Animation of Clouds

Animation of Clouds

- Realistic motion
  - complex dynamics of cloud formation
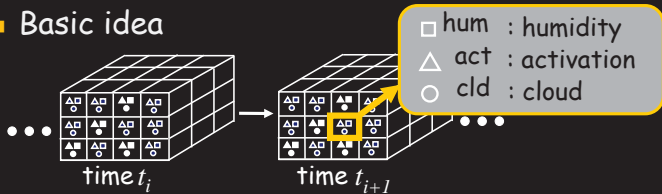 - phase transition effects

procedural simulation
(cellular automata)

physically-based simulation
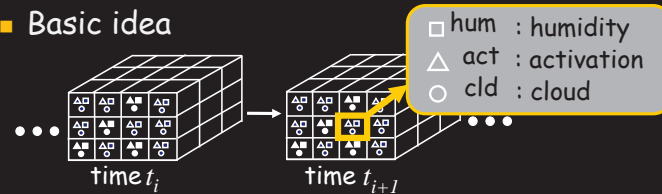(fluid simulation)

Procedural animation

- Basic idea

□ hum : humidity
△ act : activation
○ cld : cloud

time t_i → time t_{i+1}

- Three logical variables at each cell

  '*hum*' : there is enough vapor
  '*act*' : phase transition is ready to occur
  '*cld*' : clouds exist or not

Procedural animation

- Basic idea

□ hum : humidity
△ act : activation
○ cld : cloud

time t_i → time t_{i+1}
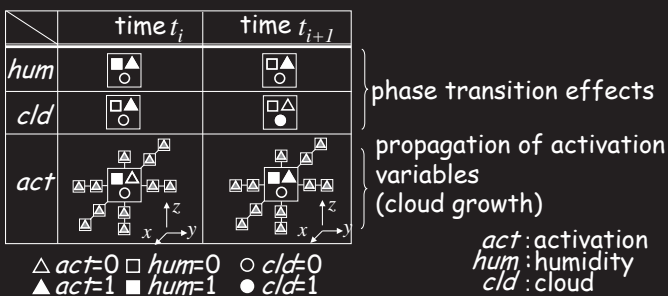
- Status of variables: 0 or 1
- Simple transition rules by Boolean operations
  - cloud growth
  - cloud extinction
  - advection by wind

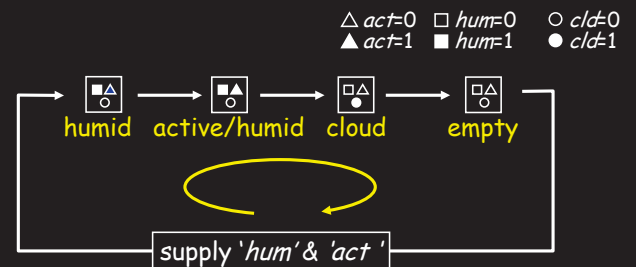# Procedural animation

- Rules for cloud growth [Nagel92]

	time t_i	time t_{i+1}	
hum			phase transition effects
cld			
act			propagation of activation variables (cloud growth)

△ *act*=0 □ *hum*=0 ○ *cld*=0
▲ *act*=1 ■ *hum*=1 ● *cld*=1

act : activation
hum : humidity
cld : cloud

Procedural animation

- Rules for cloud extinction

△ *act*=0 □ *hum*=0 ○ *cld*=0
▲ *act*=1 ■ *hum*=1 ● *cld*=1

humid → active/humid → cloud → empty
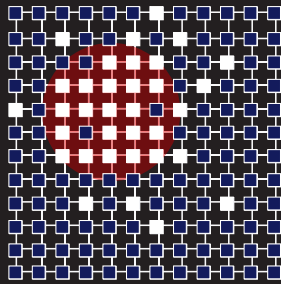
supply '*hum*' & '*act*'

Formation and extinction occur repeatedly

Procedural animation

- Controlling distribution of clouds

1 humid area
   (spheres/elipsoids in 3D)

2 change '*hum*' & '*act*'
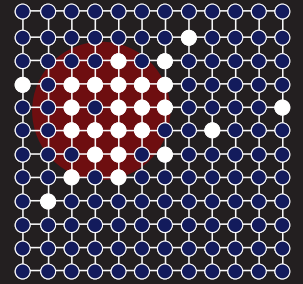   from 0 to 1

Procedural animation

- Controlling distribution of clouds

1 humid area
   (spheres/elipsoids in 3D)

2 change '*hum*' & '*act*'
   from 0 to 1

3 clouds are formed

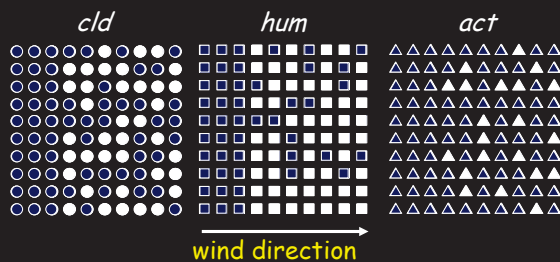4 change '*cld*' from 1 to 0

Controlling red area
→ Controlling cloud shapes & motion

Procedural animation

- Advection by wind
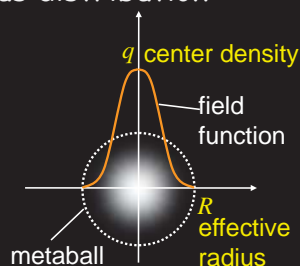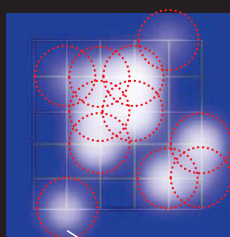 - Shifting variables toward the wind direction

cld   *hum*   *act*

wind direction

Procedural animation

- demo ▪

Procedural animation

- Creation of continuous distribution

q center density

field
function

metaball

R effective
radius

metaball

- radius: specified by user
- center density: filtered value

Procedural animation

- Example

Cloud Simulation

Modeling of Clouds

- Image-based modeling
  - Use of 2D images to synthesize density distribution of 3D clouds
- Procedural animation
  - Cellular automata: simple rules to compute motions of clouds
- Physically-based simulation
  - Numerical simulation of atmospheric fluid dynamics

Cloud Formation

- Required physical quantities
  - Velocity, water vapor, water droplet (cloud), temperature of atmosphere
- Phase transition between vapor and droplet
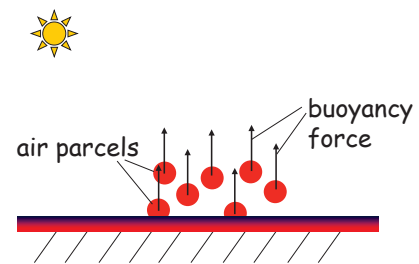 - Generation/extinction of clouds
  - Cloud growth to higher region

Overview of Cloud Formation Process
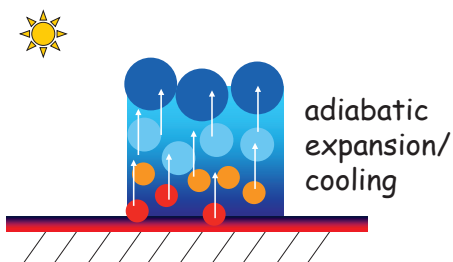
Ground is heated by the sun.
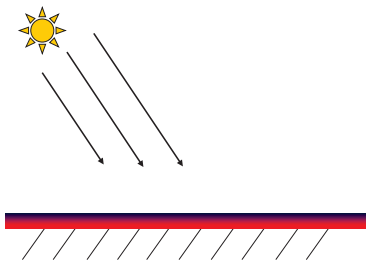
Overview of Cloud Formation Process
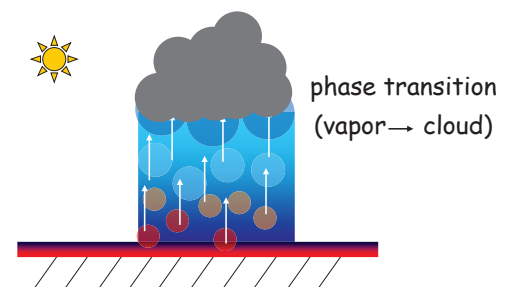
Air parcels start to move upward.

buoyancy force

air parcels

Overview of Cloud Formation Process

Temperature of air parcels decreases.

adiabatic expansion/ cooling

Overview of Cloud Formation Process

Clouds are generated due to phase transition

phase transition (vapor→ cloud)

Overview of Cloud Formation Process

latent heat is liberated due to phase transition

phase transition
(vapor → cloud)

Overview of Cloud Formation Process

latent heat is liberated due to phase transition

↓

additional buoyancy

phase transition
(vapor → cloud)

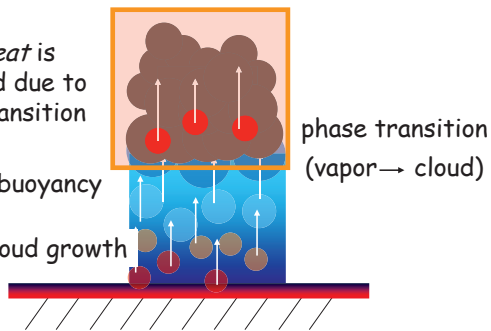## Overview of Cloud Formation Process

latent heat is liberated due to phase transition

↓
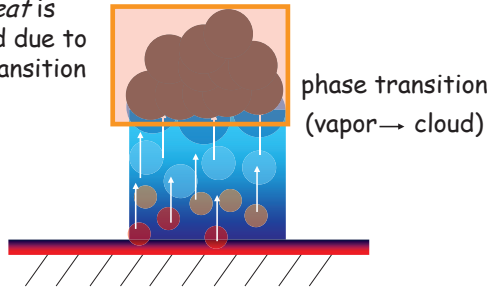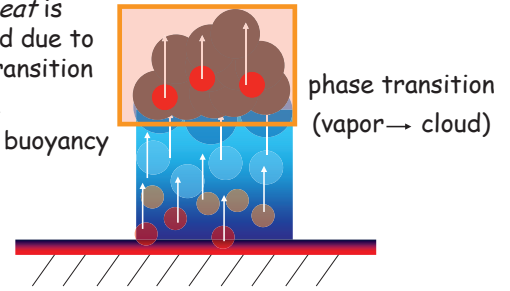
additional buoyancy

↓

further cloud growth

phase transition
(vapor → cloud)

Equations for cloud simulation

- Velocity of atmosphere
  - Navier-Stokes equation + buoyancy force

- Temperature of atmosphere
  - adiabatic cooling, latent heat, heat from ground

- Cloud formation/extinction
  - phase transition between vapor and droplets

Numerical Simulation

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} - \nabla p + \mathbf{f} + \mathbf{B}$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\mathbf{B} = k_b \frac{T - T_0}{T_0} \mathbf{z}$$

Velocity of atmosphere

$$\frac{\partial T}{\partial t} = -(\mathbf{u} \cdot \nabla)T - \Gamma_d v_z + Q C_c + S_T$$

Temperature of atmosphere

$$\frac{\partial q_c}{\partial t} = -(\mathbf{u} \cdot \nabla)q_c + C_c$$

$$\frac{\partial q_v}{\partial t} = -(\mathbf{u} \cdot \nabla)q_v - C_c$$

Water vapor and water droplet

Simulation Results

- Cumulus clouds

Number of grids : 150×120×50
Computational time: 4 sec./step

computer : Pentium III 1.2GHz

Simulation Results

- Cumulonimbus

Number of grids : 150×120×100
Computational time: 8 sec./step

computer: Pentium III 1.2GHz

Video

Control of Cloud Formation

- User draws contour line of the desired shape.
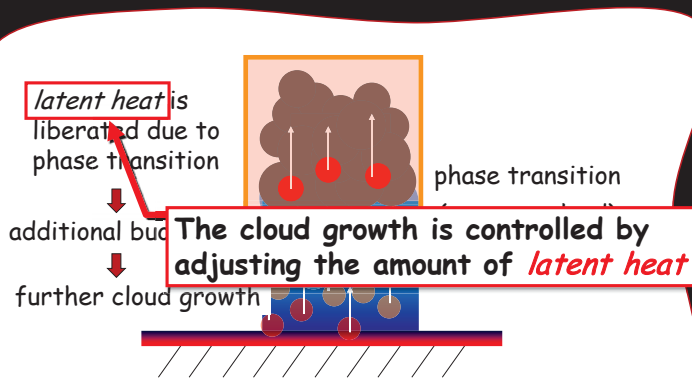

Control of Cloud Formation

- User draws contour line of the desired shape.
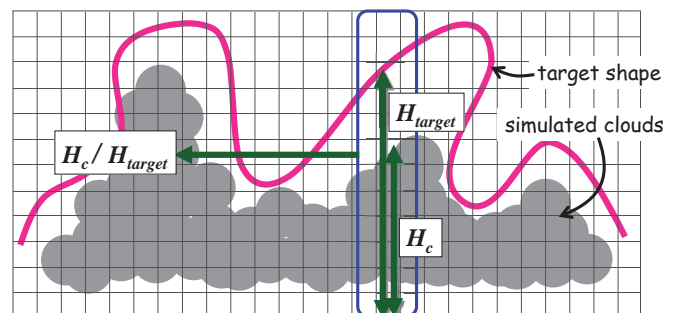- System controls simulation and generates realistic clouds
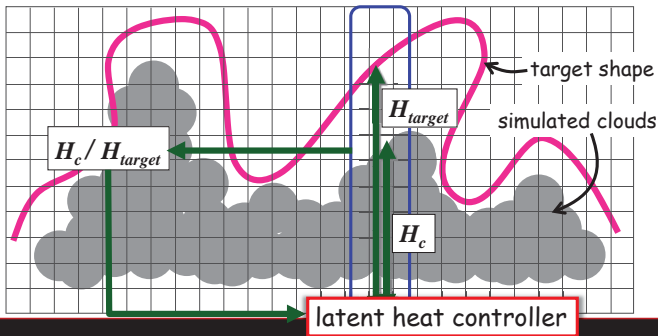

Overview of Cloud Formation Process

latent heat is liberated due to phase transition

additional bud

further cloud growth

phase transition

The cloud growth is controlled by adjusting the amount of *latent heat*

Feedback Control

- Latent heat controller
- Water vapor supplier

H_{target}

H_c / H_{target}

H_c

target shape

simulated clouds

Feedback Control

- Latent heat controller
- Water vapor supplier

target shape
simulated clouds

H_{target}
H_c / H_{target}
H_c
latent heat controller

Feedback Control

- Latent heat controller
- Water vapor supplier

target shape
simulated clouds

H_c / H_{target}
increase latent heat
latent heat controller

Feedback Control

- Latent heat controller
- Water vapor supplier

water vapor supplier
target shape
simulated clouds

H_c / H_{target}
increase latent heat
latent heat controller

Feedback Control

- Latent heat controller
- Water vapor supplier

water vapor supplier
add water vapor
target shape
simulated clouds

- Generation of clouds
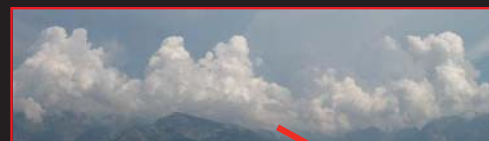- Cloud development
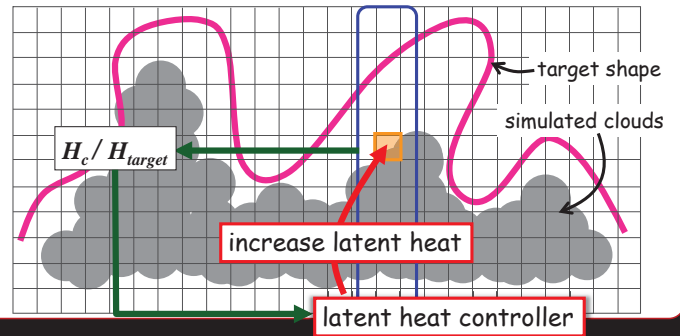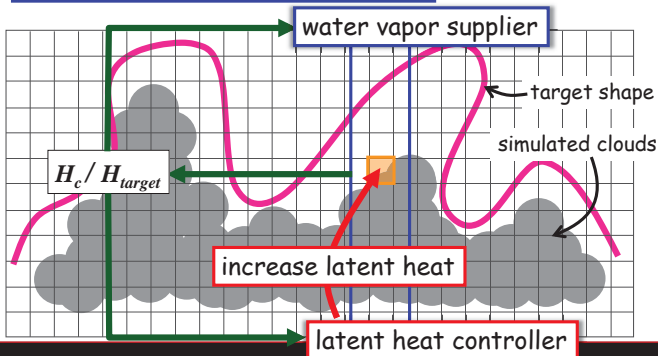
increase latent heat
latent heat controller
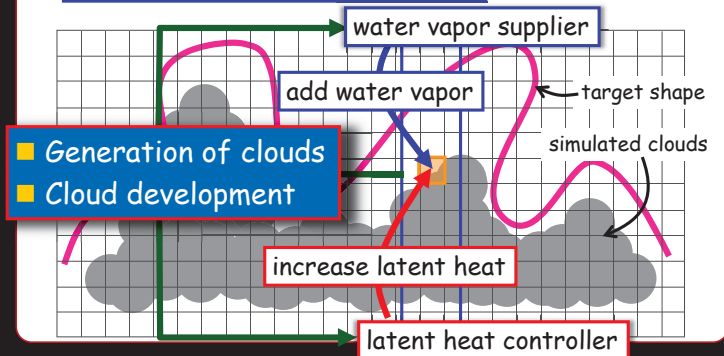
Example

- Typical cloud shapes
  No. of grid points : 320 × 80 × 100
  Comp. time : 7.6 sec. per single time step

Example using Photograph

- Creating target shape from real photograph
  No. of grid points : 320 × 80 × 100
  Comp. time : 7.6 sec. per single time step

Unnatural Clouds

- Creating holes inside clouds to form skull-shaped clouds
  - No. of grid points : 240 × 80 × 100
  - Comp. time : 5.6 sec. per single time step