Perceptually-motivated Real-time Temporal Upsampling of 3D Content for High-refresh-rate Displays

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Eurographics, 7 May 2010, Sweden

Hello everybody, Thank you for introduction and let me start with my talk.
Today I'm going to present a work done with collaboration with Elmar Eisemann, Tobias Ritschel, Karol Myszkowski and Hans-Peter Seidel on perceptually-motivated temporal upsampling.

Displays improvement

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1990's | 2000's | Today | Future

Recently we can see a tremendous improvement of off-shelf screens.

In 90's we had CRT screen that allowed for high frame rate but it could cause some flickering problems. Also the brightness and contrast of those displays were not the best.

Later the era of LCD displays started.
They offered bigger brightness and better contrast. Also the flickering problem was solved. However, the framerate of those displays was significantly reduced due to problem with response time of liquid crystals.

Today we have new LCD displays that offer even bigger brightness and better contrast. The response time is very low therefore higher frame rates are possible.
This allows to solve the problems that come from low frame rates.

In future the response time will be reduced even more allowing for even higher framerates. Also brightness, contrast and colors will be improved.

Display device as well as its properties should be taken into account as a last step of delivering an image to the viewer.
Today I would like to talk about possibilities of new high framerate displays, originally designed for stereo vision, and what problems can be solved.

Displays improvement

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1990's	2000's	Today	Future
			

- High refresh rate - more than 120Hz
- Low brightness level
- Flickering at lower refresh rates

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Displays improvement

1990's 2000's Today Future

- No flickering
- Higher level of luminance
- Low refresh rate - ~60Hz
- Long response time

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Displays improvement

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- Brighter, better contrast
- Response time reduced
- High refresh rate
  - ➡ New possibility of taking to account temporal integration of HVS

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Displays improvement

1990's — 2000's — Today — Future

- Very small response time
  - ➡ higher refresh rate possible
- Better colors, contrast and brightness

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Displays improvement

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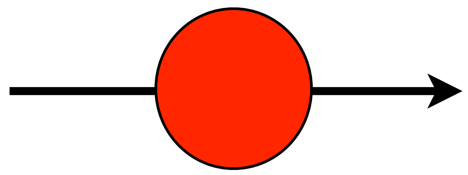
2000's

Today



We are here

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30Hz vs. 60Hz

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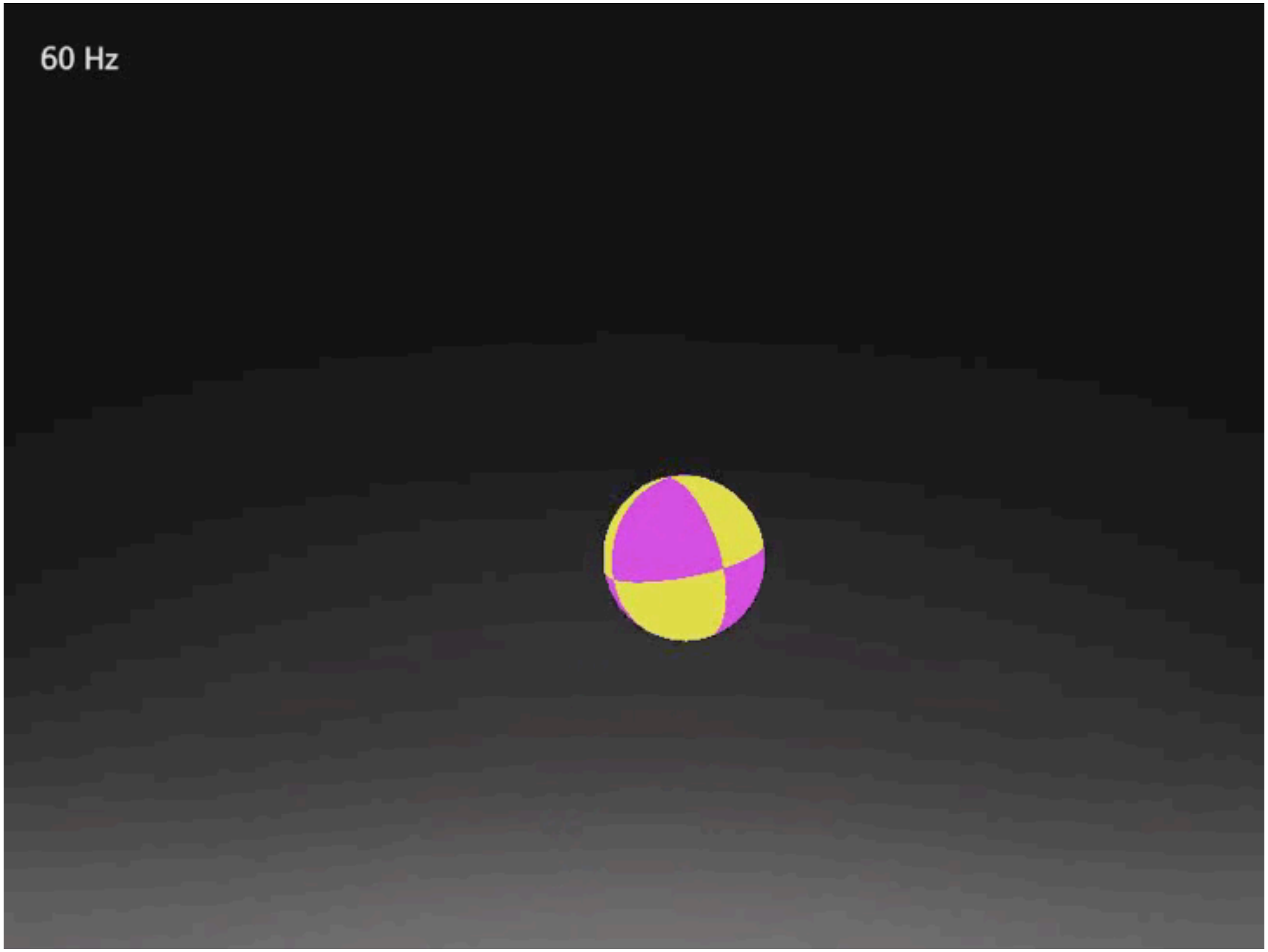
30 Hz

60 Hz

Let us consider two moving bars from left to right at 30Hz and 60 Hz.
We can clearly see that lower one is much sharper.

Hold-type blur



Human visual system is trained to tracked moving objects.
In reality doing so, we create sharp image on our retina.

If the frame rate gets lower, each frame is display for extended period of time and moving eyes blur the perceived image.
This leads to so called hold-type blur.

Hold-type blur

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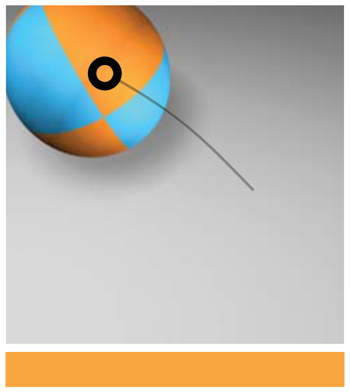
Reality



Let us look on this figure and consider one receptor tracking the ball.
In real world due to tracking the receptor will receive the same signal over time.
Looking at the screen, the receptor will move across the screen tracking the ball.
Because the ball is kept in the same position for extended time the receptor integrates different signal over time, blurring perceived image.

Hold-type blur

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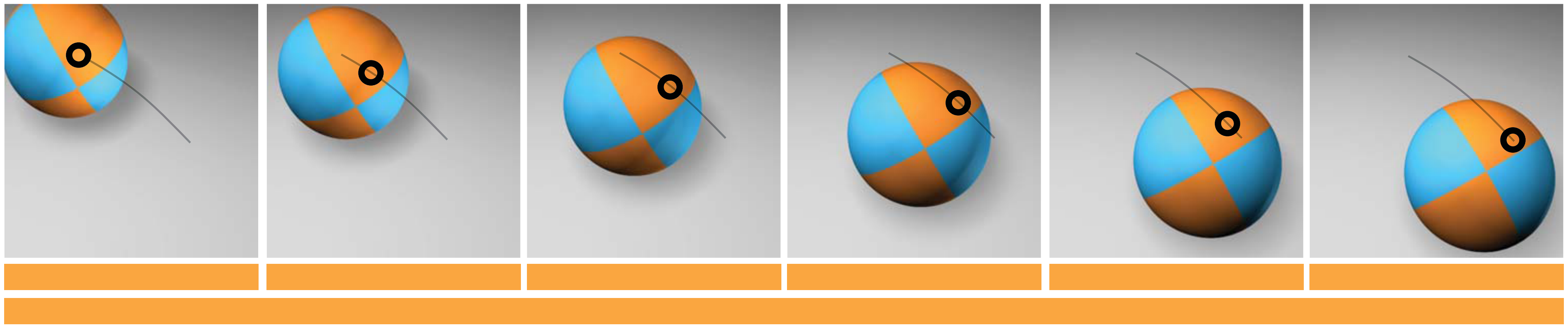
Reality



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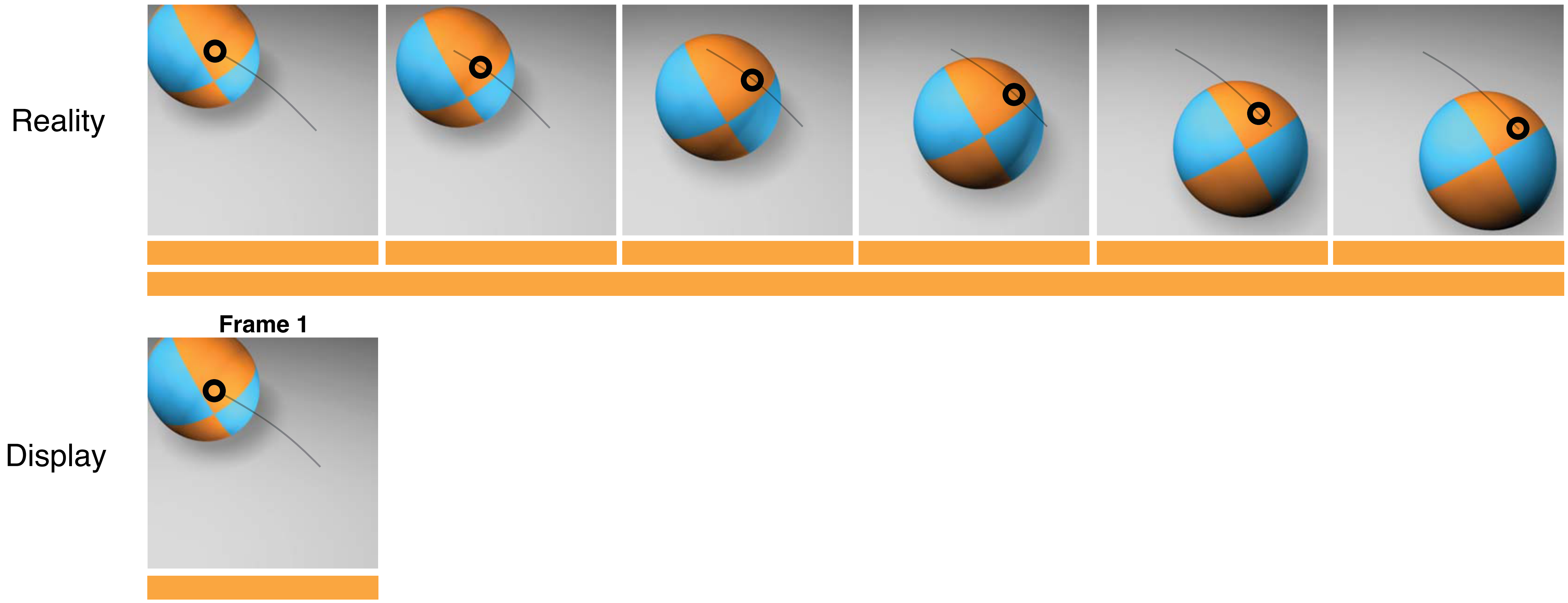

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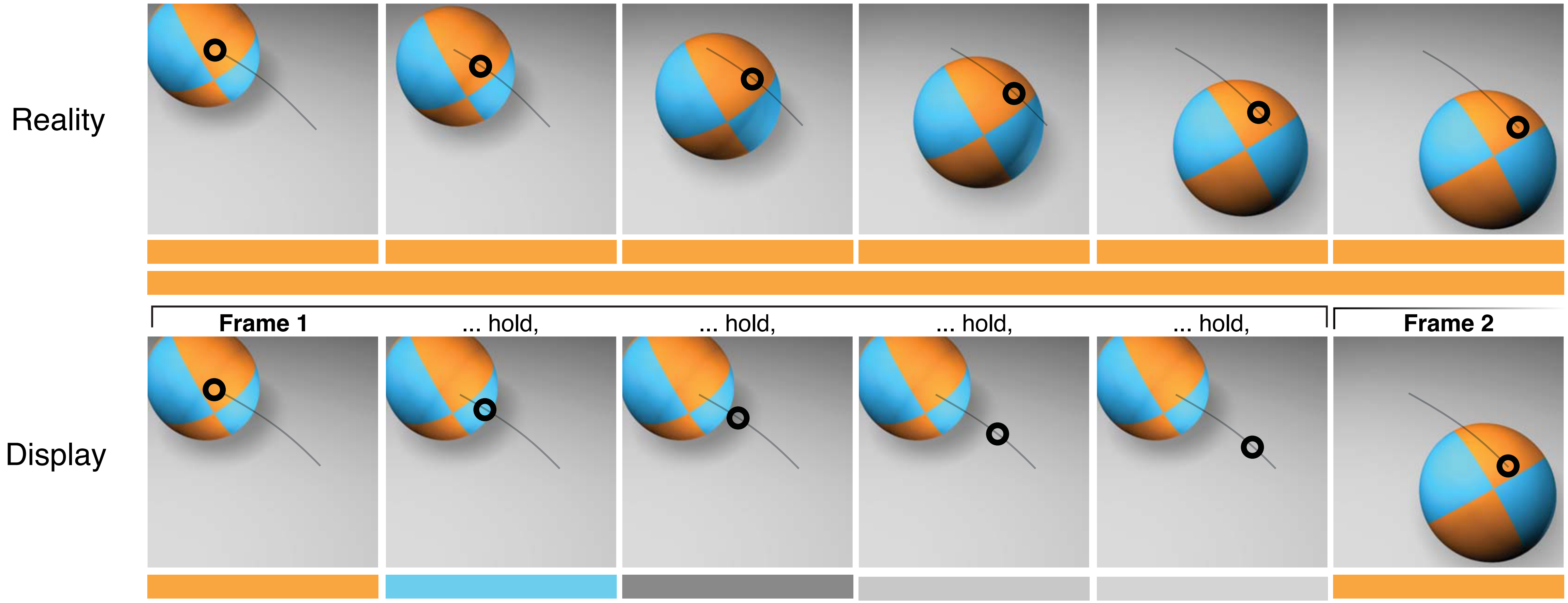

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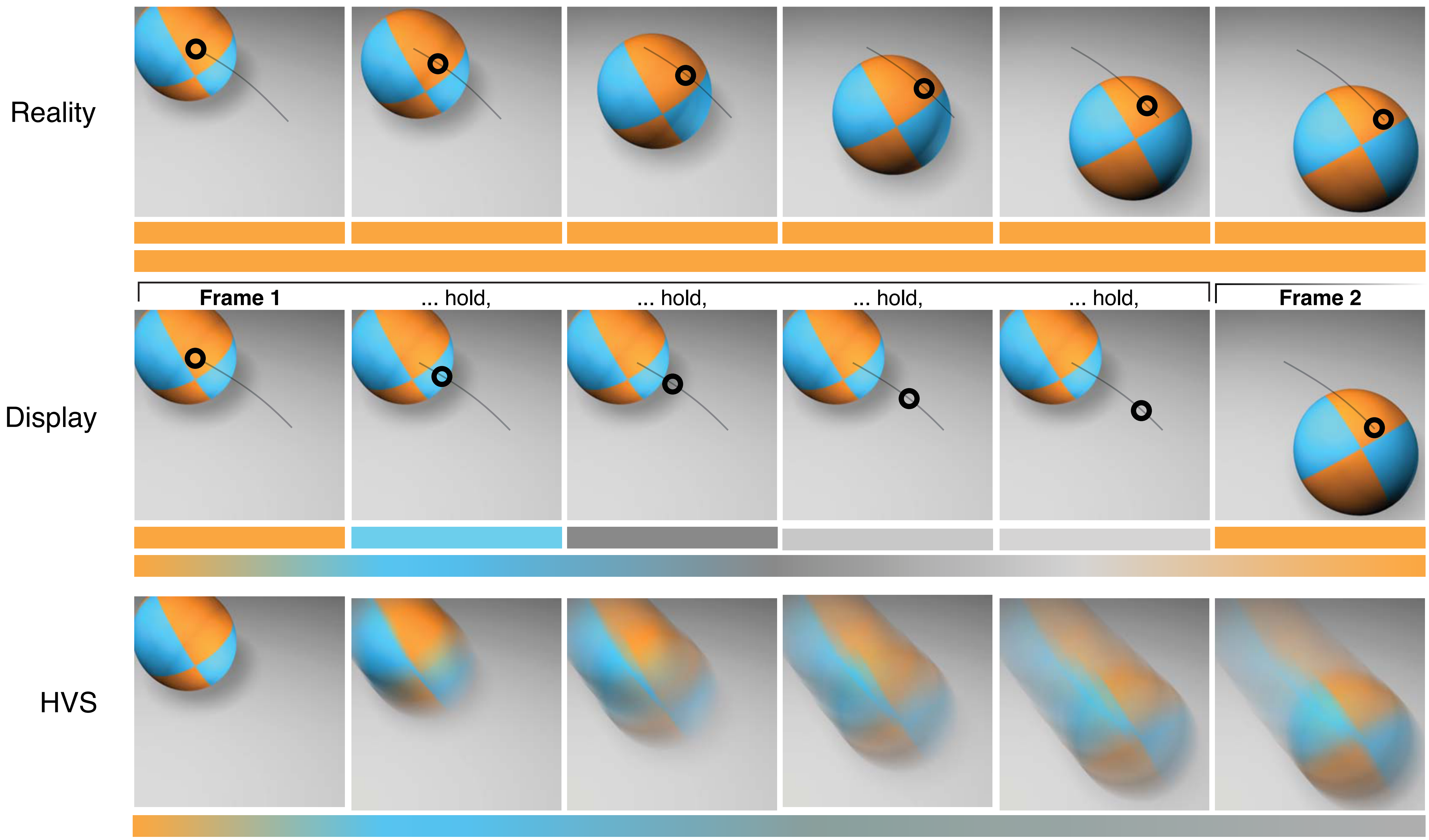

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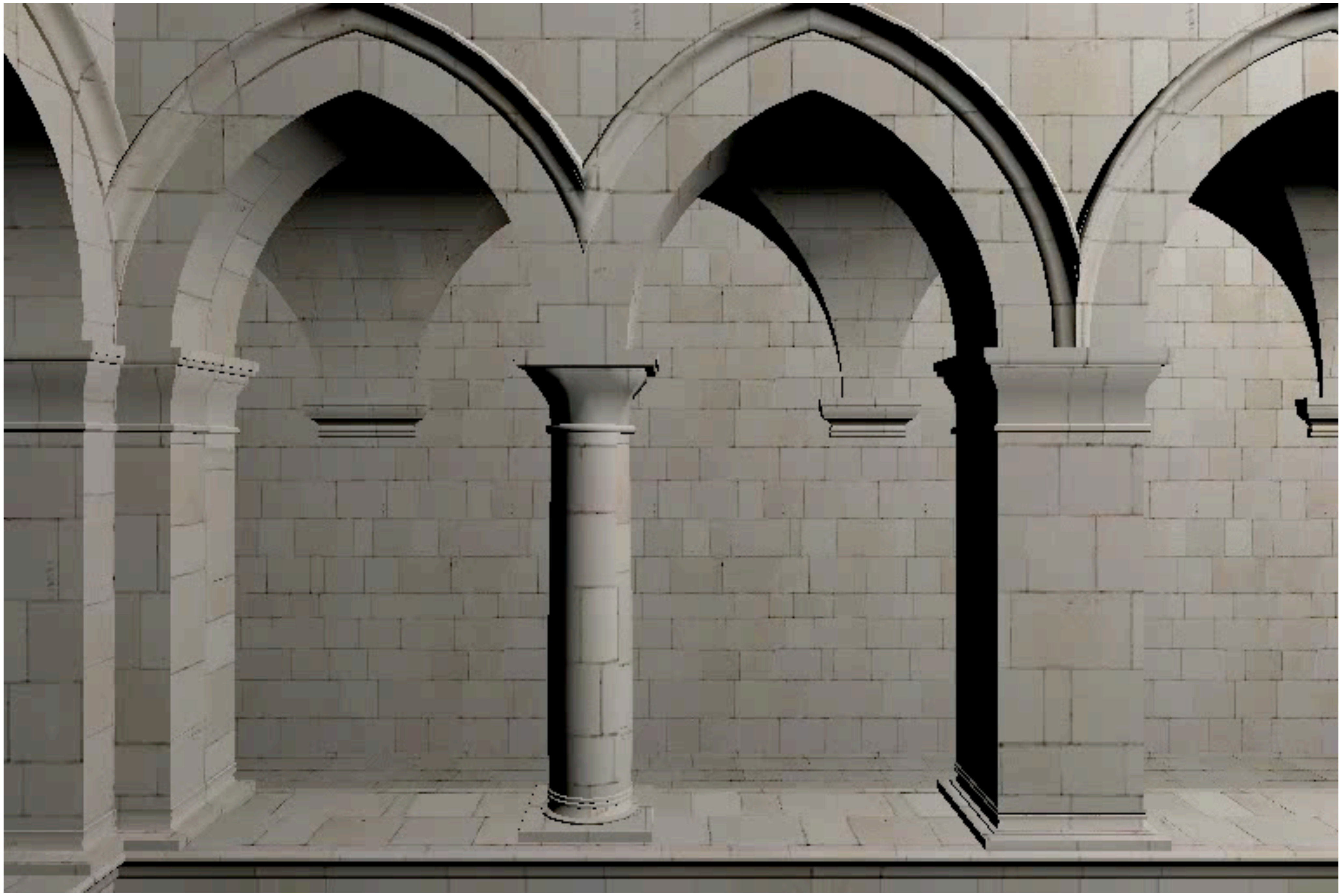
It happens in our eyes



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Here we can see hold type blur in 3D scene.
When we stop tracking, looking for example in one point of the screen, we can see that all displayed frames are sharp, although we see them blurred when we track.
This proofs that the perceived blur does not come from limitation of our display but rather from the fact of tracking.

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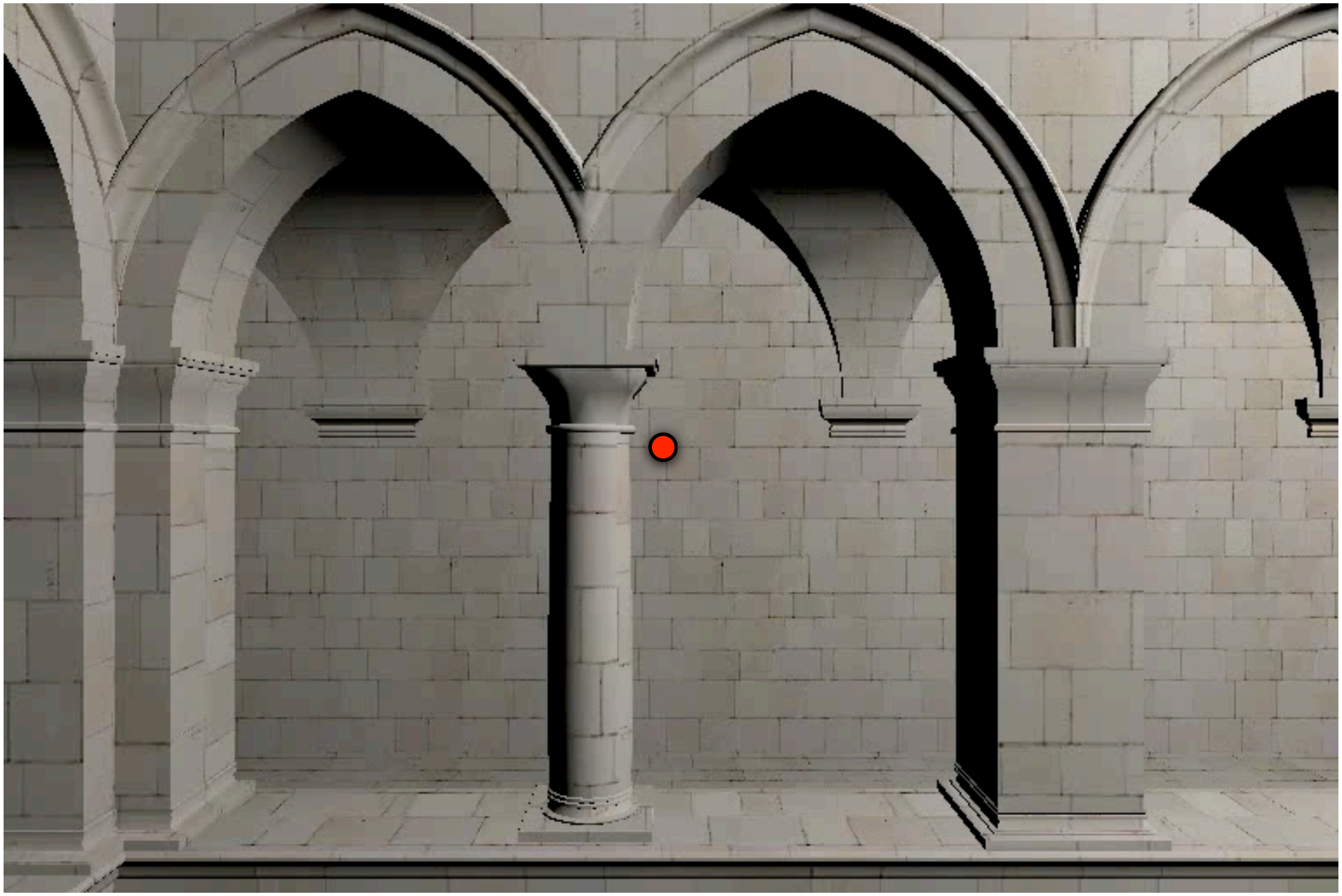

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Hold-type blur reduction

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Hold-type blur ≈ Inverse of motion blur

- content static
- eyes move

- eyes static
- content moves

The hold type blur can be seen as an inversion of motion blur.
In motion blur, eyes are kept in the same position and the content is moving.
In case of hold type blur, the eyes are moving, tracking, and the content stays static during one frame.

The general solution of the problem is to reduce the time that the same frame is displayed.
Simple solution would be to increase frame rate.
Because it is usually very expensive people came with other solutions.

Hold-type blur reduction

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General solution: **reduce the "hold" time**

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General solution: **reduce the "hold" time**

Simple solution: **high framerate**

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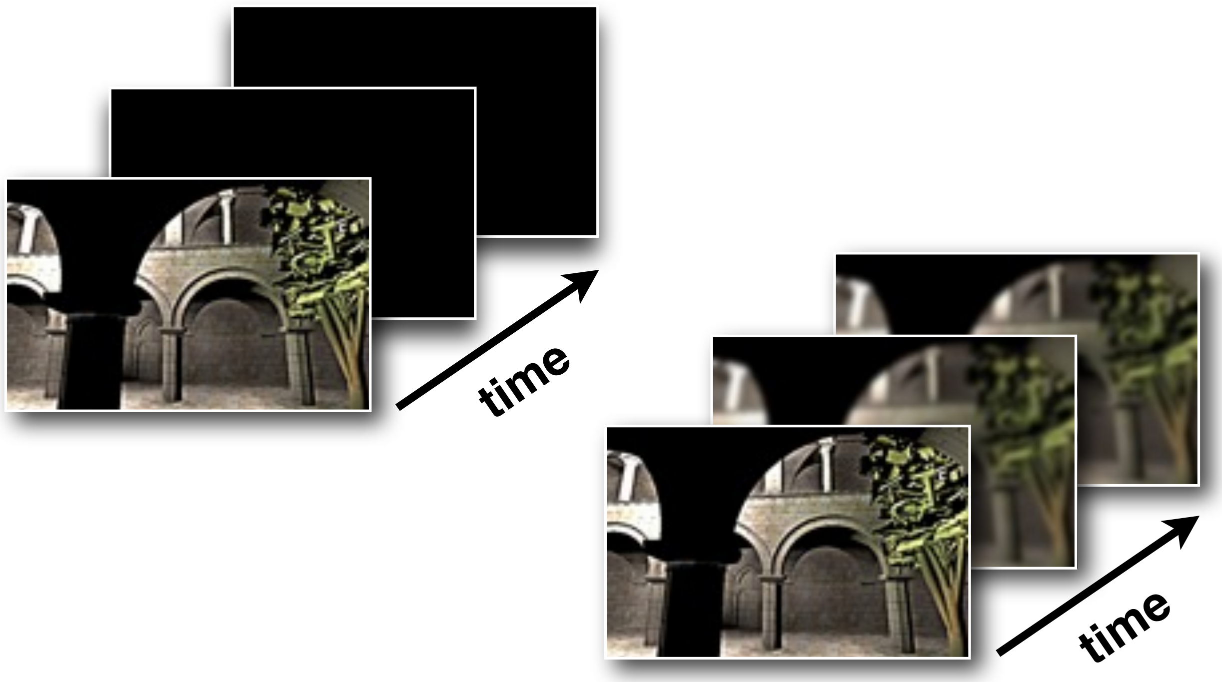
Previous Work
Hold-type Blur Compensation



- **Black-data insertion**
  [Feng et al. 2008]
- **Backlight flashing**
  [Pan et al. 2005, Feng 2006]
- **Blurred-frame insertion**
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Feng with Pan et al. described the possibility of black data insertion.
Instead of displaying one frame for a full frame time it is is displayed for a fraction of this time. For the rest of the time the screen is black.
This can lead to flickering problem as well as reduce brightness and contract.

Chen et al. came with idea of putting blurred frames inbetween instead of black.
This solve the problem of flickering as well as brightness and contract reduction but introduces ghosting behind moving objects due to lack of motion compensation.

There are also two methods commonly used in TV-sets.
Kurita et al. described how to double the frame rate using image based motion flow and Klompenhower et al. show how to inverse the model of hold-type blur to compensate it by inverse filtering.
Those methods rely on image based motion flow that in such application cannot be computed accurately due to lack of time.
Also applying sharpening as a compensation does not solve the problem completely.

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- **Frame rate doubling by interpolation**
  [Kurita 2001]
- **Motion-compensated inverse filtering**
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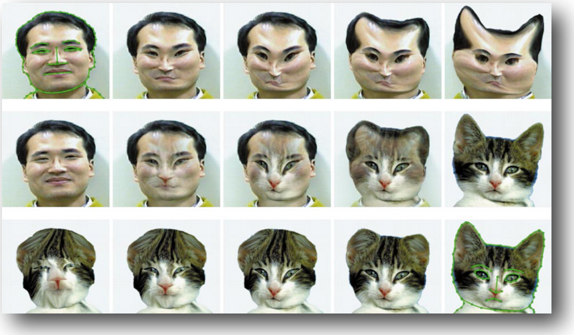

- **Image morphing**
  [Wolberg 1998]

Also temporal upsampling is well studied problem in computer graphics.

Wolberg in his survey showed how using mesh, inbetween images can be created.

Later, Stich et al. showed that edges are important issue in interpolation problem. They proposed a method that interpolates inbetween frames taking spacial care of edges.

Recently Liu at el. proposed a method for morphing between different views to create stabilized video.

There is also recent work on image interpolation by Mahajan et al., which explores knowledge of past and future to interpolate inbetween frames.

The problem of all methods listed above is that they are time costly and the interpolation introduces lag at least of one frame.

Previous Work
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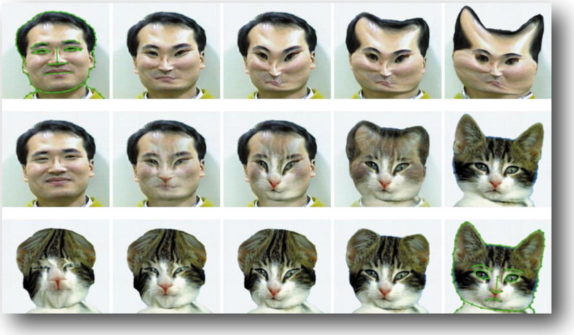

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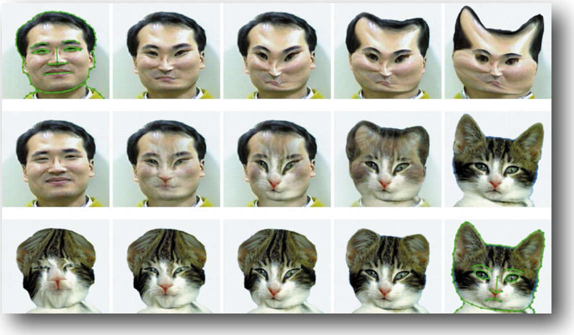

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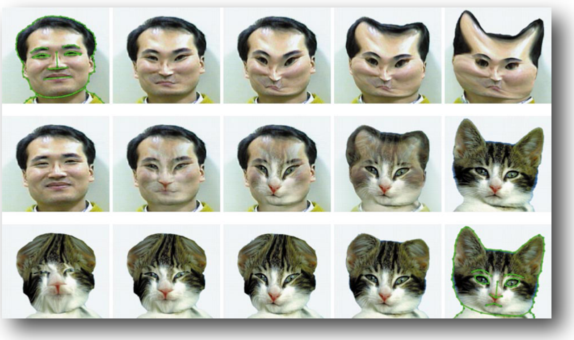

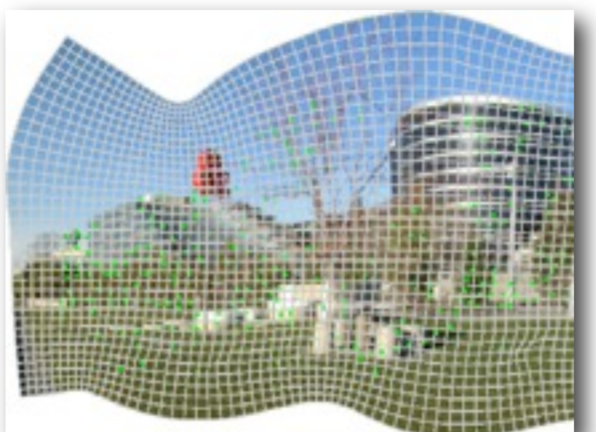

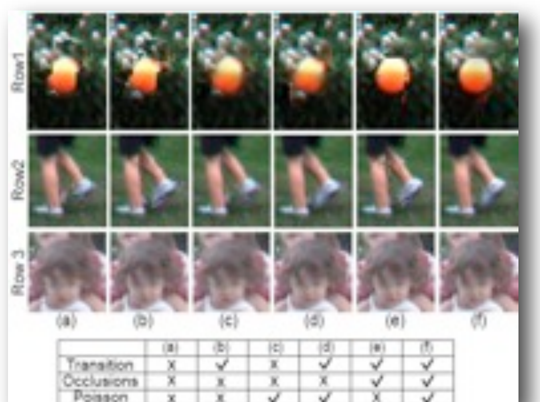

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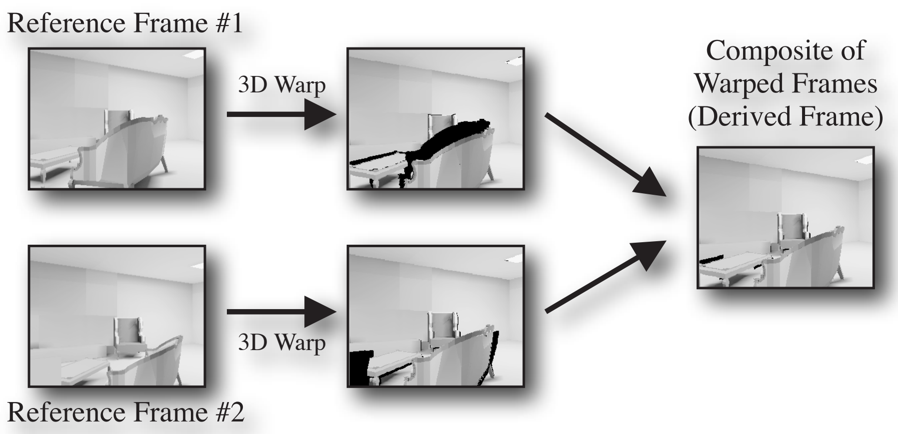

- **Post Rendering 3D Warping**
  [Mark et al. 1997]

In the context of 3D rendering and realtime application Mark et al. used warping from more than one frame to create inbetween frames.

They are also methods that use temporal domain to save on computations by reusing information from the past, increasing at the same time framerate.
Example of such work is Interactive rendering using render cache by Walter

or more recently work by Nehab et al. on reverse reprojection cashing using GPU.

Previous Work
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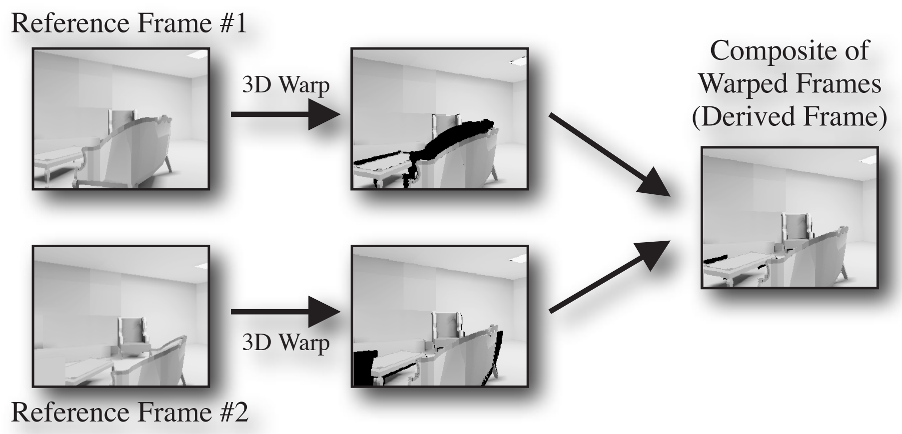

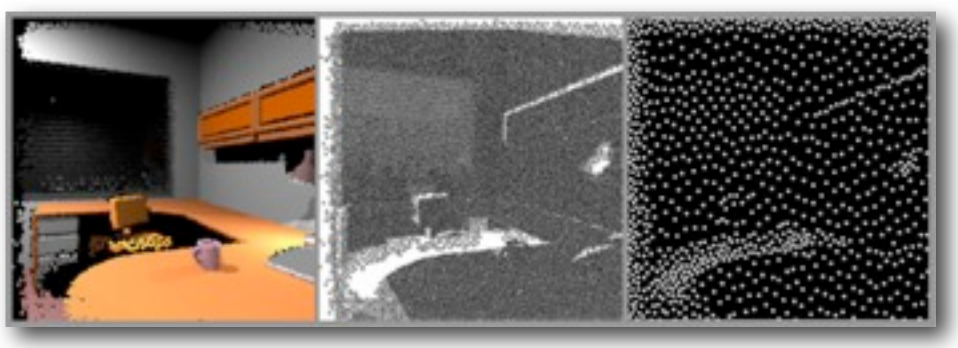

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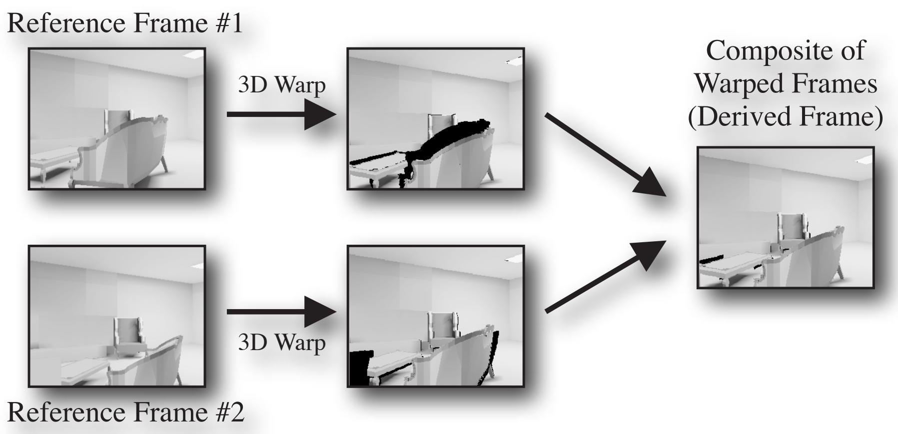

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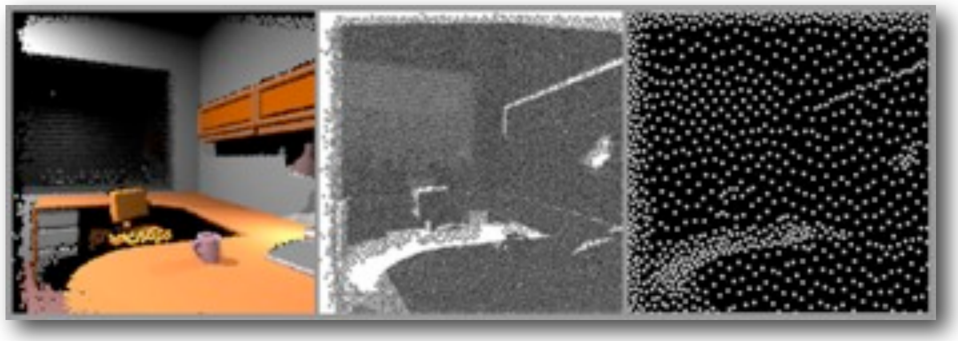

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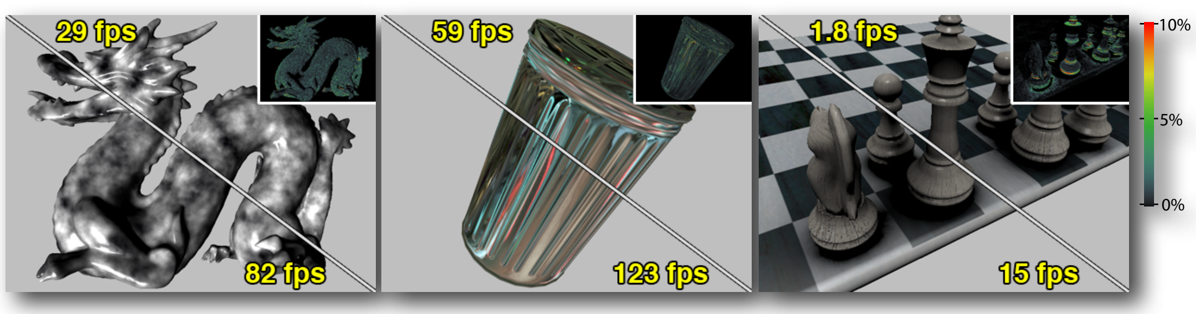

- **Accelerating real-time shading with reverse reprojection caching**
  [Nehab et al. 2007]

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Hold-type blur reduction
Our approach

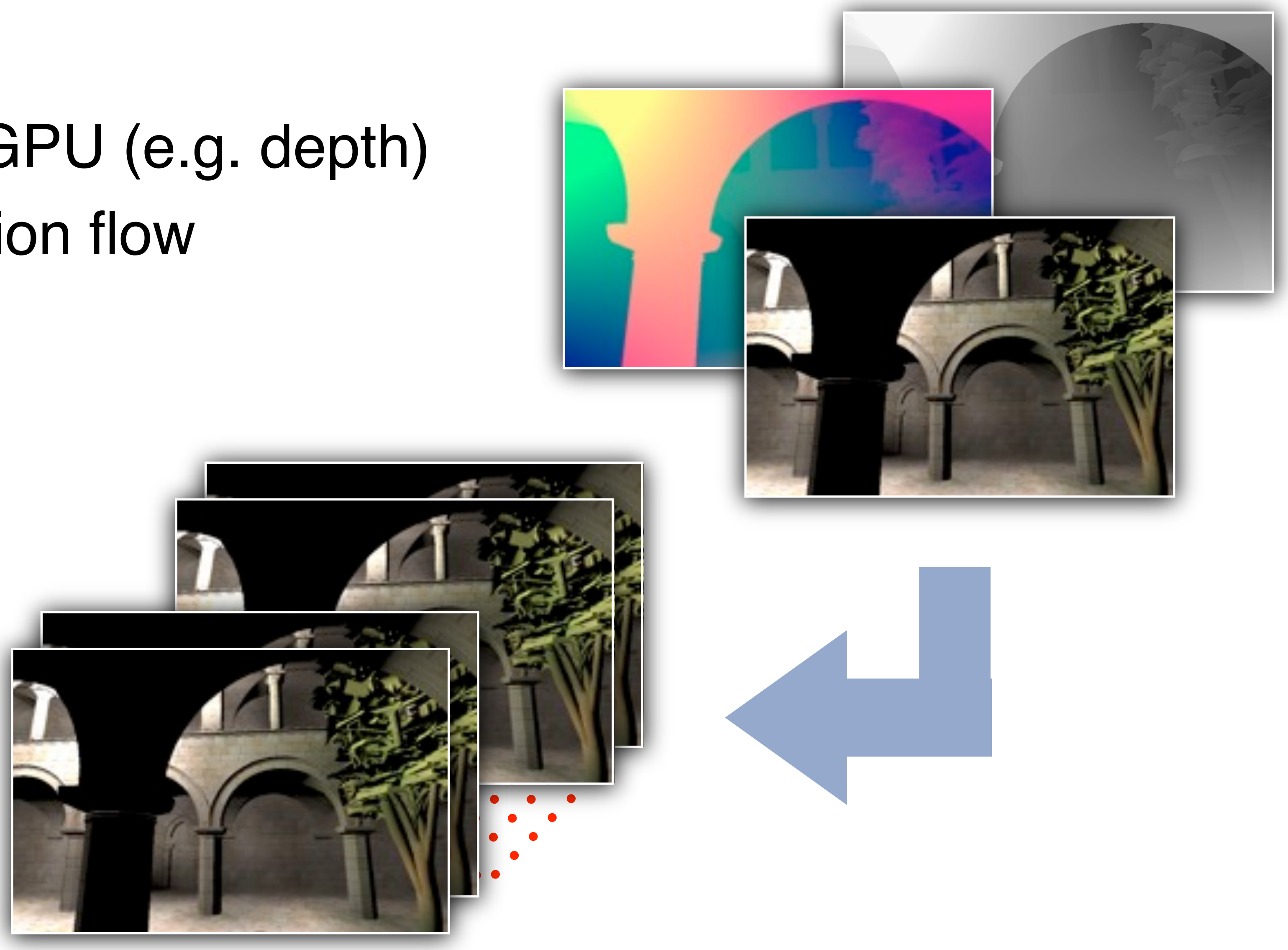
Temporal Upsampling for 3D Content

Benefits:

- Additional information on GPU (e.g. depth)
- Efficient and accurate motion flow

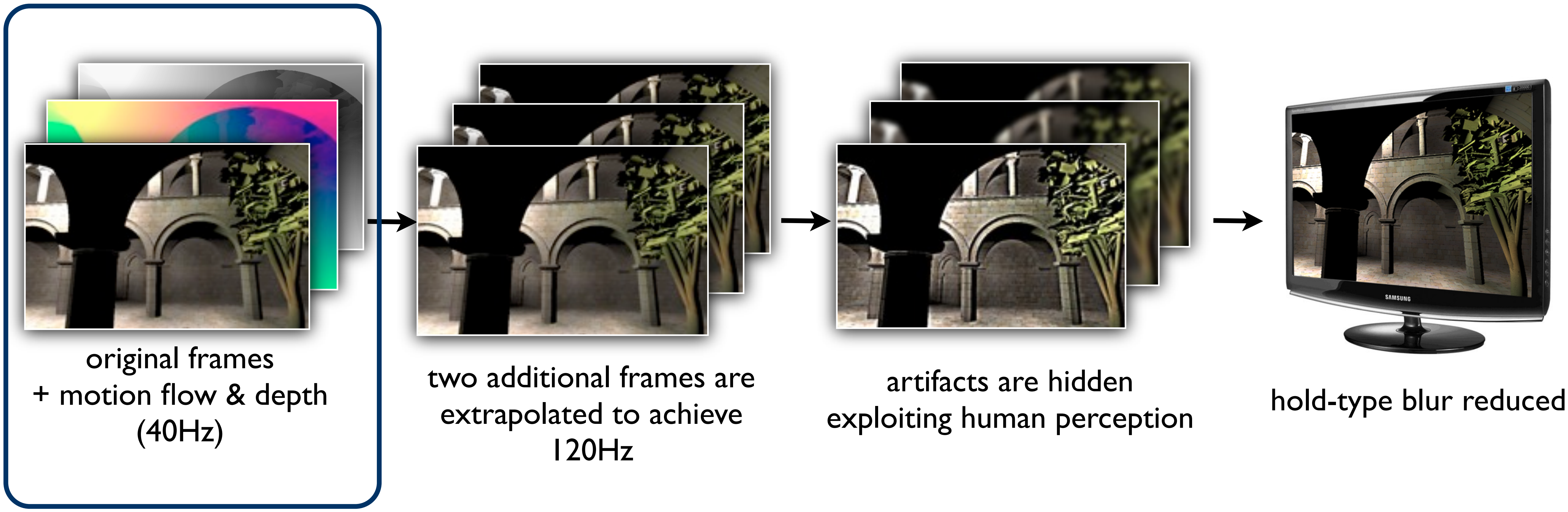
Requirements:

- Very fast
- No additional artifacts
- Extrapolation - no lag



In our project we wanted to solve the problem for 3D content, making use of additional data available on GPU such as depth and easy to compute motion flow.
To make our method beneficial it must be fast, should not introduce additional artifacts and do extrapolation instead of interpolation to not introducing lag of one frame.

Hold-type blur reduction
Pipeline



This is a pipeline of our method which as an input takes original frames along with motion flow and depth.

In our case we assume that input signal is 40Hz and we upsample it to 120Hz.

Therefore we need to provide two additional inbetween frames.

Hold-type blur reduction
Pipeline

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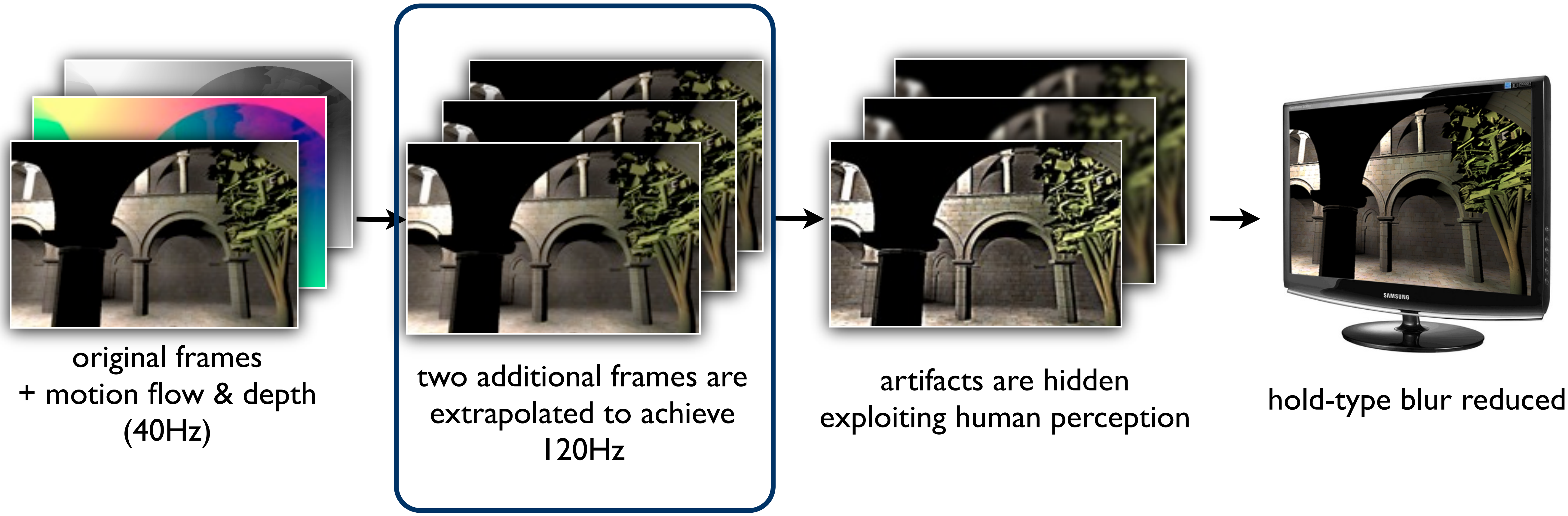

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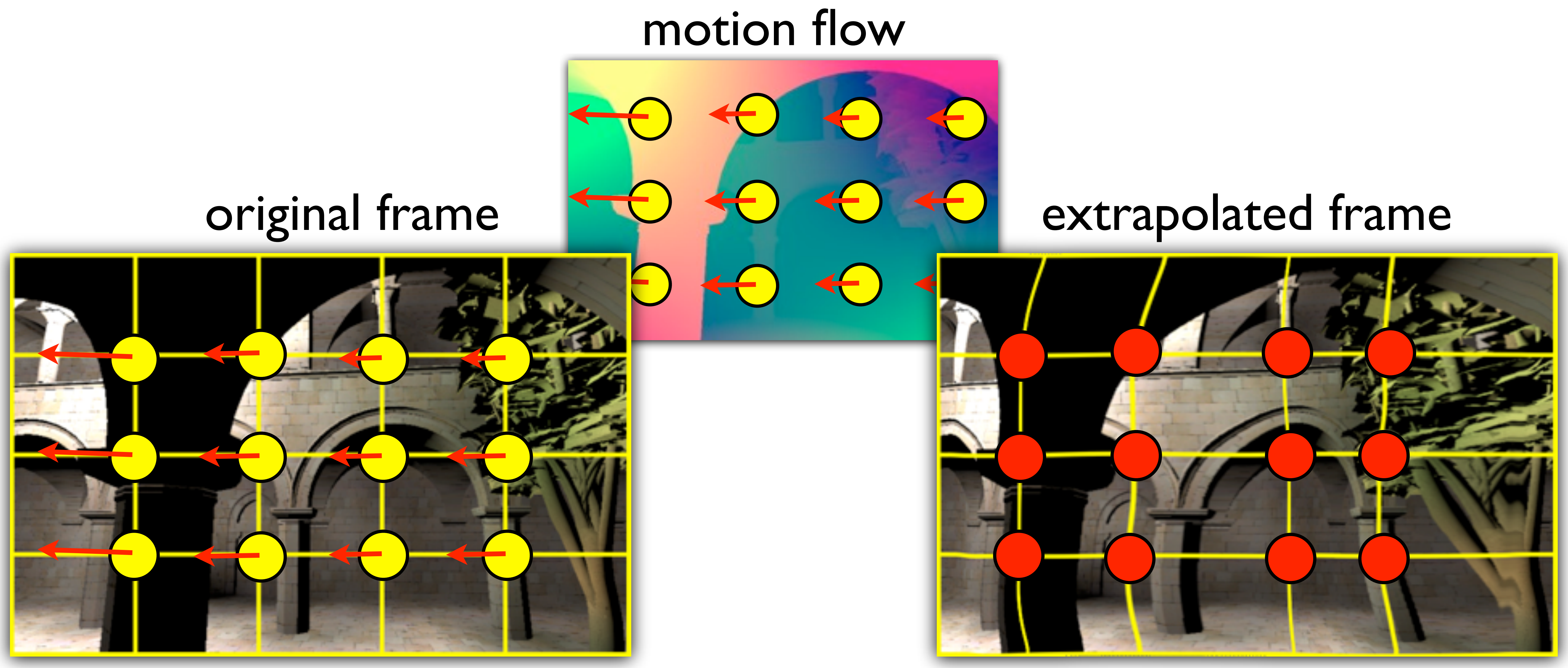

Our method take advantages from morphing methods.
The basic idea is to attach a coarse grid to the input frame and morph it using motion flow with underlying frame.

Hold-type blur reduction
Extrapolation

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So we start with original frames, on top of which we attache a coarse grid.

To minimize artifacts that can occur in places of disocclusion and occlusion we use motion map and snap the vertices to motion discontinuities .

Afterwards we assign to each vertex proper depth to solve a problem of fold overs and morph frames using computed previously motion flow.

Hold-type blur reduction

Extrapolation - Final result

original frames

extrapolated frames

Here we can see comparison of original animation with extrapolated frames.

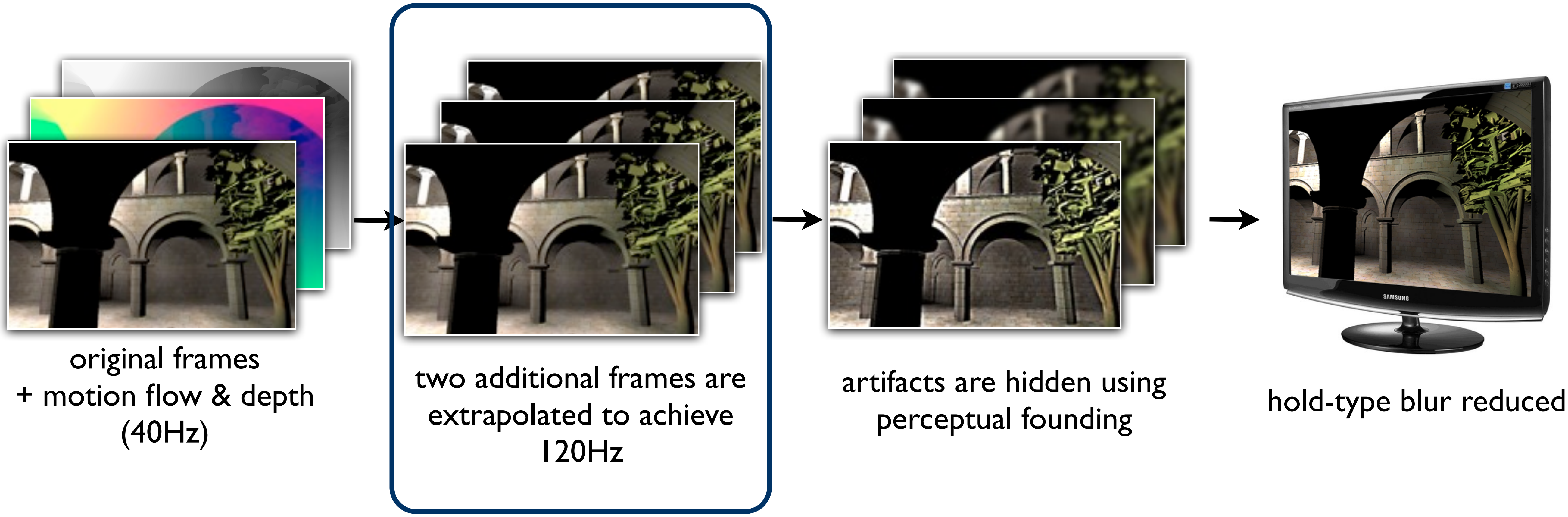
Hold-type blur reduction
Extrapolation - Final result

with snapping

without snapping

As mentioned before our snapping avoids artifacts when discontinuities of motion appear.
Here on the right you can see them as flowing edges of columns.
In our solution the edges are preserved.

Hold-type blur reduction
Pipeline



Because our morphing method still can introduce small artifacts we use perceptual finding to hide them.

Hold-type blur reduction
Pipeline

original frames
+ motion flow & depth
(40Hz)

two additional frames are extrapolated to achieve 120Hz

artifacts are hidden using perceptual founding

hold-type blur reduced

Because our morphing method still can introduce small artifacts we use perceptual finding to hide them.

Hold-type blur reduction
Removing artifacts

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The artifacts like those shown here can be removed by the idea presented by Chen et al. who showed that at high framerates it is possible to interleave blur and sharp frames.

We use this to blur possible artifacts in extrapolated frames.

Lost of high frequencies is compensated in originally rendered frames where we have correct information.

Hold-type blur reduction
Removing artifacts

- At 120Hz we can interleaving sharp and blurred frames [Chen et al. 2005]

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Lost of high frequencies is compensated in originally rendered frames where we have correct information.

Hold-type blur reduction
Removing artifacts

- At 120Hz we can interleaving sharp and blurred frames [Chen et al. 2005]
- Blur out artifacts
- Compensation in original frames

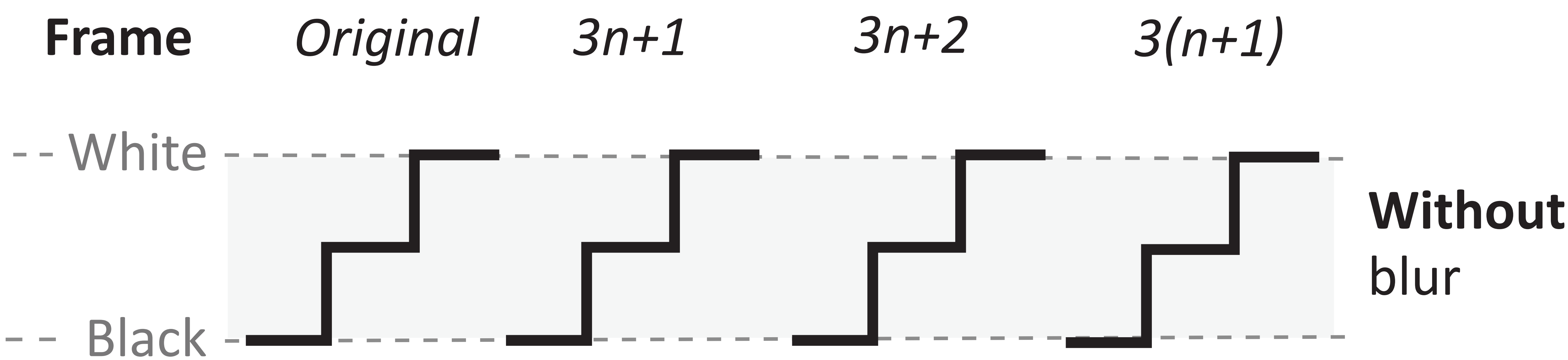
The artifacts like those shown here can be removed by the idea presented by Chen et al. who showed that at high framerates it is possible to interleave blur and sharp frames.

We use this to blur possible artifacts in extrapolated frames.

Lost of high frequencies is compensated in originally rendered frames where we have correct information.

Hold-type blur reduction
Selective blur

- Compensation may lead to clipping problems
- Distorted regions must always be blurred



Doing so we need to keep in mind that such compensation is not always possible.

Top row of a the figure shows two original frames and two inbetween.

The inbetween frames are decomposed into low and high frequency content.

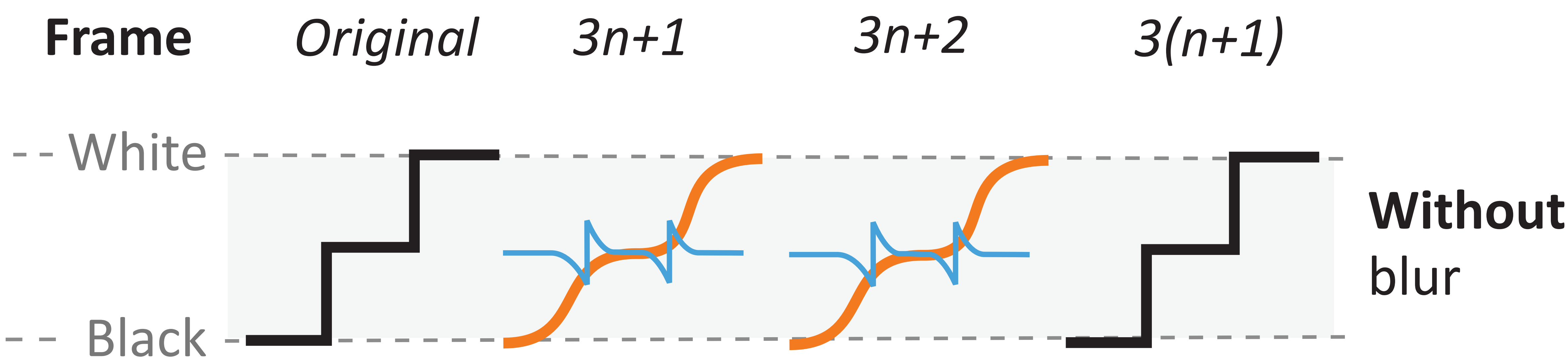
It can happen that when we move the high frequency content to the next original frame, the dynamic range will be exceeded.

To avoid clipping in such situation we need to push back the high frequency that cannot be compensated later to inbetween frames as it is shown in the second row.

In our method we are aware of places where big distortions can occur.
In such regions we do not perform operation described above to not introduce possible artifacts.

Hold-type blur reduction
Selective blur

- Compensation may lead to clipping problems
- Distorted regions must always be blurred



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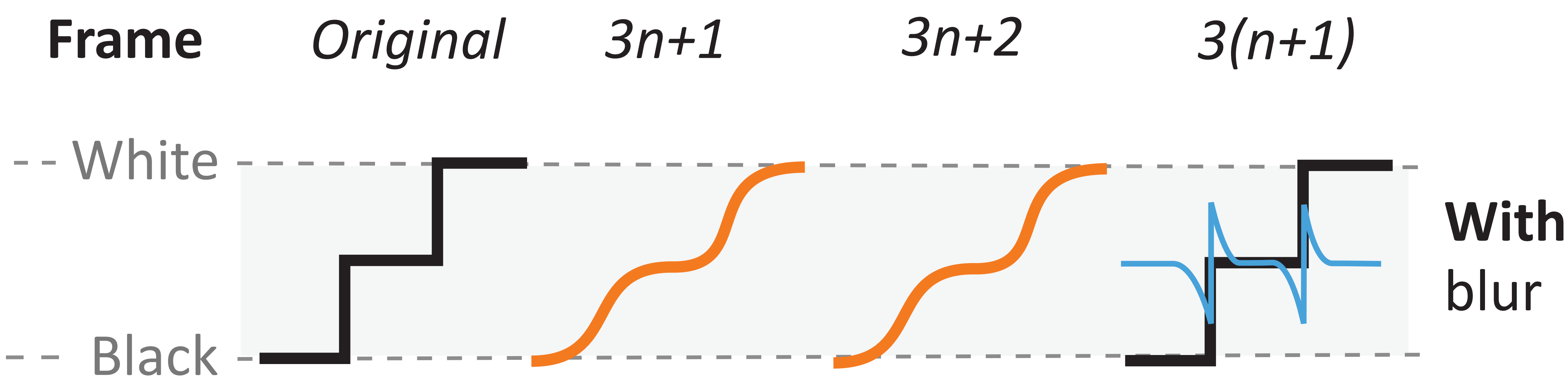

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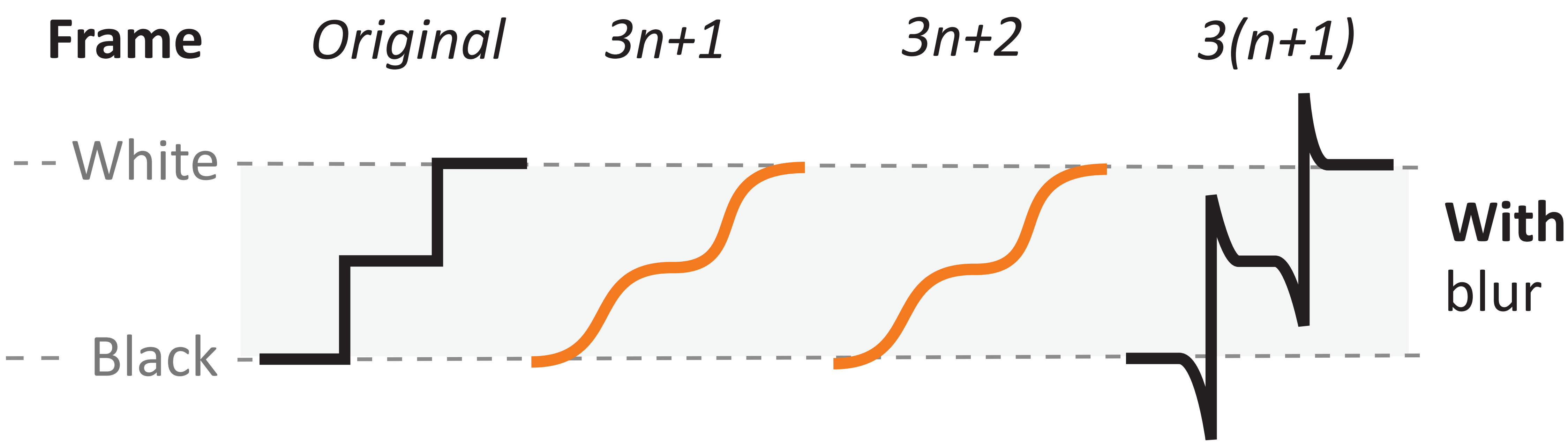

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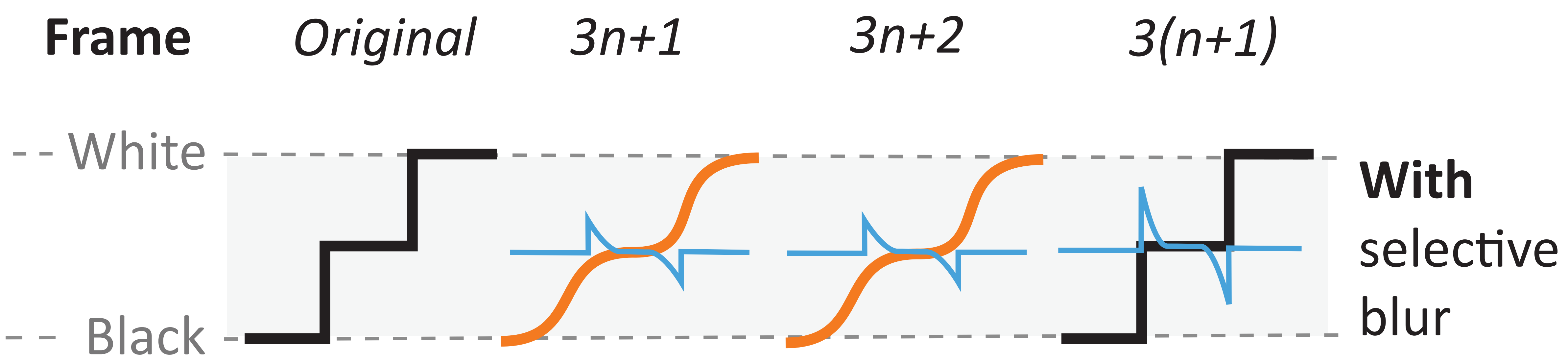

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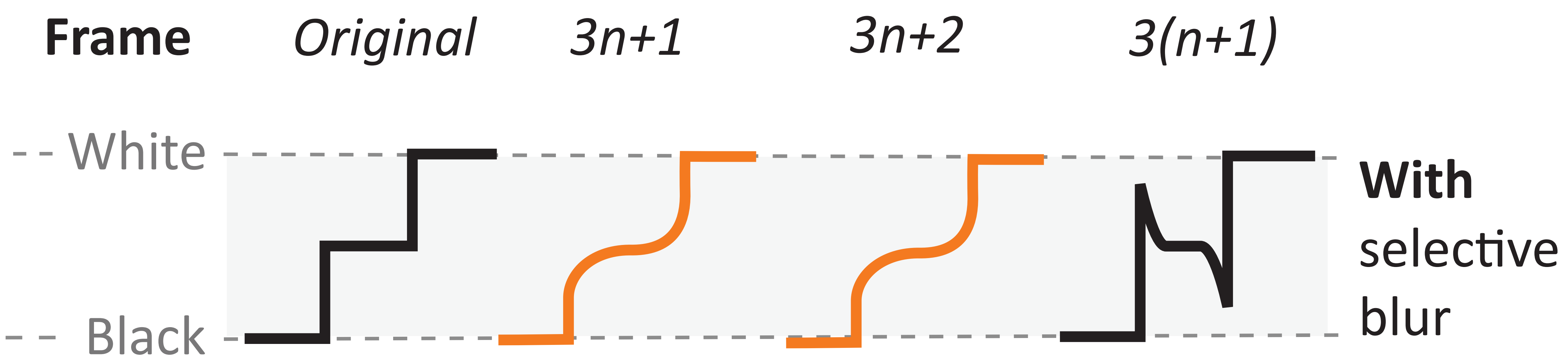

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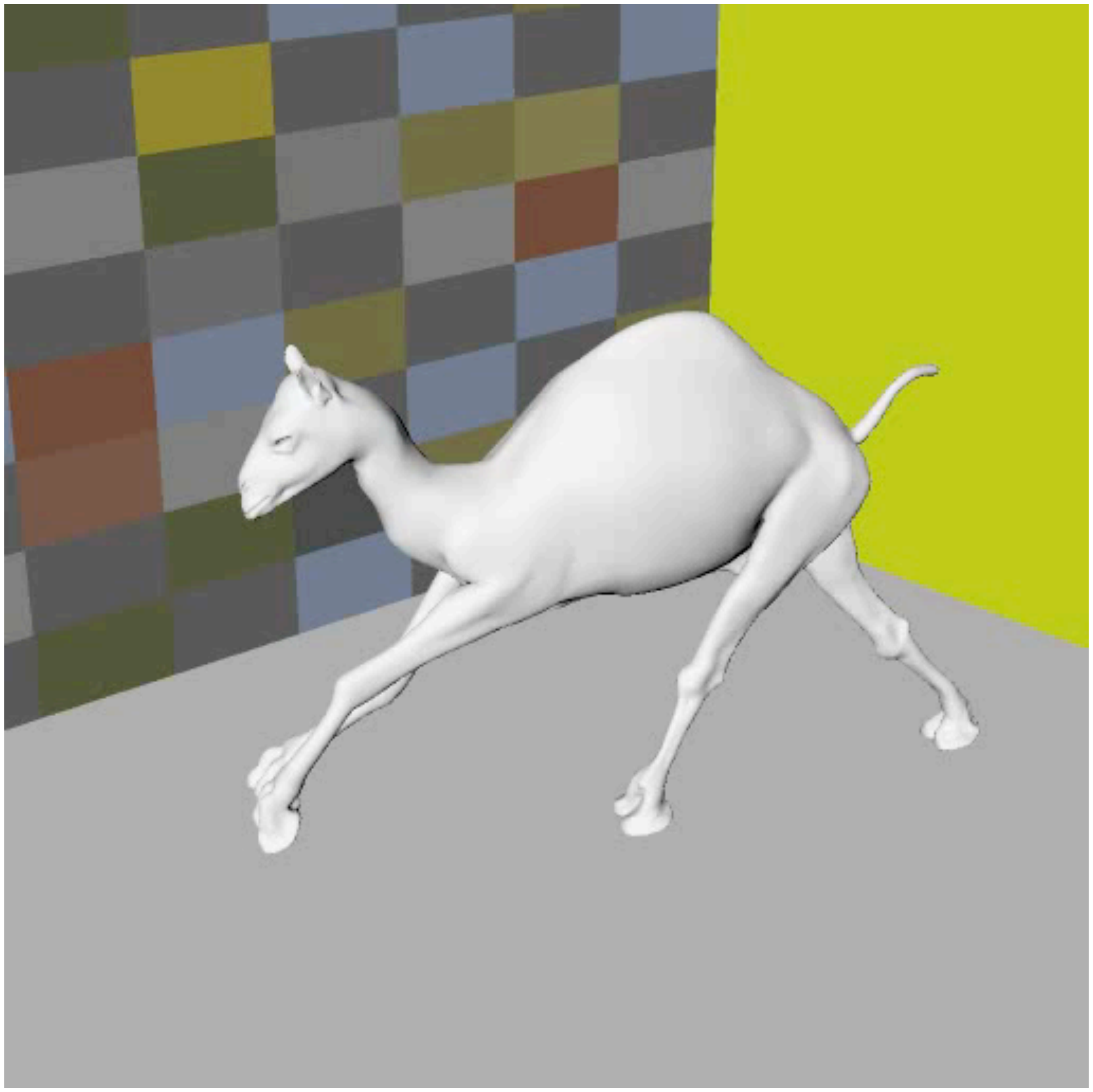
Hold-type blur reduction

Importance of tracking

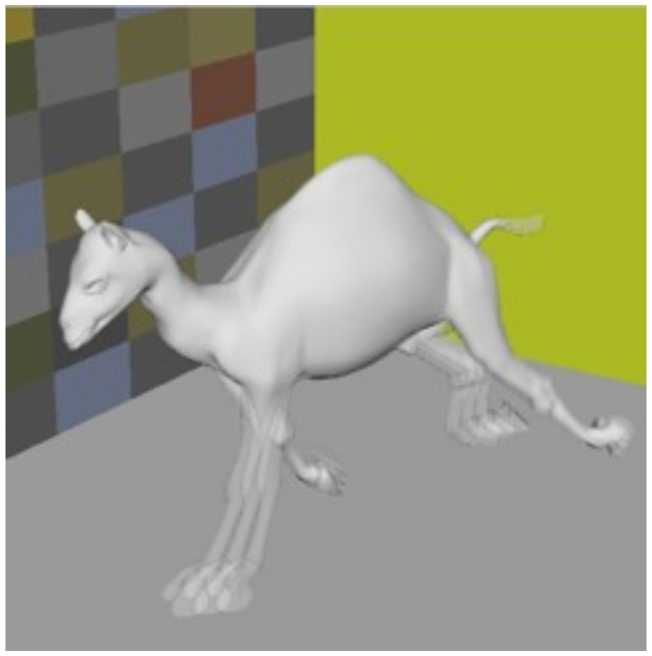


What I described before applies well in scenes where object are trackable, which for some special cases is not really true for very fast motion.

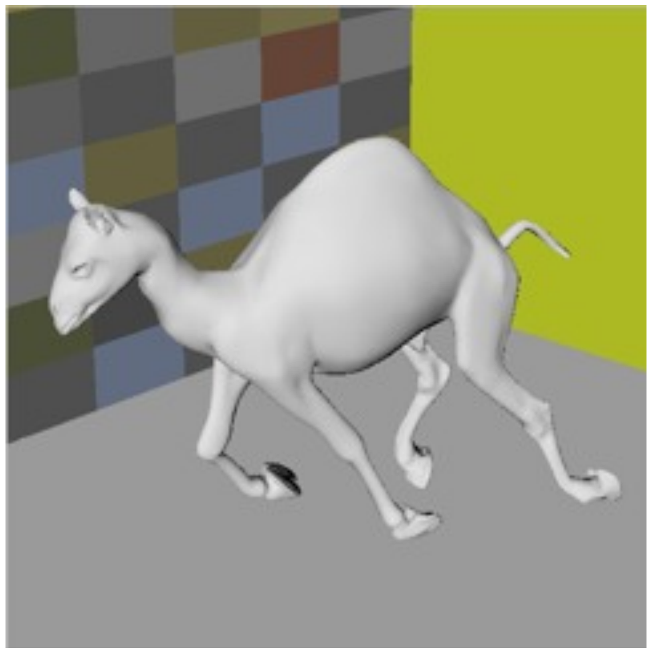
Here, for such camel, tracking legs is almost impossible.

Hold-type blur reduction
Importance of tracking

True 120Hz



Reference



Eurographics, 7 May 2010, Sweden

Due to lack of tracking we will not see hold-type blur in the region of legs but instead, copies of them.

The simulation of perceived image at 120Hz display is showed on the right hand side and next to it reference image from animation.

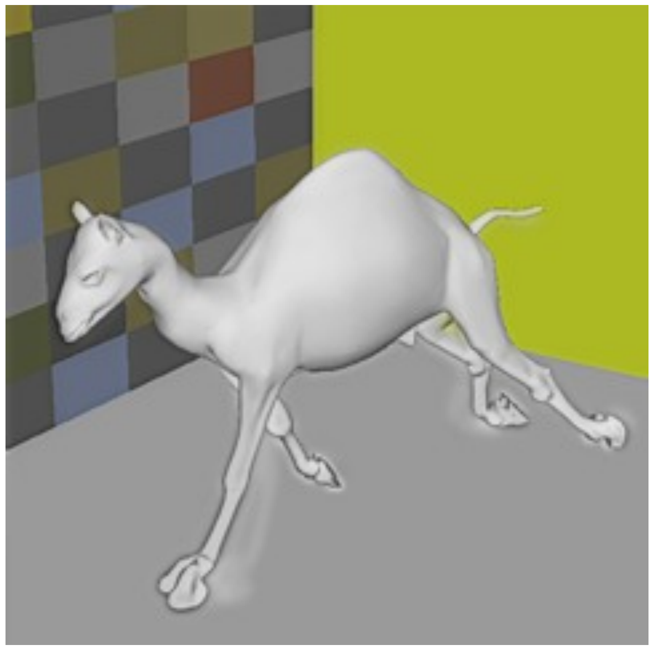
Our solution that I described so far would result also in perceived copies but blurred.

To solve the problem we need to take into account tracking of the human visual system.
Since it is complex problem perfect model does not exist.
We assume a velocity of the object to be good indicator of possible tracking.

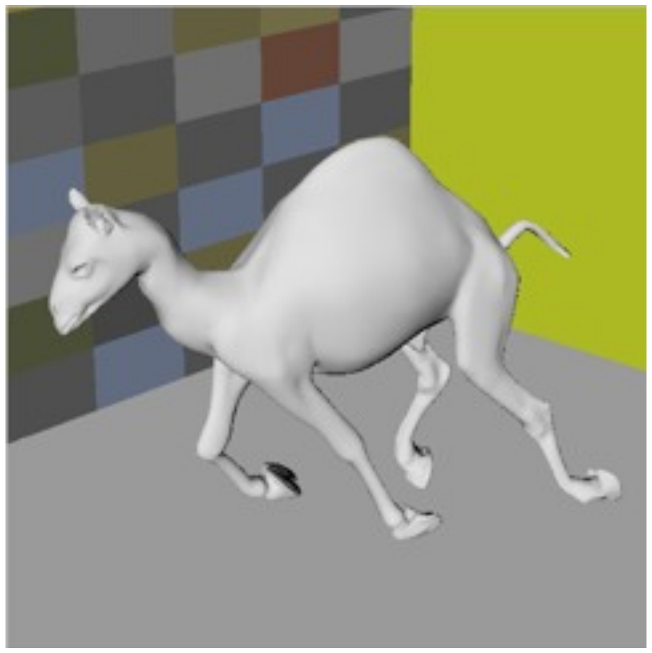
For object that move to fast we dump the velocity, which in fact results in going back to original low frame rate.
In the end blurred copies of legs almost disappear.

Hold-type blur reduction
Importance of tracking

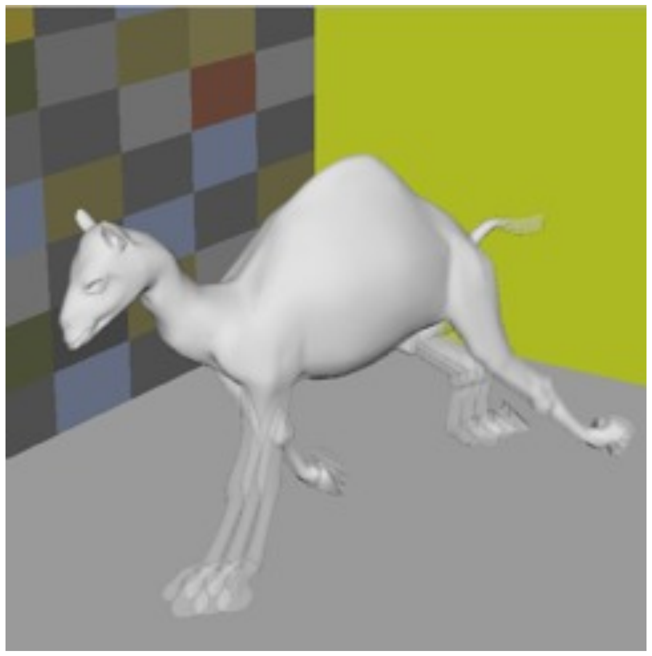
Our 120Hz



Reference



True 120Hz



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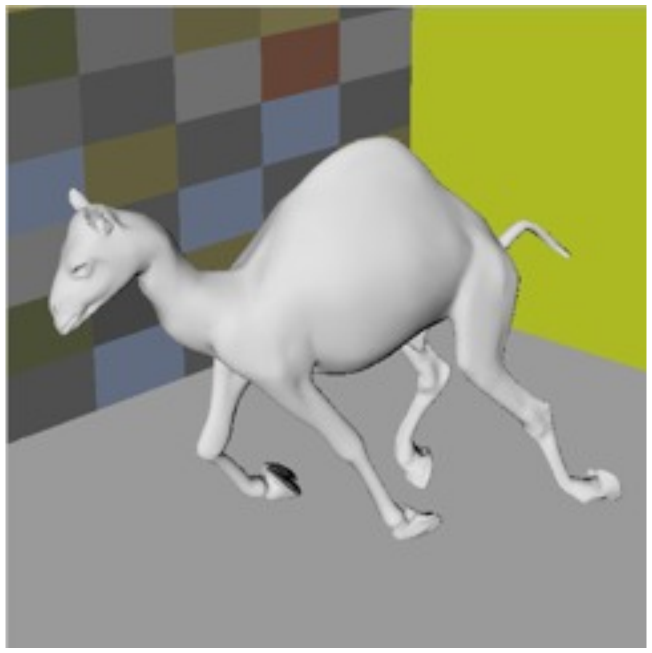
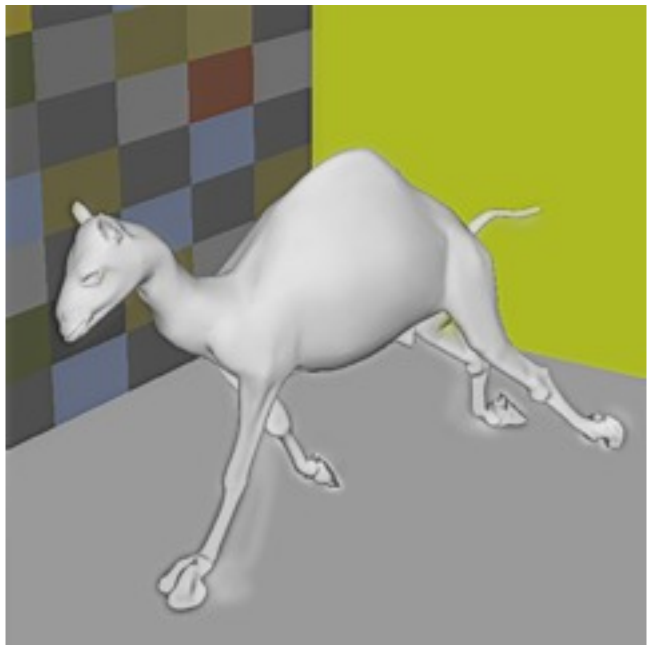
Hold-type blur reduction
Importance of tracking

- Eye tracking needs to be taken into account
- Perfect model does not exist
  - ➡ Speed as an approximation

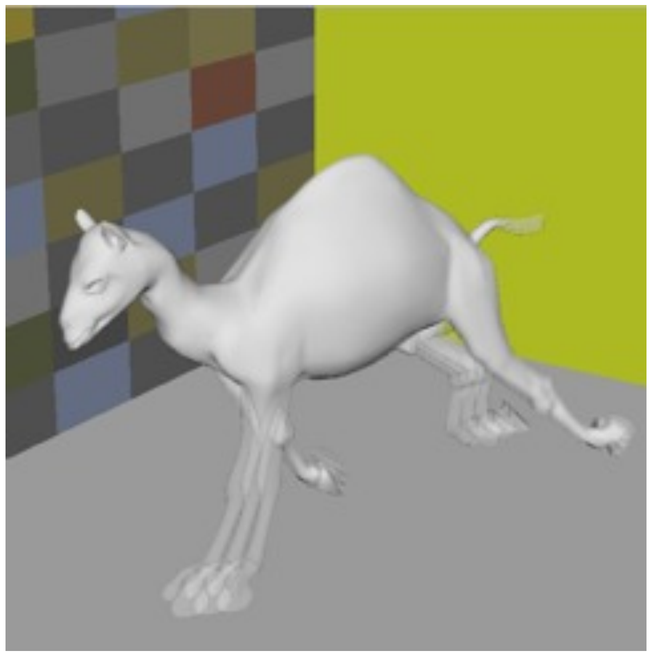
Reference



Our 120Hz



True 120Hz



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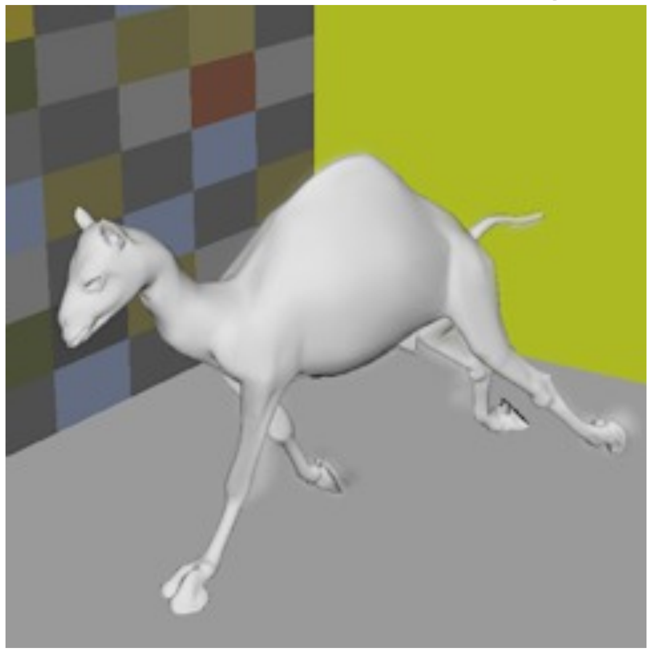
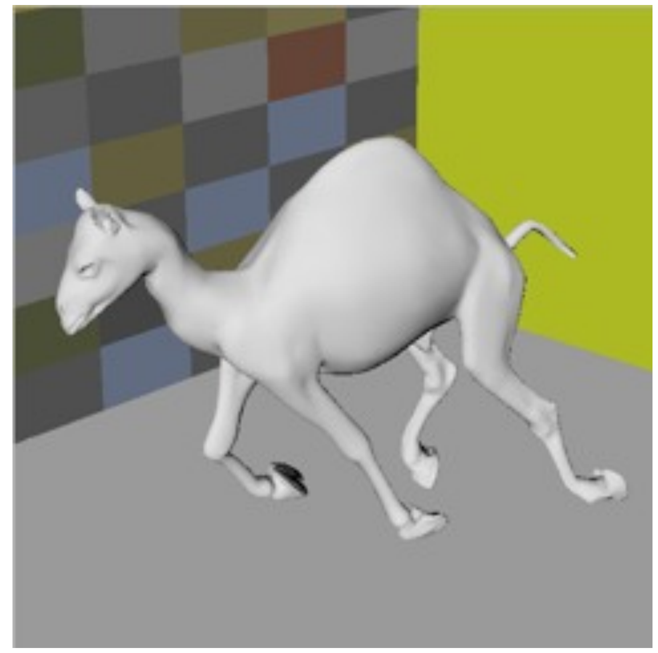
Hold-type blur reduction
Importance of tracking

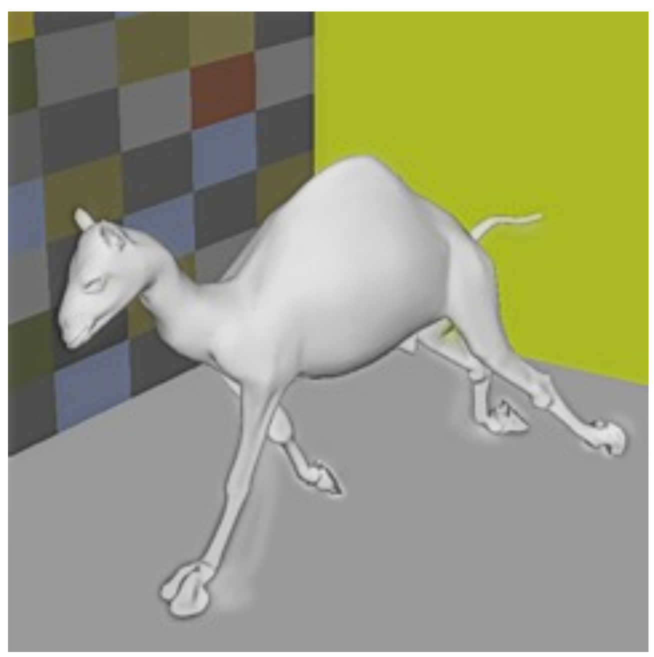
Our with tracking



Reference



Our 120Hz



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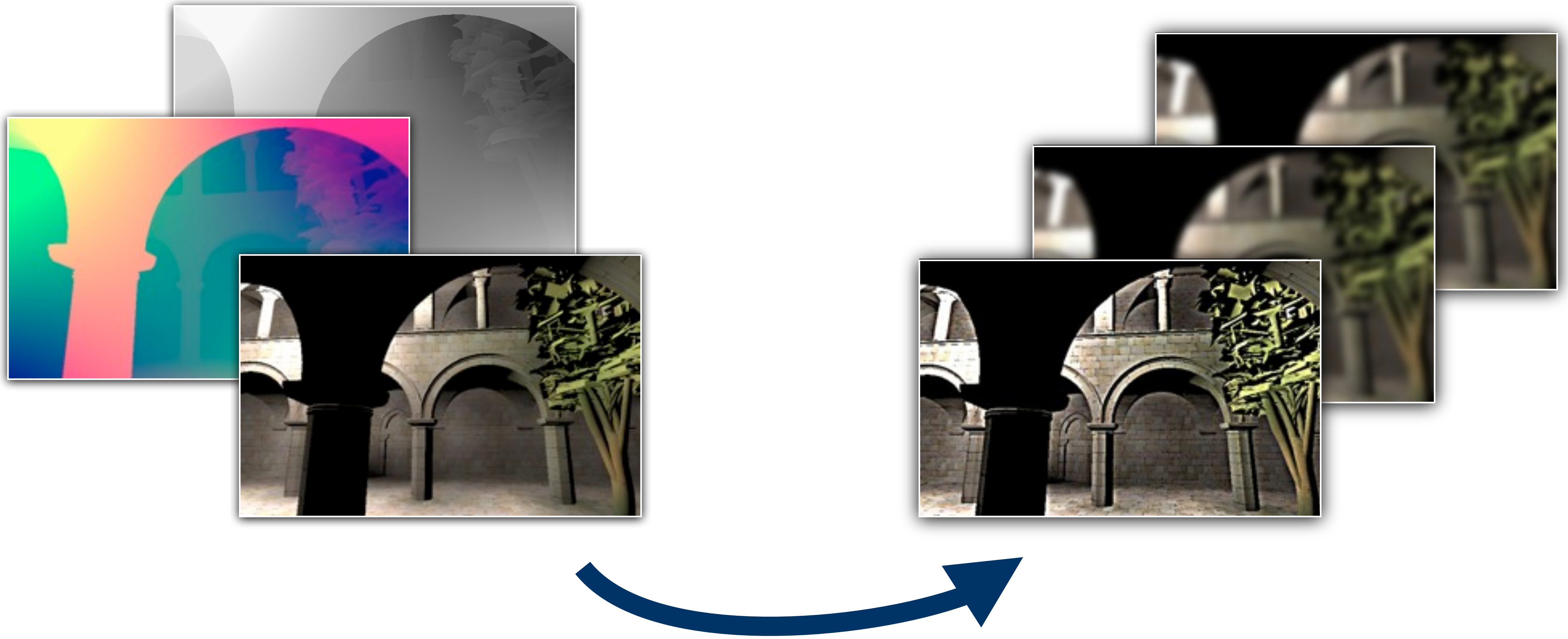
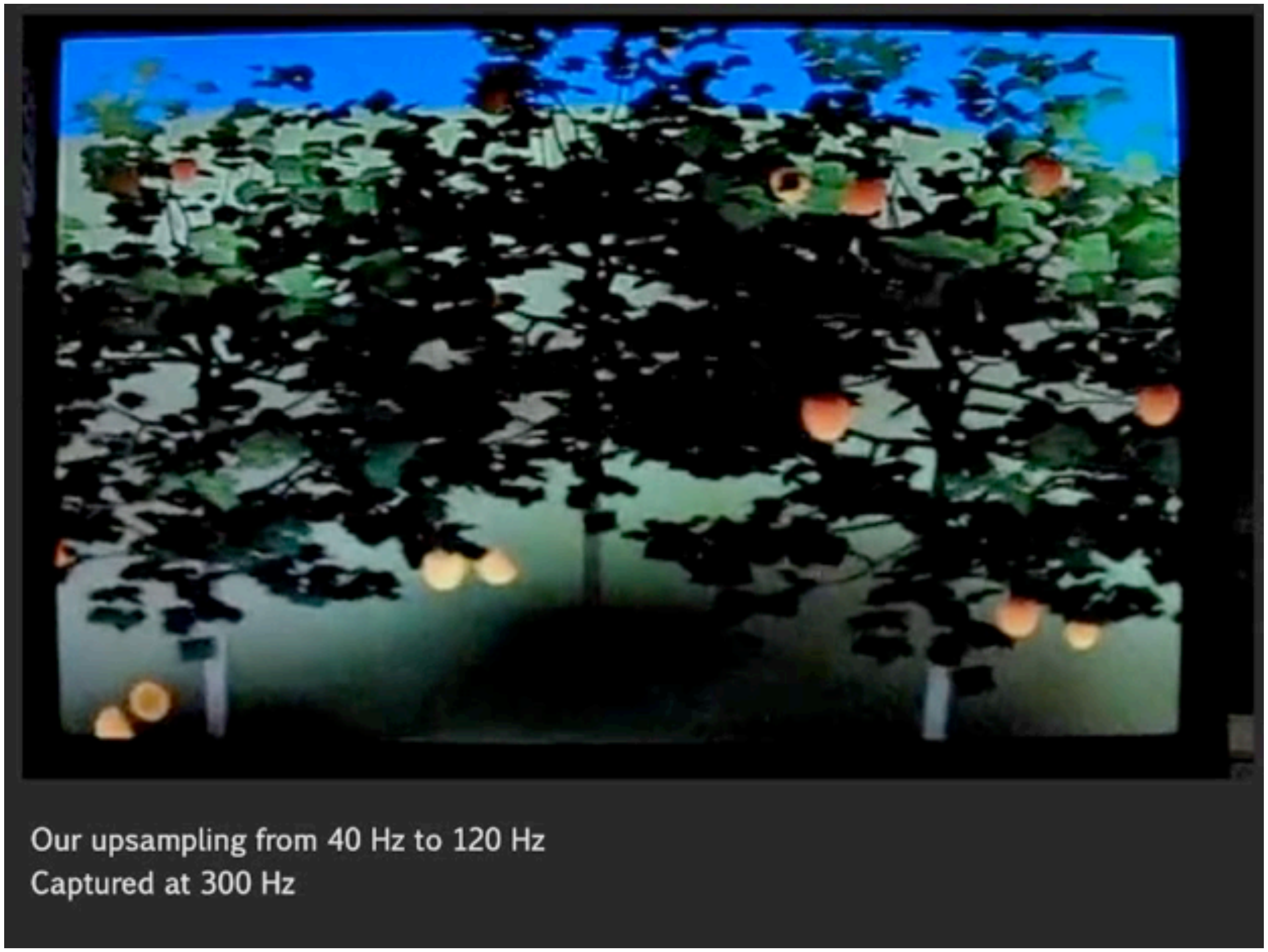


Temporal Upsampling

To summarize, our method takes as a input all information available on GPU and makes use of it, extrapolating frames.
To hide artifacts we blur inbewteen frames and compensate for lost high frequencies in original frames where we can rely on the content.

Hold-type blur reduction
Recording with a high-speed camera



Here you can see how our method looks captured by high-frame rate camera.

Hold-type blur reduction
TV-set solution

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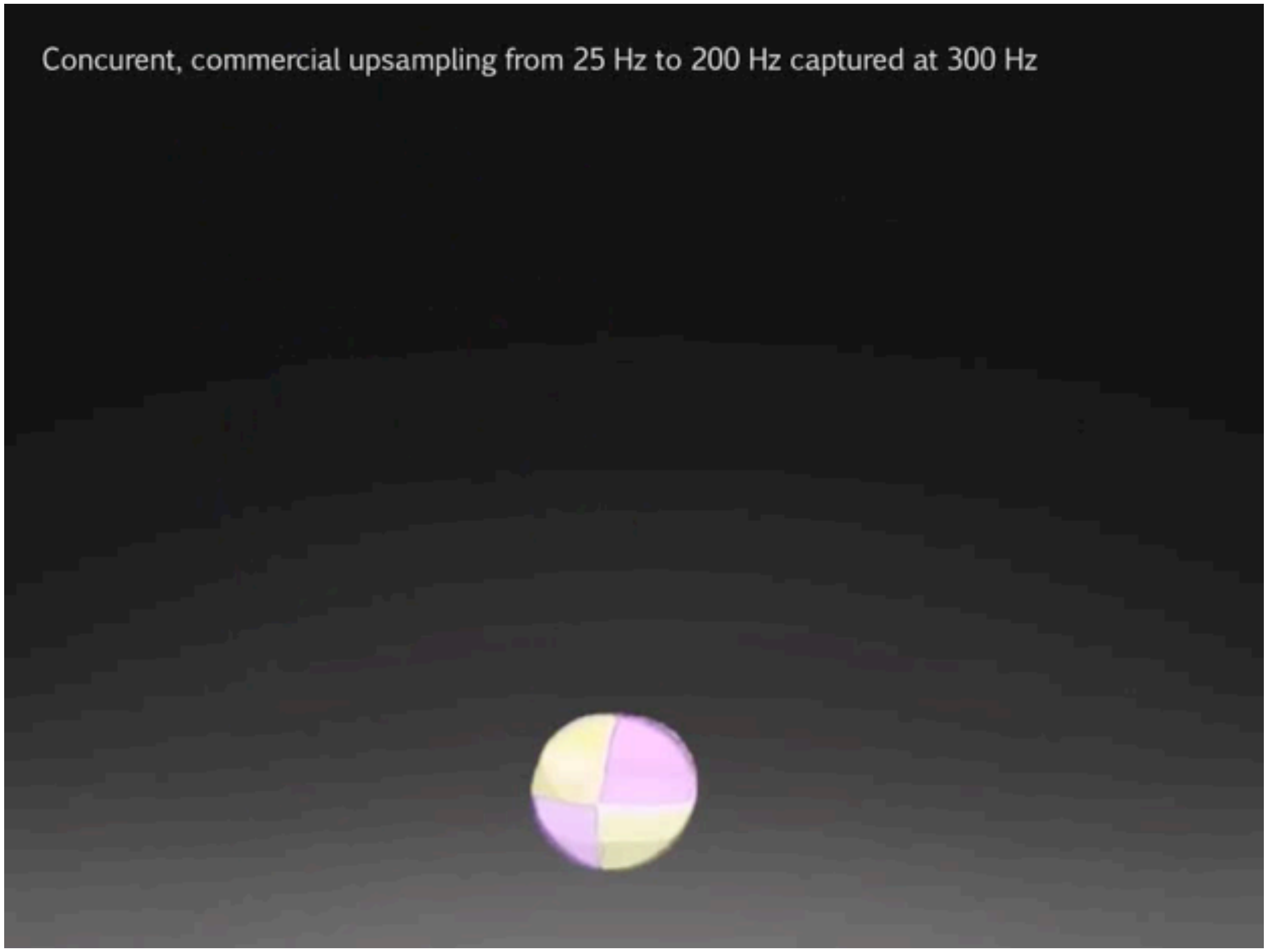

We also captured with the high speed camera and interpolation done by one of the off-shelf displays.
It is visible how limitation of motion-based optical flow limits the final solution.

Our method vs. optical flow

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Optical flow (TV sets):

Our method:

Let me summarize the advantages of our method over solutions which exist in TV-sets.

Because optical flow computed in such systems is image based, usually it has problems with occlusions and disocclussions.
On the GPU we make use of depth avoiding any possible fold overs.

Due to lack of time TV solution cannot deal with big displacements, while we have accurate per pixel motion flow.

Our solution is very fast and it needs few milliseconds on standard GPU to compute two inbetween frames.

The other advantage is also that we do not introduce any lag since we do extrapolation instead of interpolation.
This is usually not an issue in case of broadcasting applications but interactive applications it is important to reduce delay in interaction.
Some studies showed that subjects could detect such delay even beyond 90Hz.

Our method vs. optical flow

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Optical flow (TV sets):

- Occlusions & disocclusions problematic

Our method:

- Depth information available

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- Accurate per pixel motion flow

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Our method vs. optical flow

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Optical flow (TV sets):

- Occlusions & disocclusions problematic
- Problems with big displacements
- Relatively slow

Our method:

- Depth information available
- Accurate per pixel motion flow
- Very fast: ~3 ms

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Our method vs. optical flow

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Optical flow (TV sets):

- Occlusions & disocclusions problematic
- Problems with big displacements
- Relatively slow
- Only interpolation possible

Our method:

- Depth information available
- Accurate per pixel motion flow
- Very fast: ~3 ms
- We extrapolate! - no delay

Let me summarize the advantages of our method over solutions which exist in TV-sets.

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Hold-type blur reduction
Result

Because we are not able to show the hold-type reduction here we create a simulation.
On the left-hand side 40 Hz and 120Hz on the right.

Hold-type blur reduction
Result

40 Hz　　　120 Hz

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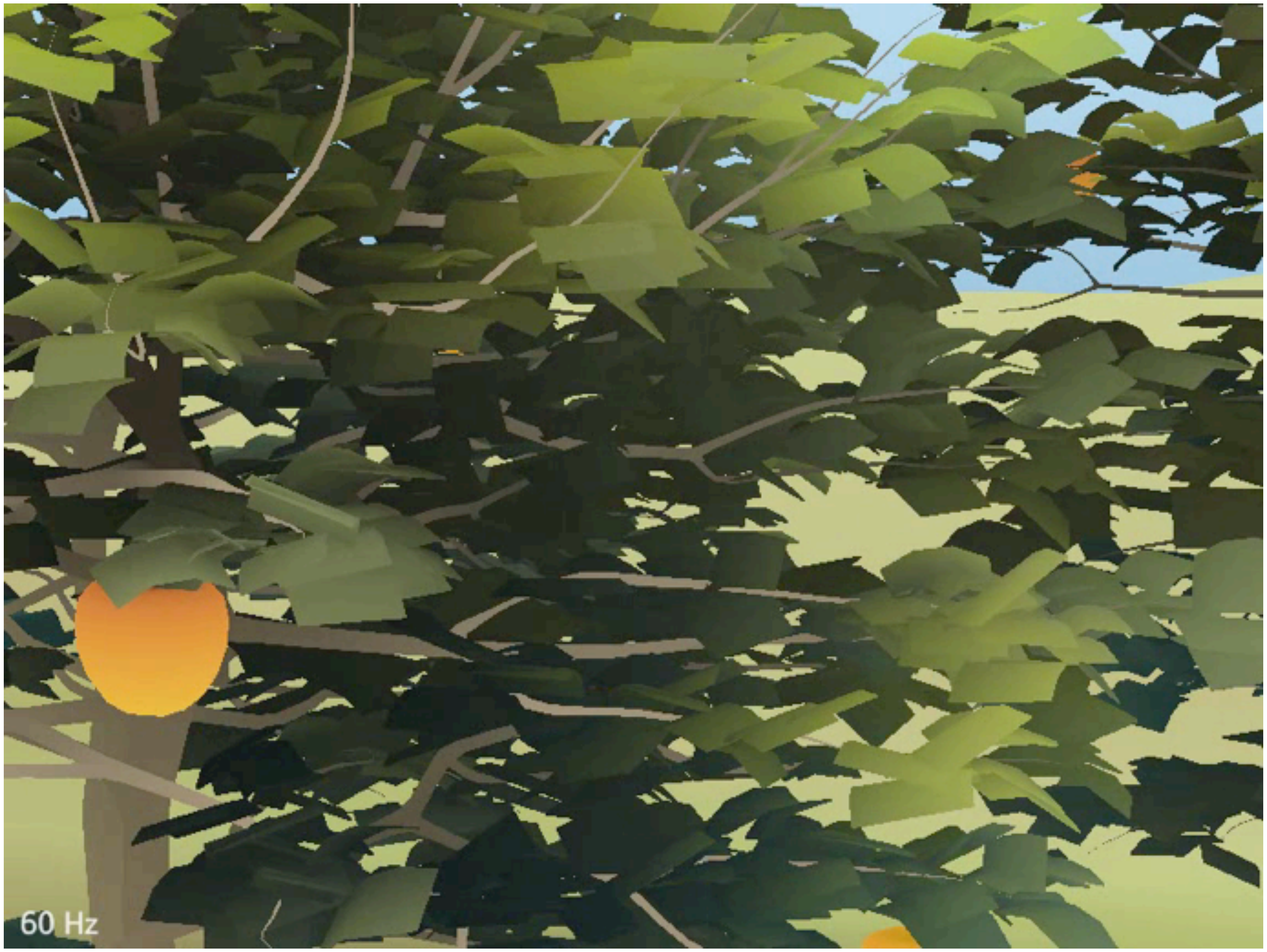
On the left-hand side 40 Hz and 120Hz on the right.

Hold-type blur reduction
Result



Here is the comparison of original 60Hz rendering, our morphing and 20Hz content.
Please note that here we do not blur inbetween frames, therefore small artifacts can be still visible, which would disappear after applying blur.

User study

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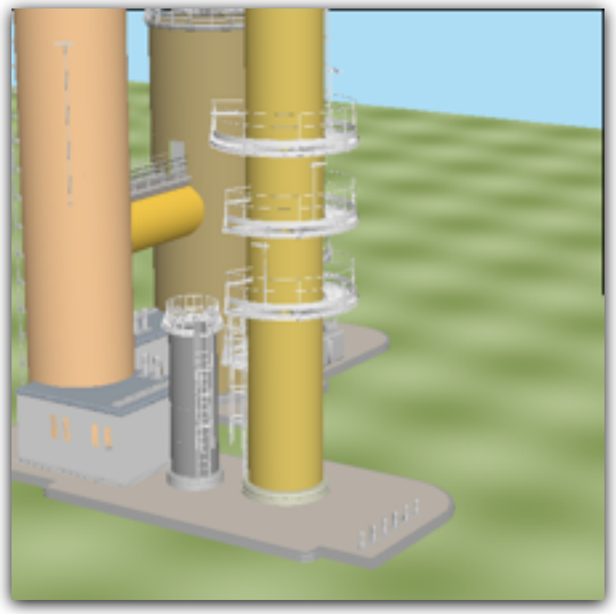
Pair-wise comparison

- 5 different sequences
- True 40Hz, True 120Hz, Our 120Hz
- Blur judgment and artifacts



To understand how our method performs we conducted a user studies to check the blur reduction as well as task performance improvement.
Using 5 different scenes with moving and complex geometry we run a study where we compared our method to true 120Hz and 40Hz.
We ask participant for judging the sharpness as well as possible artifacts.

User study

5 scenes (mean quality score + SEM)

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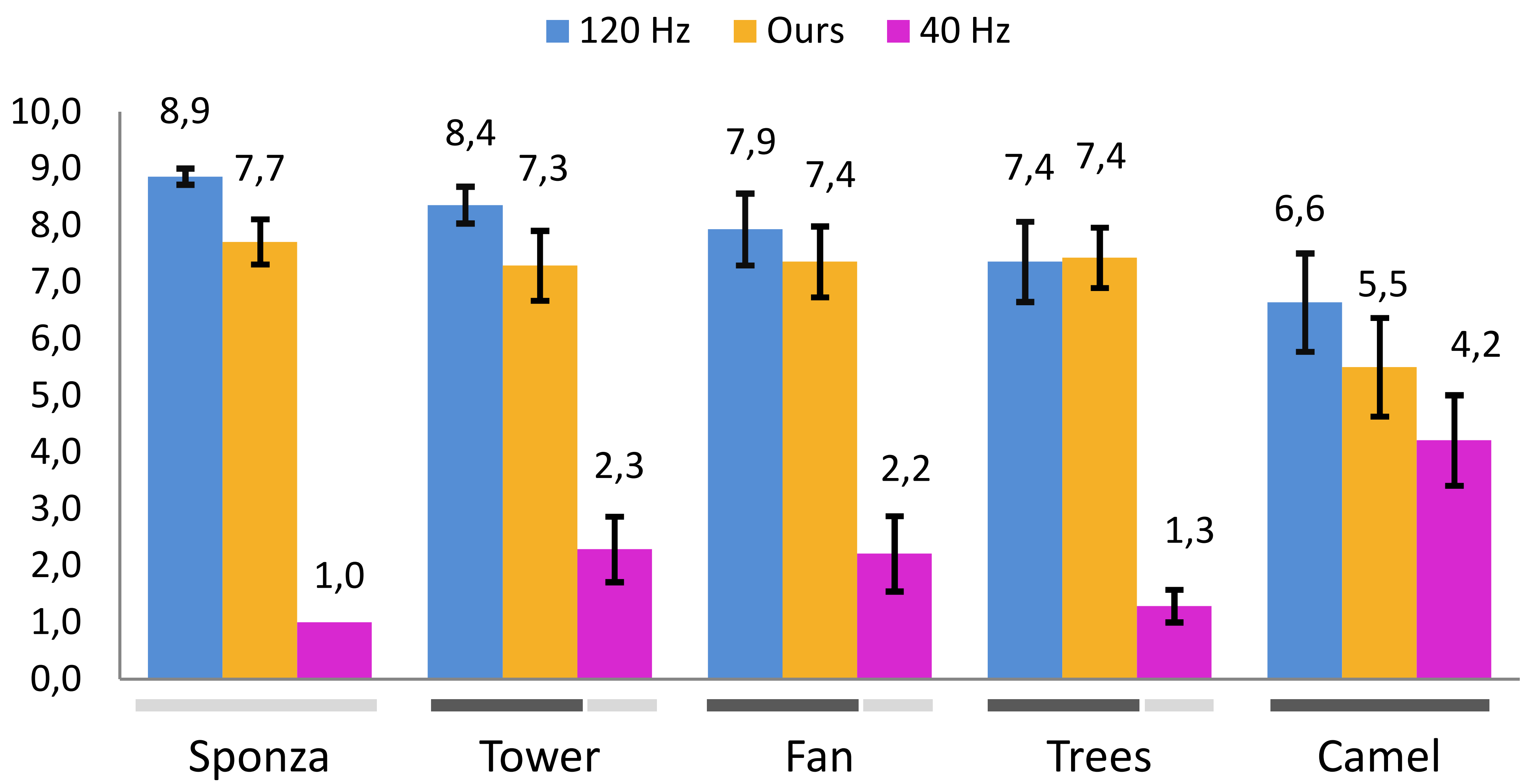
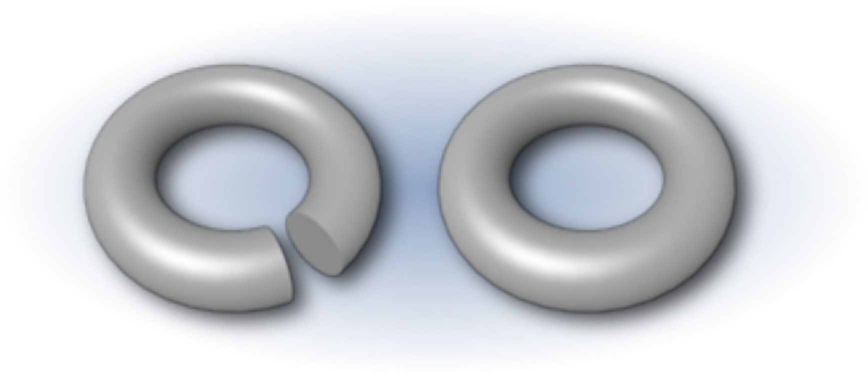


We showed significant improvement of the quality of rendering compering to 40Hz.
Our method also gives results close to original 120Hz.

User study
Game

Targets:

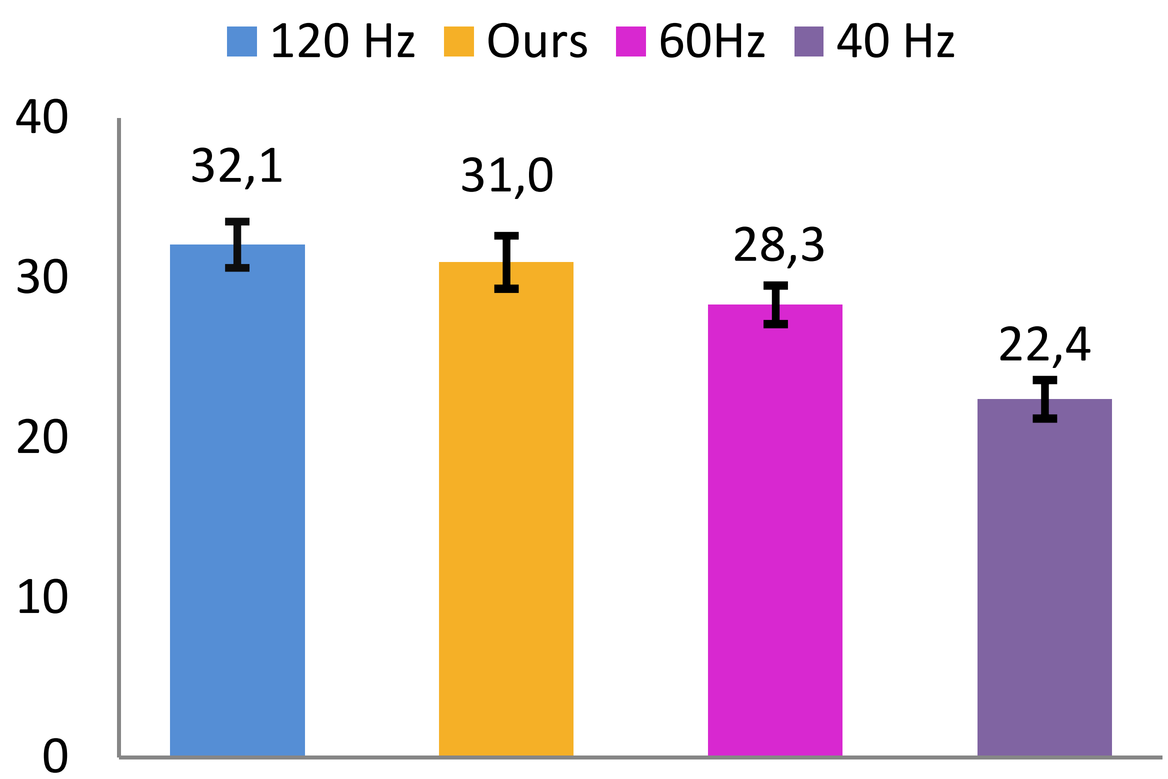


Task:

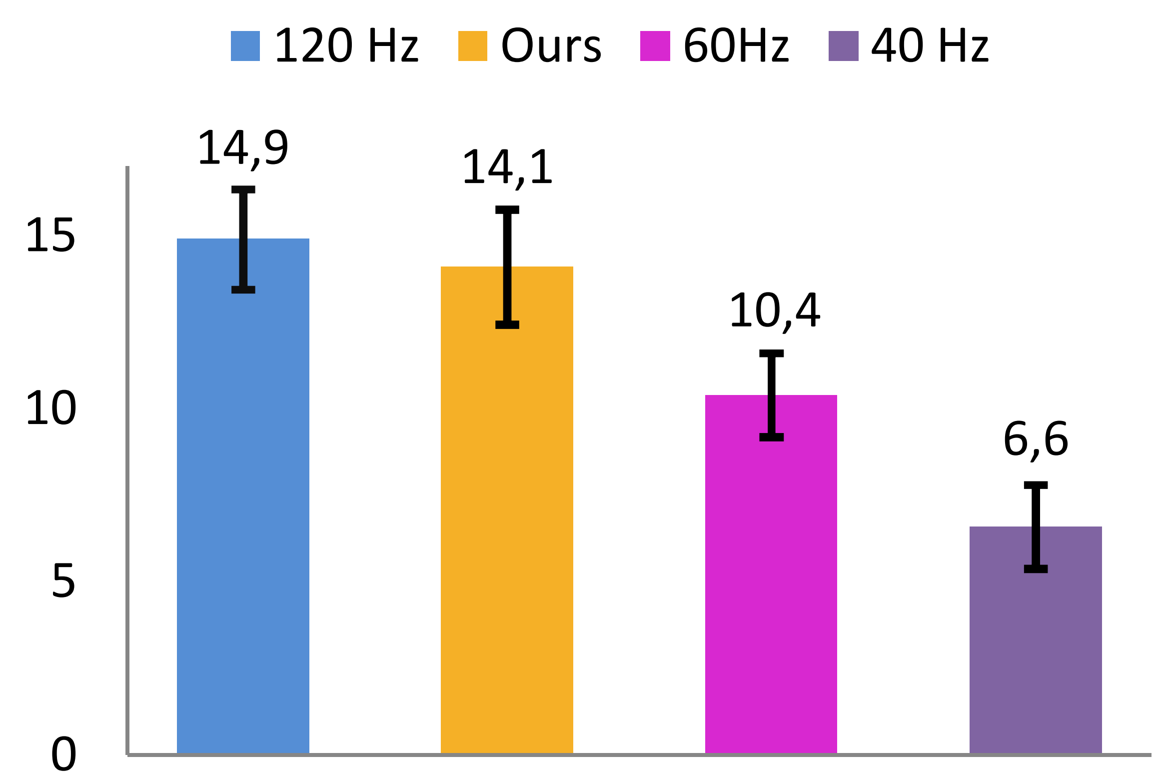
Detect open Landolt shape

To check improvement of task performance while using our method, we create a simple game where two moving targets were presented: close and open landolt shape.
The task was to detect open one.

User study
Game



Score



Succeeded Landolt detections

We showed that we can improve using our technique the task performance significantly.

Final scores as well as number of successfully detected Landolt shapes were bigger, than in case of 40 and 60 Hz and stayed close to those obtained with true 120Hz.

Limitations

- Regions affected by transparency:
  - transparent materials
  - simulated motion blur
  - depth of field

Since we rely on motion flow of geometry our method is limited to situation when it is not correct.

For example regions affected by transparency do not have correct motion flow.

Also reflection and shadows might be problematic, although first tests with shadows showed that artifacts are not disturbing.
In fact we introduce small blur to shadows whose optical flow do not agree with our motion flow.

Also big discontinuity in motion might be problematic but most of such cases are solved by our velocity dumping.

Limitations

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  - depth of field

- Reflections & shadows

  ➡ we did experiment with shadows

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Limitations

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  - depth of field
- Reflections & shadows
  - ➡ we did experiment with shadows
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Easy mapping for 2 GPUs

1st GPU
high-quality rendering

~40Hz →
frames, depth, motion flow

2nd GPU (can be slow)
frame-rate expansion

120Hz →

output device

- Both GPU units work independently
- The computation time spent on 2nd GPU is always the same i.e. it does not depend on complexity of scene

Our method can be easily mapped into two GPUs.

One, powerful could be used for rendering high quality frames along with motion flow and depth, which would be passed to small GPU responsible for extrapolation.

The advantage of such solution is that both units would work independently and time needed for extrapolation would not depend on complexity of a scene.

Conclusions

We presented:

- An efficient GPU-based temporal upsampling for 3D content

Conclusions

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- An efficient GPU-based temporal upsampling for 3D content
- Significant *hold-type blur* reduction

Conclusions

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- Higher refresh rates can improve task performance

Conclusions

We presented:

- An efficient GPU-based temporal upsampling for 3D content
- Significant *hold-type blur* reduction
- Higher refresh rates can improve task performance
- Tracking is an important issue in the context of rendering

Acknowledgments

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We would like to thank:

- **Gernot Ziegler** and **David Luebke** of NVIDIA corporation for providing a Samsung SyncMaster 2233RZ display
- **Matthias Ihrke** for helpful comments concerning the design of our user study

This work was partially supported by the Cluster of Excellence MMCI (www.m2ci.org).

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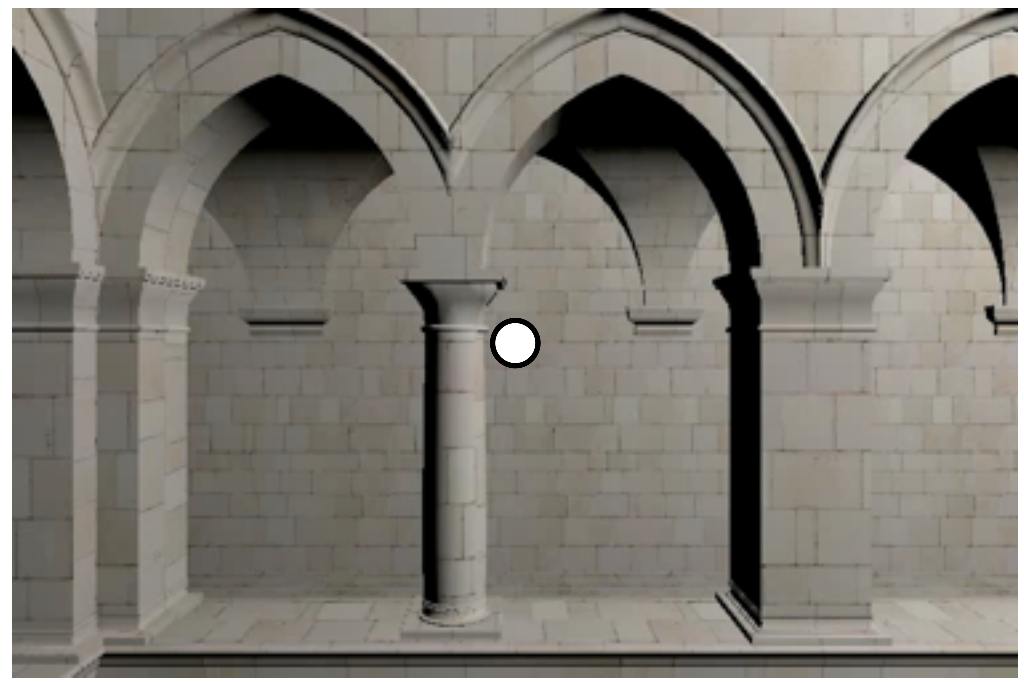
Thank you

30 Hz

60 Hz



For more information:

http://www.mpi-inf.mpg.de/resources/3DTemporalUpsampling/