EARTHQUAKE GROUND SHAKING ANIMATION SYSTEM

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ABSTRACT

An animation system was developed within the ArcGIS platform for visualization of spatial and temporal variation of earthquake induced ground shaking. The system helps depict what one feels or would feel during an earthquake - the time history effects of seismic wave arrival, wave amplitude oscillation, and shaking duration. By coupling a GIS of geology, fault rupture, attenuation modeling and ground motion recording stations to a database of readily available strong-motion datasets, ground shaking time histories, across a study area, can be produced by time-shifting and amplitude-scaling proximal records. Animations can be developed from empirical ground motion datasets from recent earthquakes (i.e. 1989 Loma Prieta, 1992 Landers, or 1994 Northride) or approximation can be developed for historic and scenario earthquakes (i.e 1906 San Francisco or a Hayward Fault rupture). Funding for this project was provided by the California Department of Conservation - Strong Motion Instrumentation Program.

Introduction

Ground shaking from earthquakes varies spatially across a region based on the distance from the fault rupture (i.e. attenuation), seismic wave propagation velocities (P-Waves and S-Waves), attenuation relationships, and bedrock geology. At any snapshot in time following the nucleation of an earthquake, a given location within that region will be in the midst of either initiating ground shaking as the seismic waves arrive, strong ground shaking, or subsiding ground shaking as the seismic waves will have passed and ceased. The behavior in terms of strength, frequency and duration of shaking during earthquakes is of interest to a broad spectrum of people from the general public to the earthquake engineering community.

Conveying the amplitude and duration of shaking felt across the state from an earthquake is critical to understanding its potential for ground shaking and therefore hazard. An animation that visualizes the spatial and temporal variation of earthquake ground shaking representing that associated with this significant earthquake will be a powerful educational tool, as well as help interpretation and understanding of strong-motion propagation and attenuation. Comparison of the 1906 San Francisco animation to recent California earthquake animations, for example the 1989 Loma Prieta or 1992 Landers earthquake, where most Californians have antidotal experiences, will exemplify the exponentially larger amplitudes (i.e. Loma Prieta released only

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3% of the energy compared to 1906) and longer duration of shaking (45 seconds to over 2 minutes) between the events.

Coupling a database of synchronized and spatially located strong motion records to a geographic information system (GIS) enables visualization of discrete instances of ground motion. Sequential viewing of these instantaneous visualizations will create an animation of ground motion for the complete event. If the distribution of recording stations throughout the study region is densely spaced and regularly distributed (stations on a 1km grid), then creating these animations would be a simple process of synchronizing the records into a GIS and extracting time-slices for visualization.

Geomatrix (Mote and Egan, 2005), in collaboration with the California Strong Motion Instrumentation Program (CSMIP), have developed a ground shaking animation system that visualizes ground shaking amplitudes, oscillations, and duration using existing strong-motion datasets from recent earthquakes. The animation system takes strong motion records, geology, seismic wave velocities, attenuation relationships and USGS ShakeMap modeled peak ground motion parameters (peak ground acceleration (PGA), peak velocity (PGV), peak displacement (PGD)) across a region to interpolate shaking by time-shifting and amplitude-scaling ground motions across a study area at any specified time-step. The animation system models ground motions across a specific area by discretizing the area into a grid and modeling a representative ground motion time history for each grid cell. Extracting ground motion values for grid cells at any instantaneous time allows for visualization of the representative ground motion at that time. Combination of a series of these visualizations in sequence will create an animation of ground shaking.

This paper presents the implementation and execution of this animation system within the ArcGIS application.

Implementation

To visualize an earthquake a ground shaking time history is developed for cells within a model grid based on available strong-motion data for a particular earthquake. The derivation of ground shaking history takes into account proximal strong-motion data, geologic conditions, seismic wave arrival times, distance from the source and appropriate attenuation relationships.

The animation system follows a work flow consisting of the following tasks:

- Acquire and process available datasets.
- Interpolate data to model ground motion records
- Visualize instantaneous ground shaking
- Animation of ground shaking.

In order to implement this system a series of standard GIS and database applications were integrated with some custom developed code. ArcGIS was coupled with a Microsoft Access database and used as the model framework to store geologic basemap data along with strong-motion data. The GIS is essential to this system as it provides a spatial link between dense strong motion datasets and a mapping environment.

The animation system has 4 main components (database, modeling, visualization, and animation) linked through the GIS.

Database Component

The database structure maintains the applicable strong motion data (historic and future) and model results. The database is executed within the Microsoft Access environment with custom developed scripts (Visual Basic for Applications, VBA). User interfaces (forms) help upload and format new ground motion data as they become available.

Modeling Component

The modeling component uses custom developed time history estimation programs within Access to approximate ground motion histories for areas of the model distant from the strong motion stations. Input and output files will be maintained in the database and linked to the GIS-based geologic map.

Visualization Component

The model results are visualized within ArcGIS. Spatial Analyst surface interpolation algorithms are used to create and visualize a ground shaking surface at set a time-slice interval (i.e. 0.5 seconds) to produce still frames for the animation. For an earthquake where shaking is 40 seconds long the model will produce 80 map frames (40seconds * 2 frames/second.). Each frame is symbolized by a standard explanation.

Animation Component

Initial animation is completed in ArcScene allowing for variation of the basemap layers, view perspective and map scale to provide various versions of the same modeling results. ArcScene will produce the ground shaking animations in standard formats. Post processing of the animation will add explanations and title blocks to the animation.

Data Acquisition and Pre-Processing

To seed the animation system, available data pertaining to the earthquake are downloaded and pre-processed into the GIS and database. Data needed for the animations include earthquake parameters (location of epicenter, hypocenter, and rupture), geology, strong motion records, and the ShakeMap model.

Earthquake Parameters

GIS layers of the earthquake epicenter, hypocenter and rupture are created to provide spatial relationships with the strong motion recording stations and the ShakeMap model grids. Epicenter and hypocenter locations are extracted from the record headers. The rupture is digitized from literature or the ShakeMap model.

Strong Motion Data

Available digital, free-field strong-motion station records for designated earthquakes are processed and parsed into a database-ready format via a customized automated parsing script. The free-field records report values for acceleration, velocity, and displacement recorded from 3 channels (2 horizontal and 1 vertical). This produces a total of 9 variables (3 channels x 3 parameters) per time interval per station.

To simplify the visualization, an absolute value of ground shaking was calculated by taking the square root sum of squares of both horizontal channel values for acceleration, velocity, and displacement. For simplicity the ground shaking animations presented here visualize only the absolute horizontal displacement. The animation system can isolate individual directional channels or the other ground motion parameters (acceleration and velocity).

Station parameters from the record header are also parsed into the database. Station parameters include station-id, location (latitude and longitude), PGA, PGV, PGD, channel orientations, trigger time, recording time interval, and total time. In order to execute the interpolation methodology, to be discussed below, a number of spatial parameters must be derived for each Station. The station-to-epicenter distance, station-to-hypocenter, and station-to-rupture distances were all calculated using standard GIS functionality.

ShakeMap Data

ShakeMap model values for all five designated earthquakes were acquired via the CSMIP Web site and imported into the model database. The ShakeMap model provides peak ground motion parameters (PGA, PGV, MMI) at constant grid spacing across the study area (Figure 1). The inherent ShakeMap grid spacing defines the animation model grid.

As with the Stations, in order to execute the interpolation methodology, a number of spatial parameters must be derived for every grid cell. The cell-to-epicenter distance, cell-to-hypocenter, and cell-to-rupture distances are calculated using standard GIS functionality.

Interpolation Methodology

Strong motion records, seismic velocities, and ShakeMap are interpolated to estimate ground motion time histories for any grid cell in the model. A critical step in animating is selecting appropriate strong motion records to model ground motions at specific grid cells in the model. The interpolation methodology can be summarized as follows:

For any model cell in the model area…

- **Select** the strong motion records based on similar geology and a minimal difference in distance between cell-to-rupture versus station-to-rupture and cell-to-hypocenter versus station-to-hypocenter distances.
- **Shift** the time of each of the selected records by a time interval derived from the difference in arrivals times of the P- and S- Waves respectively.
- **Scale** the amplitude of each of the records based on a ratio between the ShakeMap derived ground motion parameter at the model cell and the recorded ground motion parameter at the station.
- **Interpolate** values from the appropriate shifted and scaled records into one value with the Inverse Distance Weighted algorithm using the respective cell-to-station distances.

Details of these modeling components are discussed below

Select

Integral to the interpolation methodology is the selection of appropriate stations from which to extract strong-motion records when estimating ground motion for any grid cell in the model. Selecting the closest cell-to-hypocenter and station-to-hypocenter distances is the most simplistic solution, but does not accommodate ground motion related to the rupture.
Ideally, the stations selected should have both a station-to-hypocenter and station-to-rupture distance similar to the cell being modeled. This supports a better estimation of records, as attenuation and seismic wave arrival times would be theoretically similar. In addition to selecting appropriate spatial relationships, only stations with similar geologic conditions are selected.

Criteria were developed to select the most appropriate station records to use when modeling any grid cell. The criteria are based on both hypocenter/rupture distances and geology. The algorithm uses the square root sum of squares to minimize the difference in distance between the cell-to-hypocenter versus station-to-hypocenter and cell-to-rupture versus station-to-rupture. Using similar geologic conditions further refines the selection. Stations seated in soil are only used to model grid cells in soil of the model and stations seated in rock are only used to model grid cells covering rock portions of the model. While theoretically correct, it is not always feasible to invoke a strict use of geology as a selection key due to the limited number of stations. When a cell is in the near-field (<50 km from the rupture), the geologic criteria is relaxed because near-field effects may override geologic attenuation. In the far-field if there are no stations with similar geology that have relatively similar station-to-rupture and station-to-hypocenter distances (i.e. within 1/3 of the cell-to-hypocenter distance) then the geologic criteria is removed.

Shift

To interpolate a ground shaking time-history from a station to any model cell the selected records are shifted to accommodate for travel times of seismic waves through the geologic medium. The shift is based on empirical P- and S- wave arrival times, rather than models of seismic wave velocities to account for heterogeneity in the geology.

To accommodate both P-wave and S-wave arrival components of the records, different time-shifts were applied based on the distinct arrival times of the two waves. Initially, this time-shift is based on P-wave arrival times. As the model time progresses and the arrival of the S-wave occurs, the time-shift is based on the S-wave arrival times. This methodology essentially separates the wave components to synchronize the arrival of both the P-wave and S-wave throughout the model.

Scale

To account for attenuation of seismic energy with distance from the rupture to any model cell the selected record are scaled to account for attenuation of the shaking amplitude. ShakeMap provides a model structure where attenuation relationships and geology have been included in algorithms to estimate peak ground motion parameters. Using the ShakeMap model integrates these attenuation relationships into the animation tool.

Station values for acceleration, velocity and displacement are scaled by the ratio of the appropriate ShakeMap-modeled peak ground motion parameter (PGA or PGV) at the model grid cell to the peak ground motion parameter at the recording station. Since the ShakeMap models ground motions generally decreasing away from the fault rupture, using this ratio will dampen or heighten amplitudes as you move away or closer to the rupture, respectively, across the model area (Fig. 3). To modeling displacement, PGV ratios are used as the scaling factor because ShakeMap does not report PGD.

Interpolation

With the appropriate records selected, shifted, and scaled to account for attenuation and seismic velocity travel times, new time histories for every model grid are calculated. At every time interval, the shifted and scaled values are interpolated with the Inverse Distance Weighting algorithm and the respective square root sum of squares of difference in cell-to-hypocenter versus station-to-hypocenter distances and difference in cell-to-rupture and station-to-rupture distances to calculate an instantaneous ground motion. Iteration of this process through the desired time duration on a cell-by-cell basis generates complete time histories for every cell in the model.

Visualization

Extraction of values from the interpolated ground shaking time histories for each model cell allows creation of instantaneous surfaces of ground motion at specific time intervals. Values (e.g. displacement) are extracted and interpolated into the ground shaking surface using a Kriging interpolation algorithm (ArcGIS 3D Analyst). Kriging adds a degree of smoothing to the surface. The model time intervals can be as small as the raw strong motion data which typically is 0.005 seconds, although the general application of the model uses a 0.1 second time interval.

Animation

The ground shaking surfaces and rupture vectors are layered onto the GIS basemap (digital terrain model, roads, and station locations) to provide a spatial reference frame. Custom symbology, scaling, zooming and panning of the animation can be implemented by built-in functionality of the GIS. The sequential visualization of synchronized ground shaking surfaces at a desired time interval produces the animation (ArcScene).

Earthquake Animations

Historical Californian earthquakes (1992 Landers (Figure 1), 1989 Loma Prieta, and 1994 Northridge (Figure 2) earthquakes) and a simulated 1906 San Francisco earthquake (Figure 3, 4) animations were developed to visualize ground shaking amplitudes, oscillations, and duration over 2 minutes of these well known events. The animation shows ground shaking at 0.5 second intervals from the initial rupture at the hypocenter, extending outward from the epicenter until the shaking has subsided.

The earthquake animations depict the patterns of ground shaking onset, intensity oscillation, and duration likely experienced throughout California during an event. The overall dynamics of the ground shaking animation captures the behavior of seismic waves traveling through the geologic medium. The earthquake animations show strong-motions proximal to the epicenter at the nucleation of the event and decreasing motions emanating away from the source with time. Both P-Wave and S-Wave can be recognized and tracked at their respective velocities in the animations. Attenuation relationships, integrated from ShakeMap, can also be recognized as well as the interaction between rock/alluvium surface geology and the shaking.

These animation depicts the areal extent and long duration of shaking from events in a way that is understandable to the general population; i,e, the way that they would feel the ground shaking arrive, oscillate, and diminish in time. Comparisons of this model to similar models developed for other California events show the order of magnitude difference between these events that are comprehensible by the non-seismologic community and may be used as a powerful educational tool.

Acknowledgements

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References

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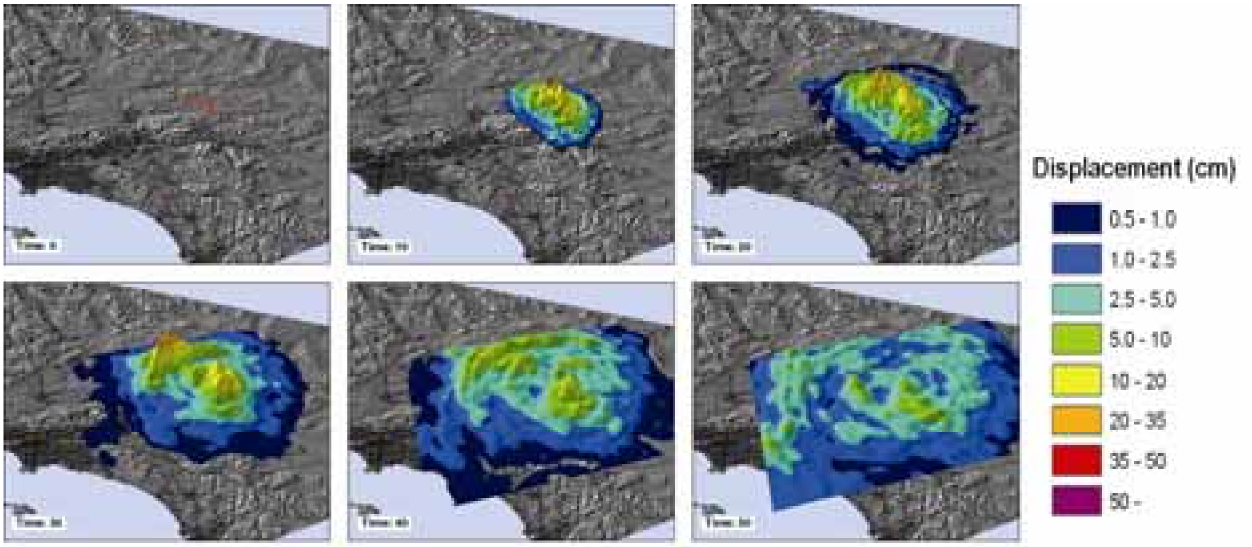

Figure 1 1992 Landers Animation Still Frames

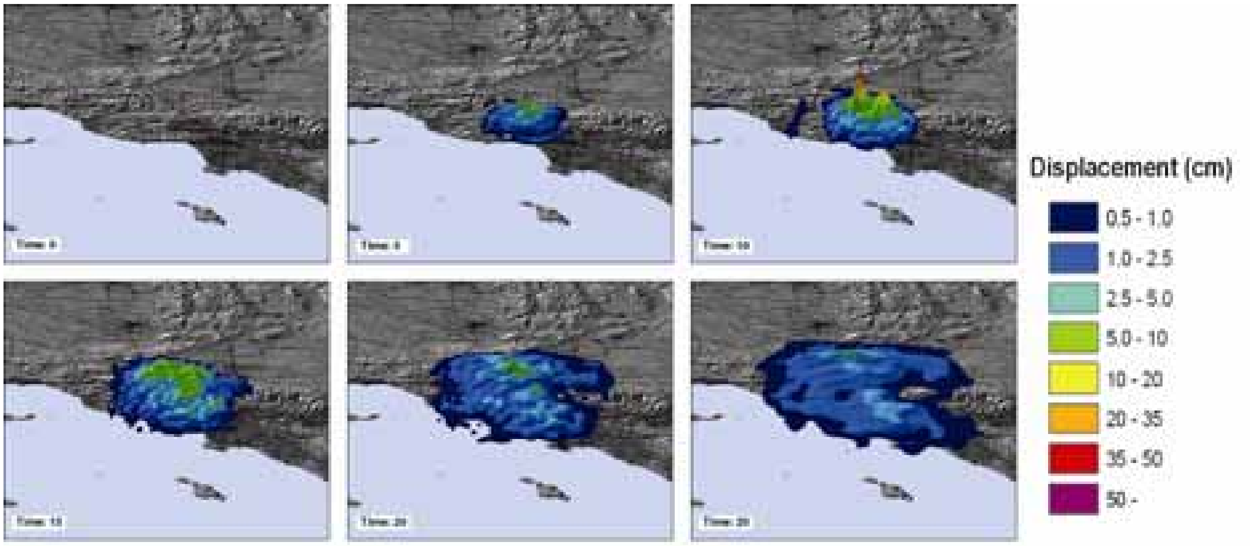

Figure 2 1994 Northridge Animation Still Frames

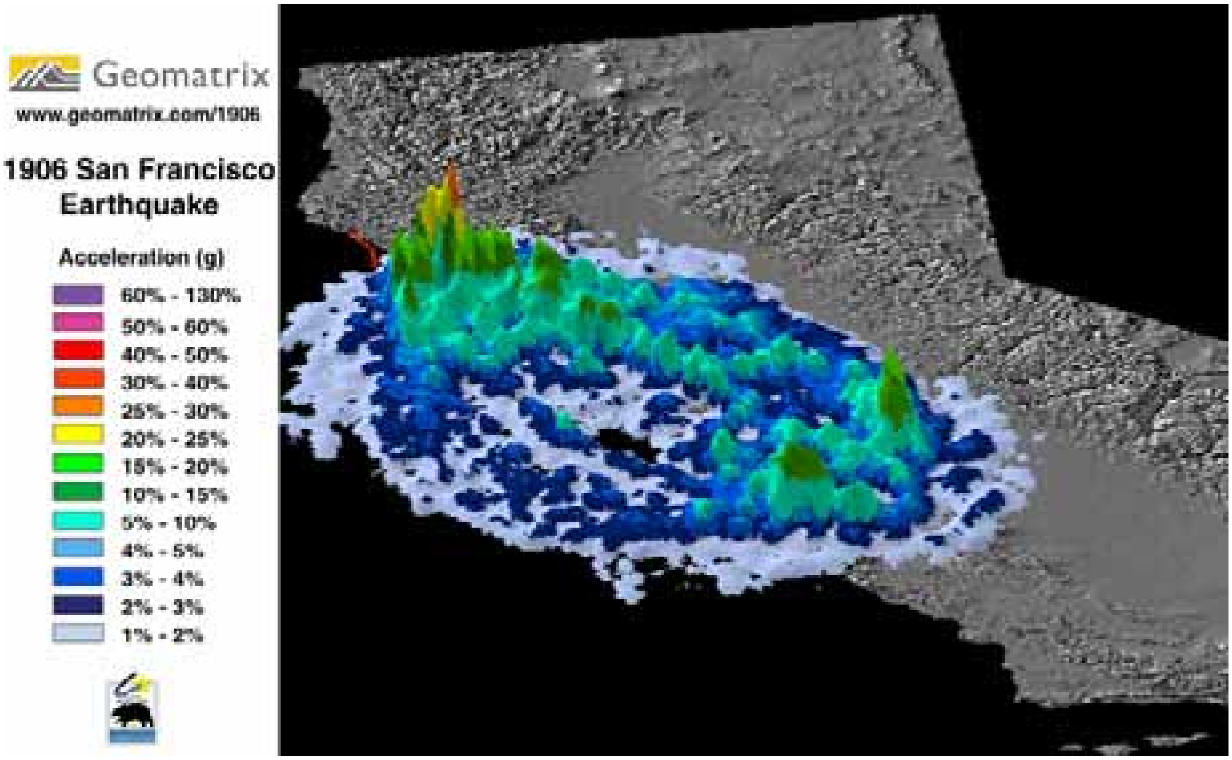

Figure 3 1906 San Francisco Simulation – Time = 45 seconds

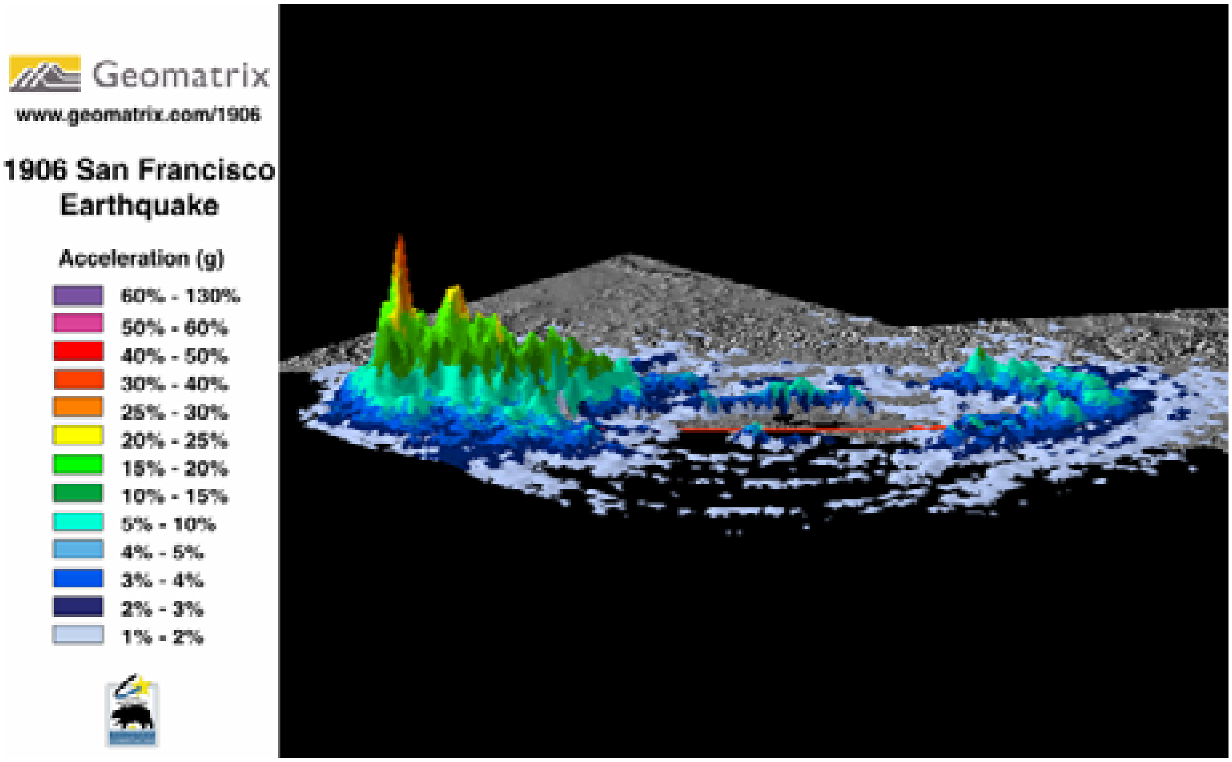

Figure 4 1906 San Francisco Simulation – Time = 120 seconds

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