faster than the sun. There is no more structure in the model. From Copernicus we know, that the geocentric model is not the optimal basis for the object space. Thus the danger to make astronomic mistakes in this model with loosely linked parameters is big – this was one of our first bitter experiences!
On the other hand, there was no need for a tight synchronization of all relevant motions; in particular, the rotation of the earth had not to be adjusted to the speed of the moon and of the sun on the outer sphere for the firmament. The deeper reasons for an eclipse are rather difficult to explain in the geocentric model.
The geocentric animation must be embedded into a natural scenery of surfaces for the landscape in connection with an appropriate illumination.We use NURBS on the basis of approximating control vertices (CVs). The foreground contains water of a lake, the waves are animated by the phase of the space warp, the reflection of the shining objects on the water is animated in the video. The possible variations of the relevant parameters (length and width of the surfaces, number and weight of the vertices, amplitude, wavelength and phase in x- and y-direction) have been fixed only after several psychological and esthetic experiments with students of the seminar.
Appropriate textures have been selected from the material editor. The only difficult problem was – of course – the design of the sun. Using the Gizmo technique a satisfying impression was achieved. In order

to animate the brilliant radiation of the sun, we make use of lens effects, which are usually undesirable in illuminated scenes.
One has to take care of some well-known optical illusions: Usually the size of the sun is over-estimated, since the time when the sun is observable without protection filter is usually about sunset and sunrise, and then the horizon gives rise to a wrong illusion. In our context we recommend to ignore the real size and not to correct the incorrect expectations of the viewer. Furthermore, people have in mind a yellow sun, even though the "real" color is white. In keeping the sun yellow we also renounce to teach the viewer too many things at a time.
The sudden and strong darkening effect at the moment of beginning totality, which was mentioned above, has as far as we know never been presented on a video in a realistic manner. Since people usually did not personally experience a total solar eclipse before, one is unable to produce realistic impressions on a virtual basis. The range of sensitivity of the human eye is by far greater than that of any usual film-material. Only very recently there seem to exist new techniques for photo-reproduction, which have the ability of good adjustment to fast changes of illumination intensity and thus will yield natural examples for virtual animation. But surely we have to work for the time being with a hand-controled color-animation.
Since the blinding effect of the sun cannot be simulated on a screen, the abrupt transition between the partial occultation – when observation with the naked eye is dangerous – and the phase of full totality has to be simulated in a different way: We change the background of the sky abruptly from light blue to black.

3.2 Heliocentric visualisations from different positions in space

For this more difficult task we need a model in the heliocentric object space. Sun, earth and moon are the basic objects, they form a hierarchy in this order [6]. As hierarchical auxiliary objects we introduce:
Orbit of the earth around the sun, orbit of the moon around the earth (the corresponding orbit-plane is realized as a mesh-plane), umbra and penumbra of moon and earth; moreover the knot-line of the plane of the present moon-orbit and possibly the line of the apsides, i. e. the main axis of the present ellipse of the moon orbit.
This system of objects is equiped with reasonably defined parameters:
Radii of sun, earth and moon, the axes of the moon-orbit-ellipse, furthermore rotation and inclination of the corresponding plane around and against the ecliptic, rotations of earth and moon and the inclinations of the axes of rotation; velocity of the earth on its course around the sun and of the moon around the earth, respectively.
The choices for these parameters can be made a posteriori with the help of the selected software in a dynamic manner – but the optimization is difficult: The distance between the sun and the earth-moon-system must be decreased by more than a factor 100, the distance between earth and moon must be reduced by 50%. In a similar manner the radius of the sun has to be reduced very much, while the relation between earth- and moon-radius has to be maintained. We also change the inclination of the moon-orbit-plane from 5 to 10 degrees.
We use different cameras with independent motion dynamics as a standard tool of animating visualisation software.
From all these requirements it is obvious, that a physically based simulation of the system as it might be suggested by Hégron [6] is impossible. Only a cinematic model tolerates those parameter manipulations.
One could ask, whether an arbitrary change of geometric and temporal scales affects the physical plausibility of our animation. Is it really desirable to couple the dimensions of our system and the temporal conditions in the orbits according to Kepler's laws? In our opinion the answer is no, since Kepler's laws are direct consequences of Newton's gravitation theory – and gravitation forces between cosmic objects are extremely non-intuitive. The apparent area of an object grows with the square of its linear dimension, but the volume (and therefore the mass) grows with the third power. Each shrinking model of cosmic objects under-estimates the influence of gravitation by the reduction factor in the model.
Therefore, man has no direct feeling for the gravitation forces which come from sun and moon – e.g. the tides. And the influence of the planet Jupiter, e.g., on the motion of the earth in space is much bigger than it is usually supposed. Therefore, we have a wrong intuition concerning celestial motions anyway, and coupling between size and motion of these bodies does not improve plausibility.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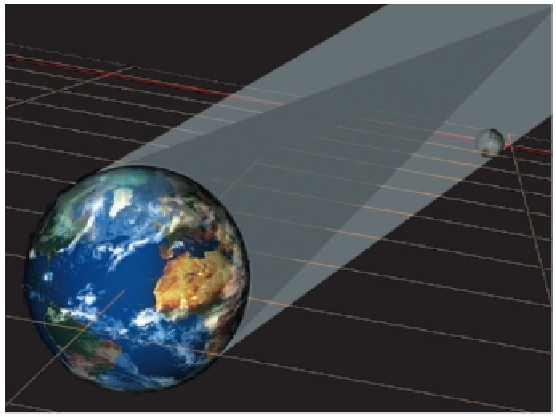
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Fig. 4. Planetary system overview showing orbits of earth and moon
Fig. 5. Lunar eclipse

In summary, it was possible to get a good compromise between the values of the real world and those values, which are optimal from a psychological point of view.
But there are limits of the effectiveness of model coherence! These limits are connected to illumination- and coloring problems.
A realistic modeling of the sun as a source of light is impossible with the available software for visualization. The ultimate solution at least for the shadows in the empty space was somewhat dirty, but efficient: In order to get a convincing fog manipulation we added two nested semi-transparent cylinders for each of moon and earth; then using the anti-aliasing tools of the system, we got a seemingly realistic view to the shadows in space.
The techniques of spot-lights and of parallel lights are unable to simulate penumbra phenomena, which occur with an extended light source of the sun's radiation power. Initially we worked with a dozen of different sources of light, which were distributed over the surface of the sun. But the gradual decrease of the penumbra near the totality-region was simulated only badly, and the sharp contrast to the central umbra was also not achieved.A useful further improvement for these defects consists in postprocessing the rendered frames with the video software system.
What is the "correct" model to show the moon's shadow on earth if we are virtual observers in space? It might seem that the number of photons is the correct illumination measure – and not the subjective Weber–Fechner-controlled perception of an earth-bound observer. Thus the border between umbra and penumbra should not be sharp – according to curve A in Fig. 3. Since we are still lacking real photos from space in the extraordinary event of a total solar eclipse, we are uncertain about the optimal modeling of the umbra's sharpness: Our own subjective evidence according to curve m_V might encourage us to model a very sharp border. This discussion raises doubts, wether it is reasonable at all to conceive a virtual observer in space, who is not equiped with some artificial protection and support for his eyes.
Another related problem is the visualization of umbra and penumbra in the empty space without any objects which are hit. Here we implant appropriate cones into the scene, which give the control for fog manipulations.
Summary: The development of a general optimization technique for the illumination of planetary objects in a scaled object space is not yet solved!
Viewing the earth during a total solar eclipse from the position of the moon or from nearby space has to take into account the rotation of the earth. While it is easy to cover the globe with a texture of the continents and make it rotate around the inclined earth axis, the choice of the rotation-speed-parameter requires a loose linking to the speed for the moon, which runs in front of the earth. We accelerated the moon in his orbit by 50%. We also had to choose a camera viewpoint, which is close to the direction of the sun – only a little bit different from it.

If we want to establish a realistic texture for the surface of the moon in order to look at him from space, we have to adapt the rotation speed of the moon to his orbit-speed. Then the moon shows his front side always to the viewers from earth, however from outer space the back side is also partially visible.
In principle this model can easily be refined, if we model the periodic change of the form (excentricity) of the momentary lunar orbit ellipse. Then phenomena like annular solar eclipses and also the libration of the moon can be visualized, (we have to design the speed on the ellipse in the spirit of Kepler's second law).
Another new task is to visualize longtime periods, which extend over a lot of years, like the Meton- or the Saros-cycle. Here we have to link the rotation time of the knot-line and the (different) rotation time of the apsides-line with the annual revolution of the earth around the sun and of the moon around the earth.
In order to make these long periods also for short videos comprehensible, a reasonable design of the ratios of velocities is required. Here the renunciation of simulations on a gravitational basis makes a complete relaxation of the spatial and the temporal order of events possible.
But there are limits of relaxation, as we have seen: The automatic animation of light and colour changes with spatial and temporal zooming. Furthermore, there is an informal tradeoff between the tight linking of the model parameters and the reliability of the output with respect to astronomic correctness.
The heliocentric model is also good for the visualisation of conjunction events other than solar eclipses. As an example we have created a video for a lunar eclipse. Here the shadow of the earth really works as cause for the eclipsing of the moon.
Here the radiosity approach would be possible in principle, since the illumination of the earth-atmosphere is responsible for the colour of the eclipsed moon. But considering the various possible conditions of the atmosphere which might affect this coloration, we confined ourselves to the anti-aliasing technique mentioned above.
In a similar manner the standard technique of several moving cameras with independent zooming enables us to visualize situations from quite uncommon perspectives. We produced a journey (video) over the dragon line of the earth-moon system with some fantastic illuminations.
There seems to exist a certain need to produce realistic videos and movies for virtual travels to other celestial objects of the planetary system or to objects in deep space. The present technique to produce space mission movies relies mostly on pure fantasy with only very little physical background.
The use of an object space and coherence in visibility are the first requirements for those productions. A "correct" view to Saturn from a position on its ring or to Jupiter from one of its satellites is a major challenge for future video artists.
A "realistic" modeling of the illumination effects could be achieved with a model of that kind which was discussed for the total eclipse: With respect to Weber–Fechner's law the occlusion of a shining object like the sun shows a development, which depends on the brightness of the shining object, on the atmosphere of the occluding object and on the visibility conditions at the position of the observer. A sunset on Mars with the very thin atmosphere there or the immersion of a spacecraft into the gaseous world of Jupiter might be designed with a serious scientific background and with an illumination model behind. The animation of a movement under exotic gravity conditions is one of the dreams, the realization of which is far beyond the present possibilities: It would be very attractive to model a realistic soccer game on moon or on mars automatically with the only need to fix the appropriate gravity parameter – but such a solution seems to require heavy physical simulation efforts and is – as we mentioned in 2.2 – the task of another discipline of informatics.

4 Conclusion

We have given solutions for geocentric and heliocentric visualisations of solar eclipses on the basis of professional software. Some specific shading problems which arise from the cosmic dimensions of our model have to be solved separately. For student team purposes, the rendering time is considerable and prevents us to give ideal and professional solutions.

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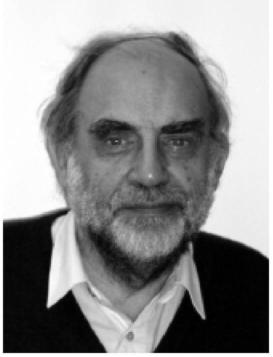

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