Title: Conformal field theory in the laboratory: quantum dots, Kondo effect, non-Fermi liquids and all that

Date: Nov 01, 2006 02:00 PM

URL: http://pirsa.org/06110000

Abstract: Boundary conformal field theory finds applications not only to high energy physics but also to condensed matter systems containing quantum impurities, whose world lines can sometimes be modelled as boundaries of 2-dimensional space-time. This technique leads to exact predictions for the low temperature behaviour of gated semi-conductor quantum dot devices which have been recently confirmed experimentally. I will give a non-technical overview of both the theory and the experiments.

Conformal Field Theory in the Laboratory: Quantum Dots, Kondo Effect, Non-Fermi Liquids and all that

Ian Affleck
Perimeter Institute, November 1, 2006

UBC

CIAR The Canadian Institute for Advanced Research

High Energy | Condensed Matte

1970

Wilson

Nozières & Blandi

Wess, Zumino

Andrei & Destri

Witten

Tsvelik

Knizhnik

Cardy

& Zamolodchikov

Affleck & Ludwig

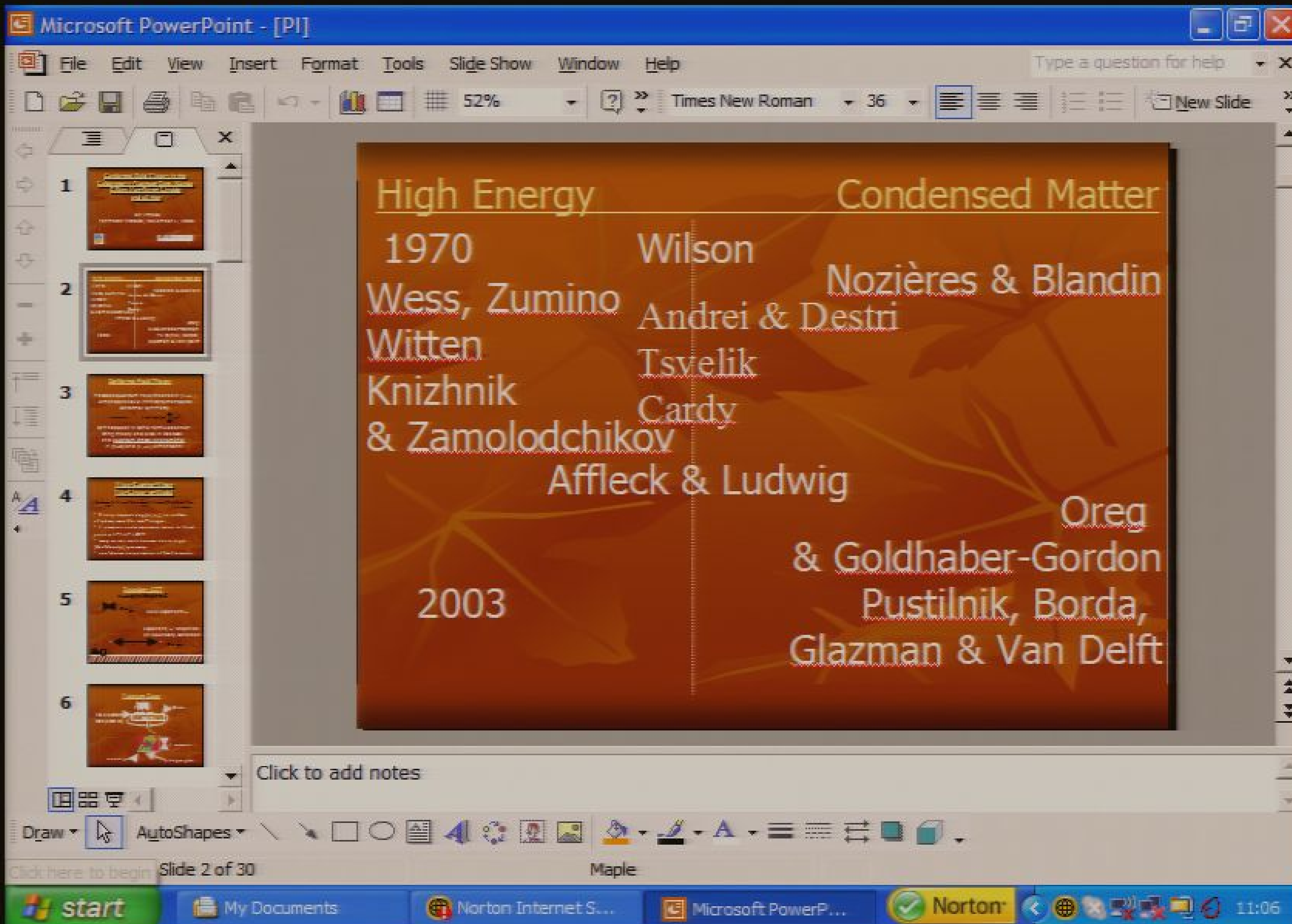
Oreg

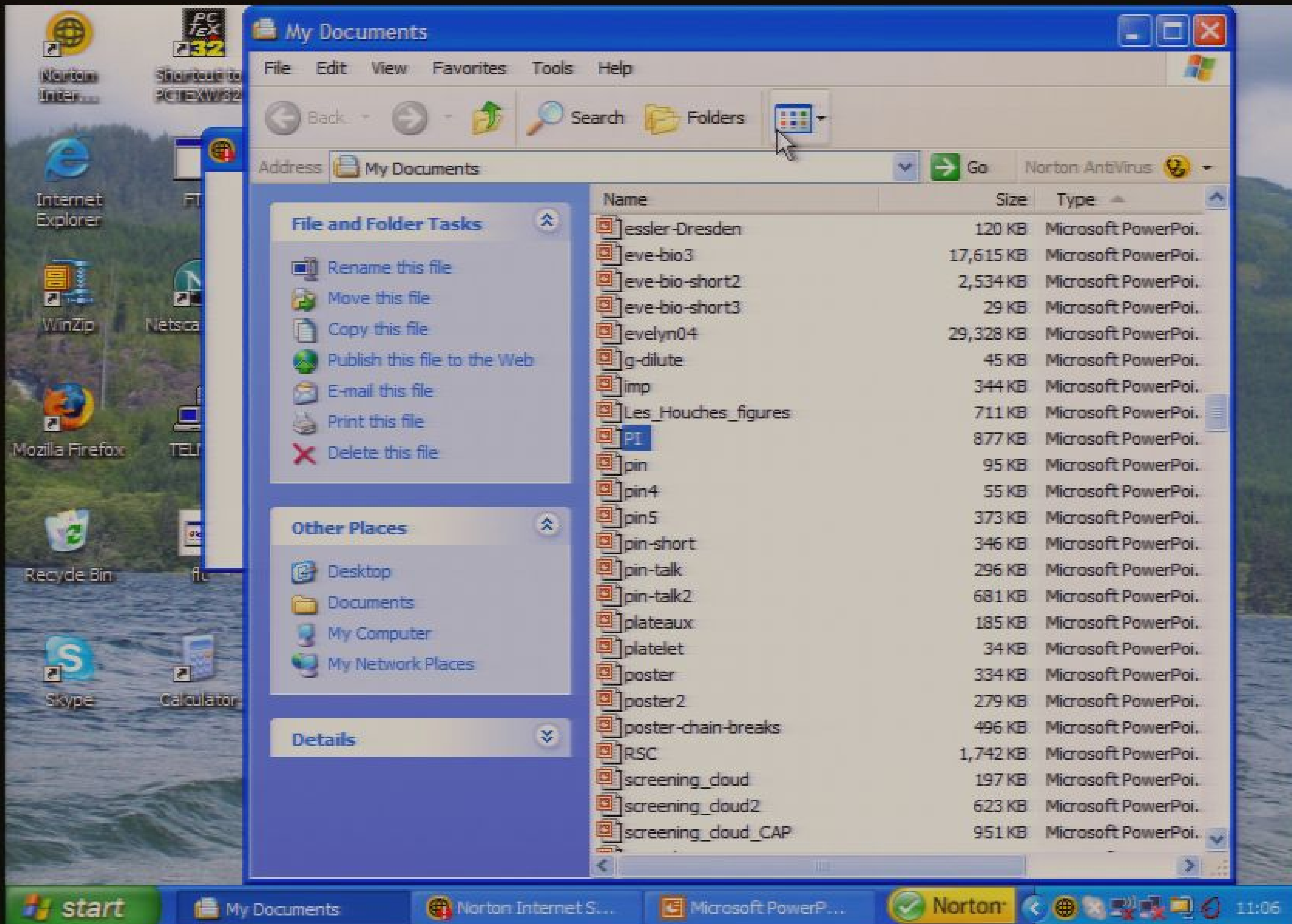
& Goldhaber-Gordo

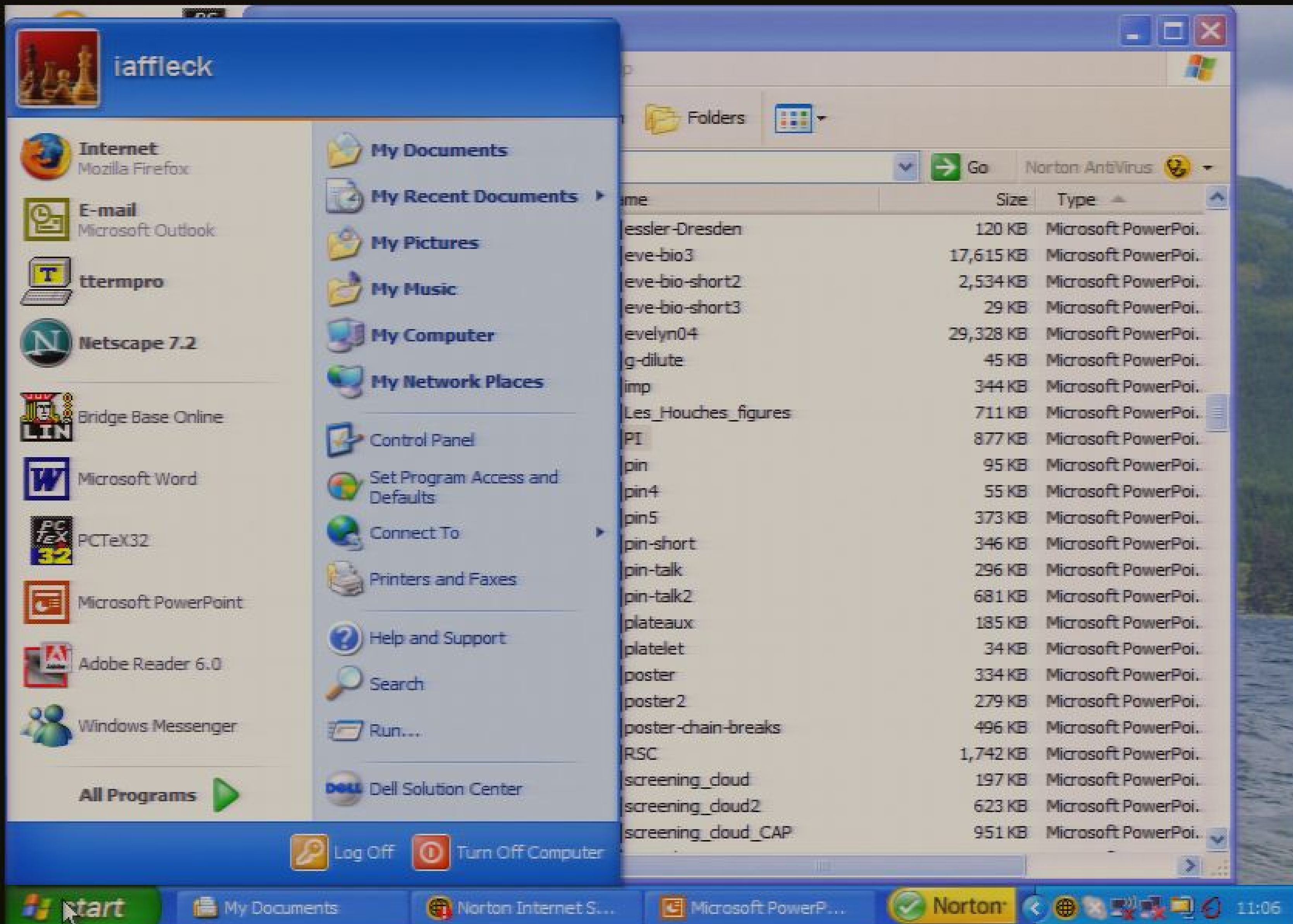
2003

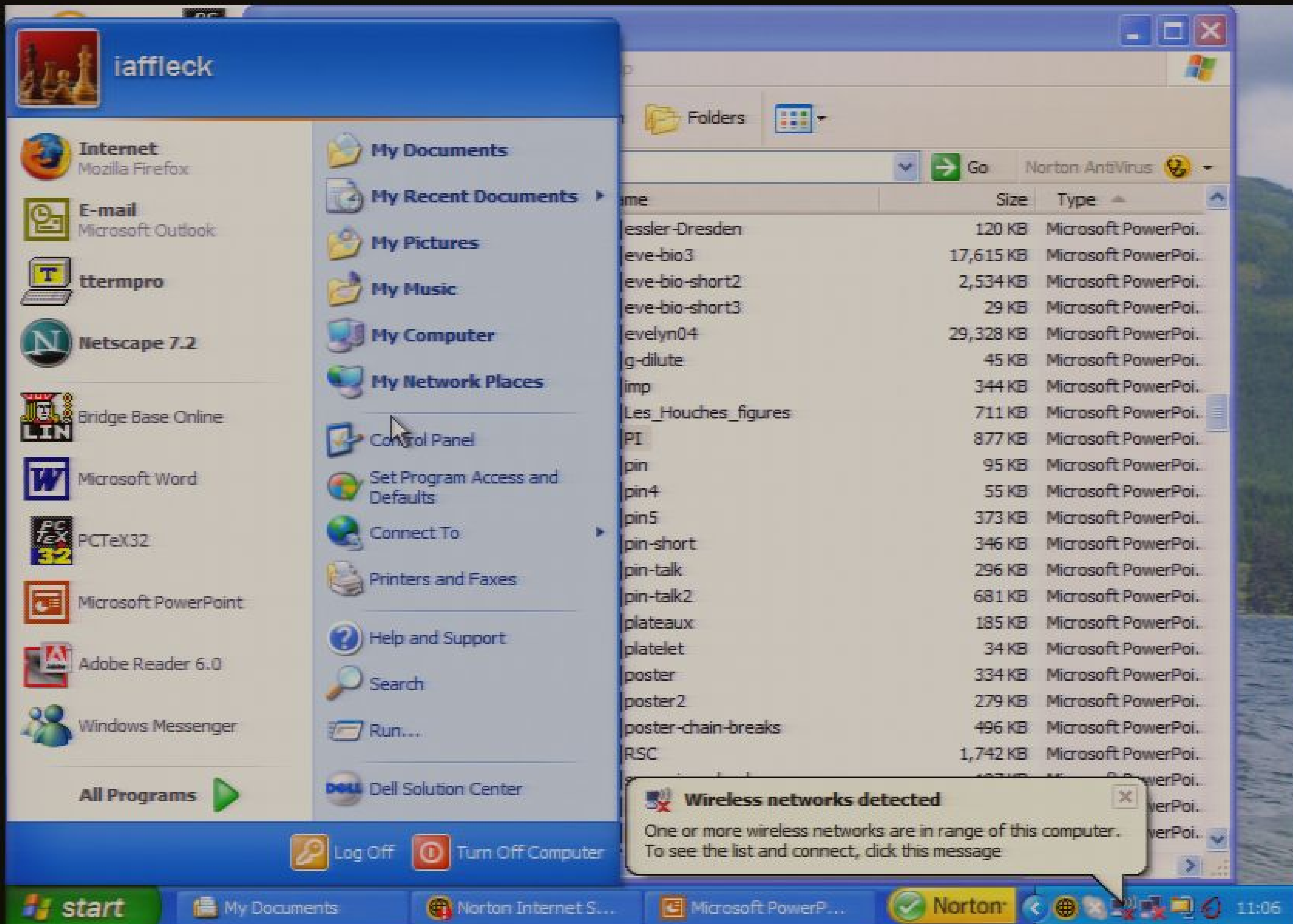
Pustilnik, Borda

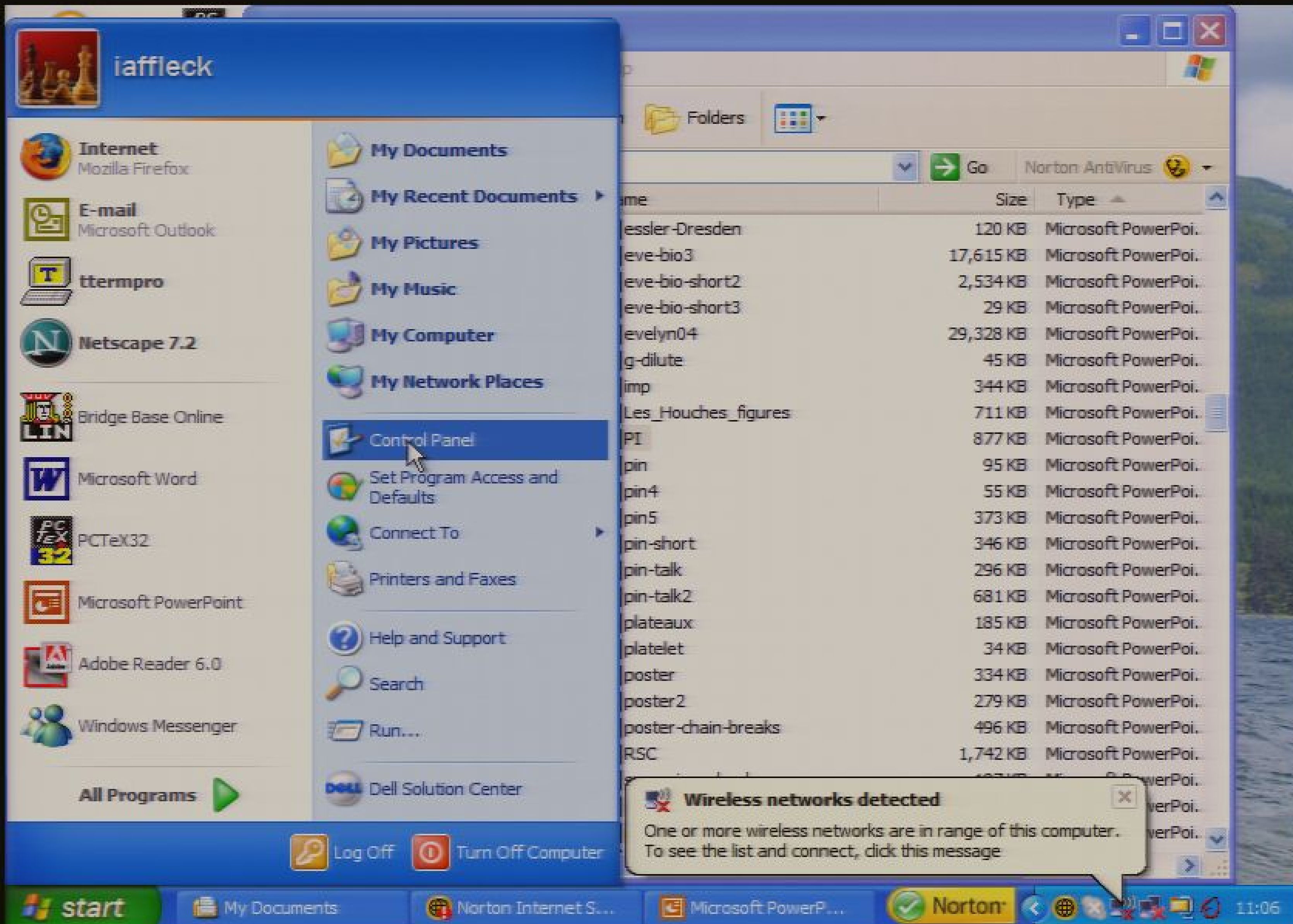
Glazman & Van Del

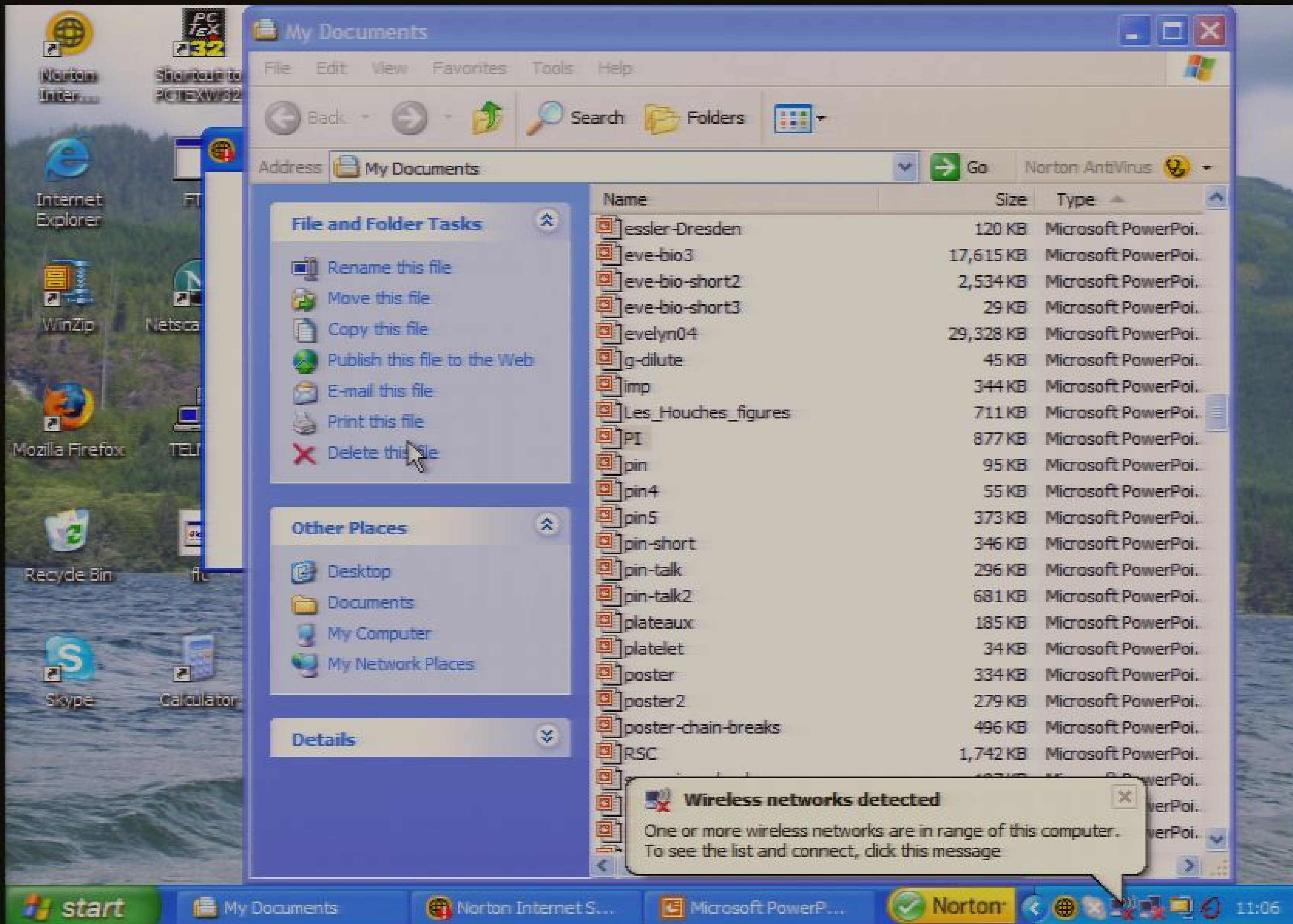

Microsoft PowerPoint - [PI]
High Energy
Condensed Matter
1970
Wilson
Nozières & Blandin
Wess, Zumino
Andrei & Destri
Witten
Tsvelik
Knizhnik
Cardy
& Zamolodchikov
Affleck & Ludwig
Oreg
& Goldhaber-Gordon
2003
Pustilnik, Borda,
Glazman & Van Delft
Click to add notes
Slide 2 of 30
Maple


My Documents
File Edit View Favorites Tools Help
Back
Search
Folders
Address
My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name Size Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
screening_cloud 197 KB Microsoft PowerPoi...
screening_cloud2 623 KB Microsoft PowerPoi...
screening_cloud_CAP 951 KB Microsoft PowerPoi...
Norton Inter...
Shortcut to PCTEXW32
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

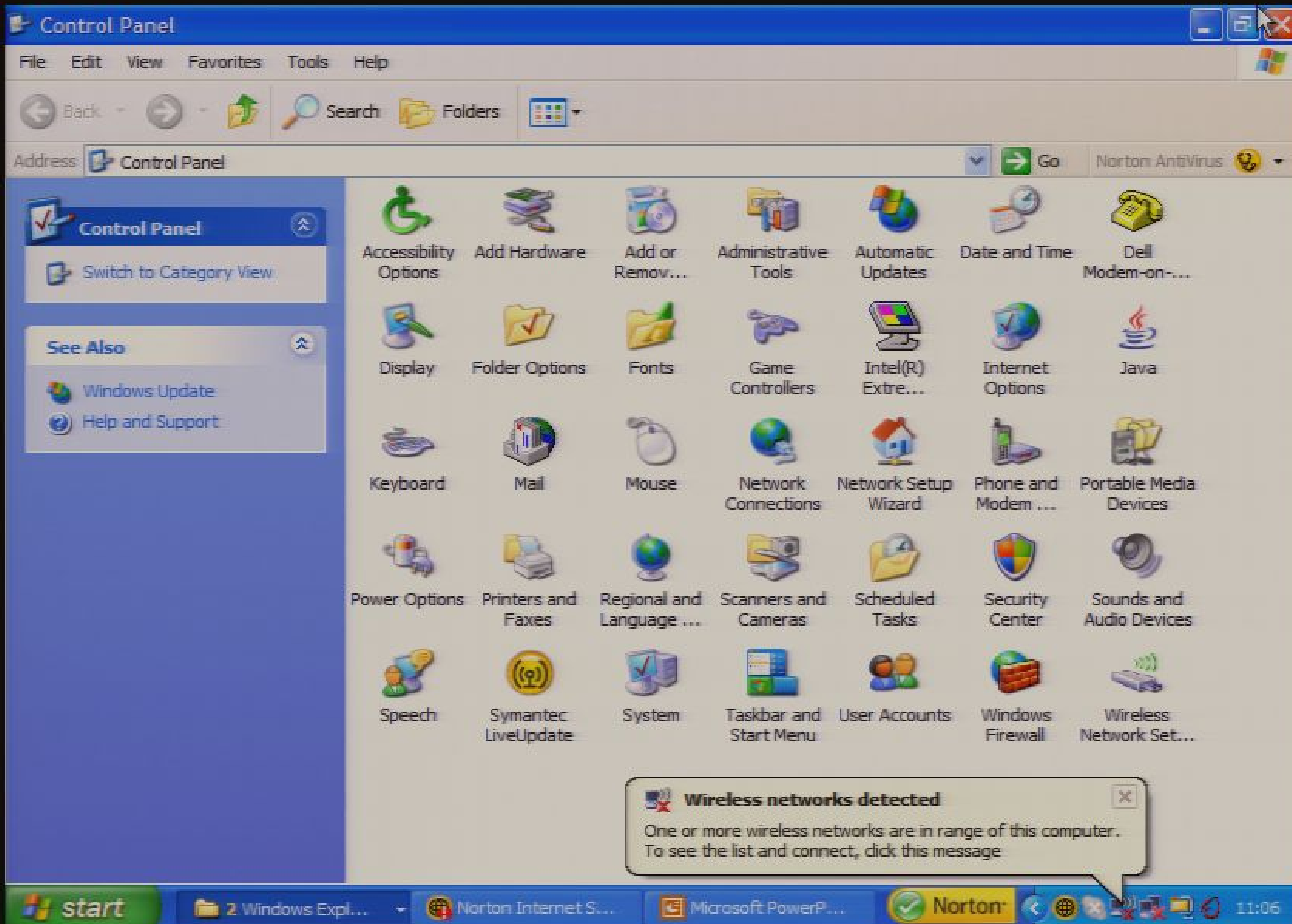

iaffleck
Internet
Mozilla Firefox
E-mail
Microsoft Outlook
ttermpro
Netscape 7.2
Bridge Base Online
Microsoft Word
PCTeX32
Microsoft PowerPoint
Adobe Reader 6.0
Windows Messenger
All Programs
My Documents
My Recent Documents
My Pictures
My Music
My Computer
My Network Places
Control Panel
Set Program Access and Defaults
Connect To
Printers and Faxes
Help and Support
Search
Run...
Dell Solution Center
Log Off
Turn Off Computer
Folders
Go
Norton AntiVirus
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
screening_cloud 197 KB Microsoft PowerPoi...
screening_cloud2 623 KB Microsoft PowerPoi...
screening_cloud_CAP 951 KB Microsoft PowerPoi...
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

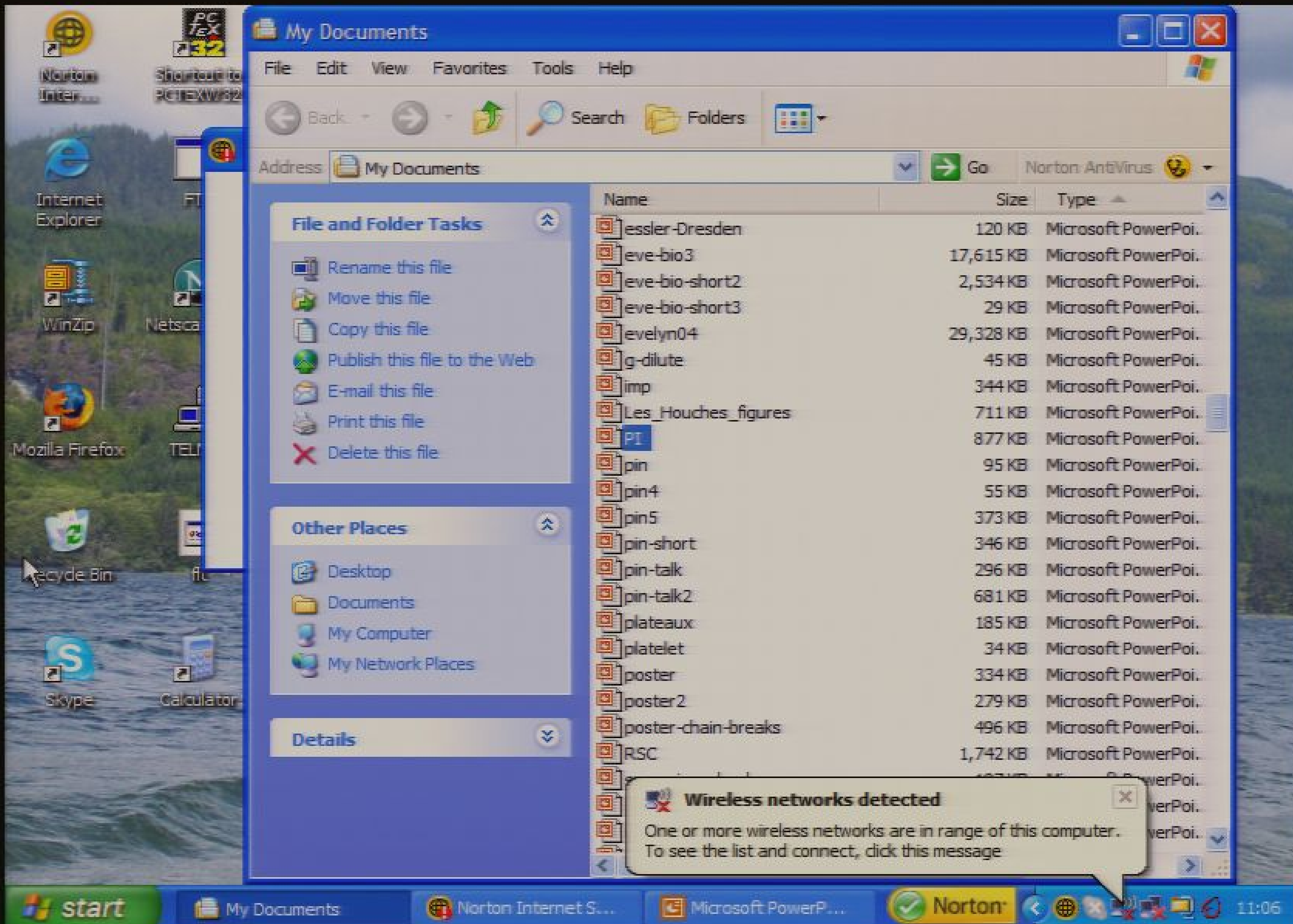

iaffleck
Internet
Mozilla Firefox
E-mail
Microsoft Outlook
ttermpro
Netscape 7.2
Bridge Base Online
Microsoft Word
PCTeX32
Microsoft PowerPoint
Adobe Reader 6.0
Windows Messenger
All Programs
My Documents
My Recent Documents
My Pictures
My Music
My Computer
My Network Places
Control Panel
Set Program Access and Defaults
Connect To
Printers and Faxes
Help and Support
Search
Run...
Dell Solution Center
Log Off
Turn Off Computer
Folders
Go
Norton AntiVirus
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06


iaffleck
Internet
Mozilla Firefox
E-mail
Microsoft Outlook
ttermpro
Netscape 7.2
Bridge Base Online
Microsoft Word
PCTeX32
Microsoft PowerPoint
Adobe Reader 6.0
Windows Messenger
All Programs
My Documents
My Recent Documents
My Pictures
My Music
My Computer
My Network Places
Control Panel
Set Program Access and Defaults
Connect To
Printers and Faxes
Help and Support
Search
Run...
Dell Solution Center
Log Off
Turn Off Computer
Folders
Go
Norton AntiVirus
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

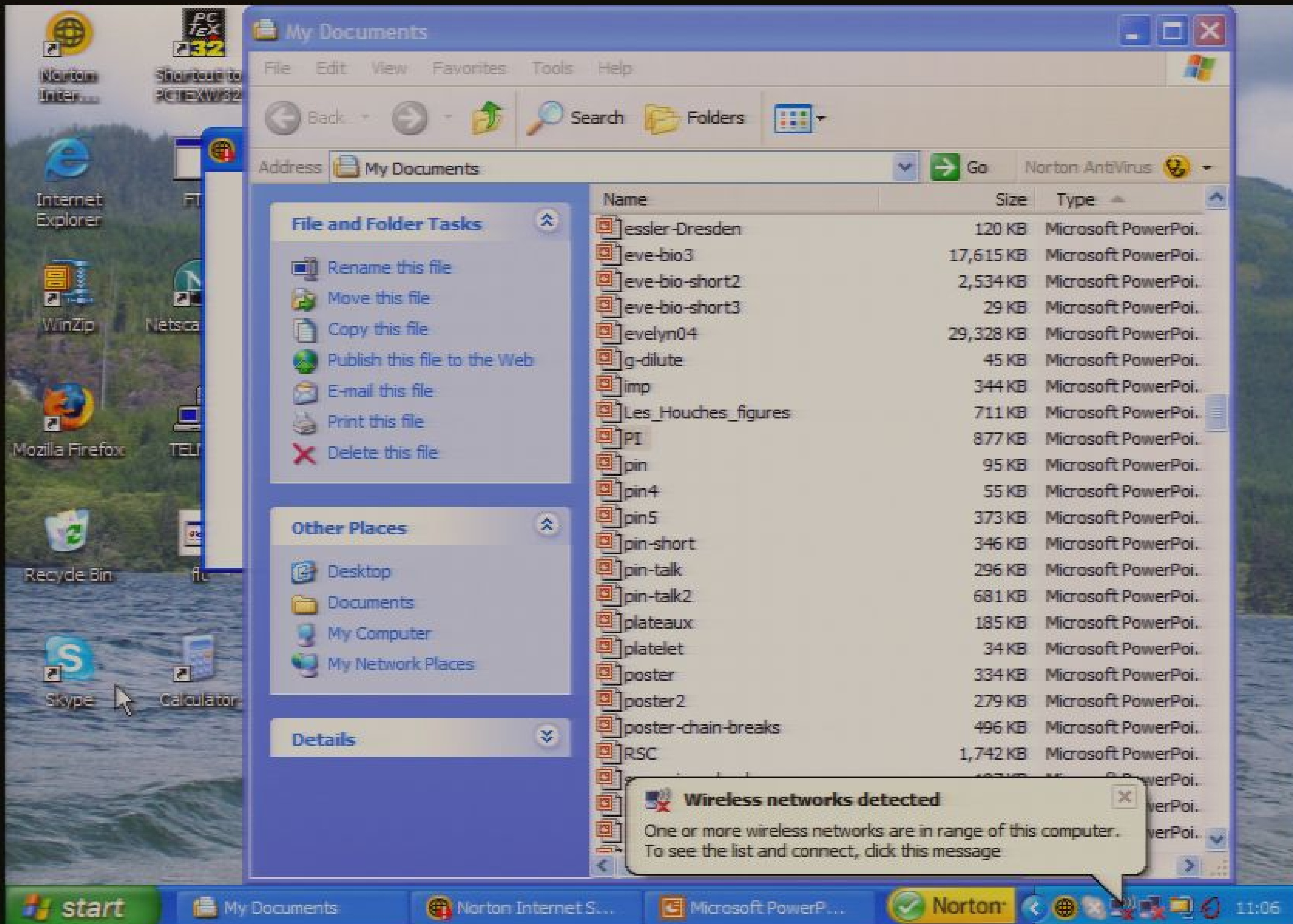


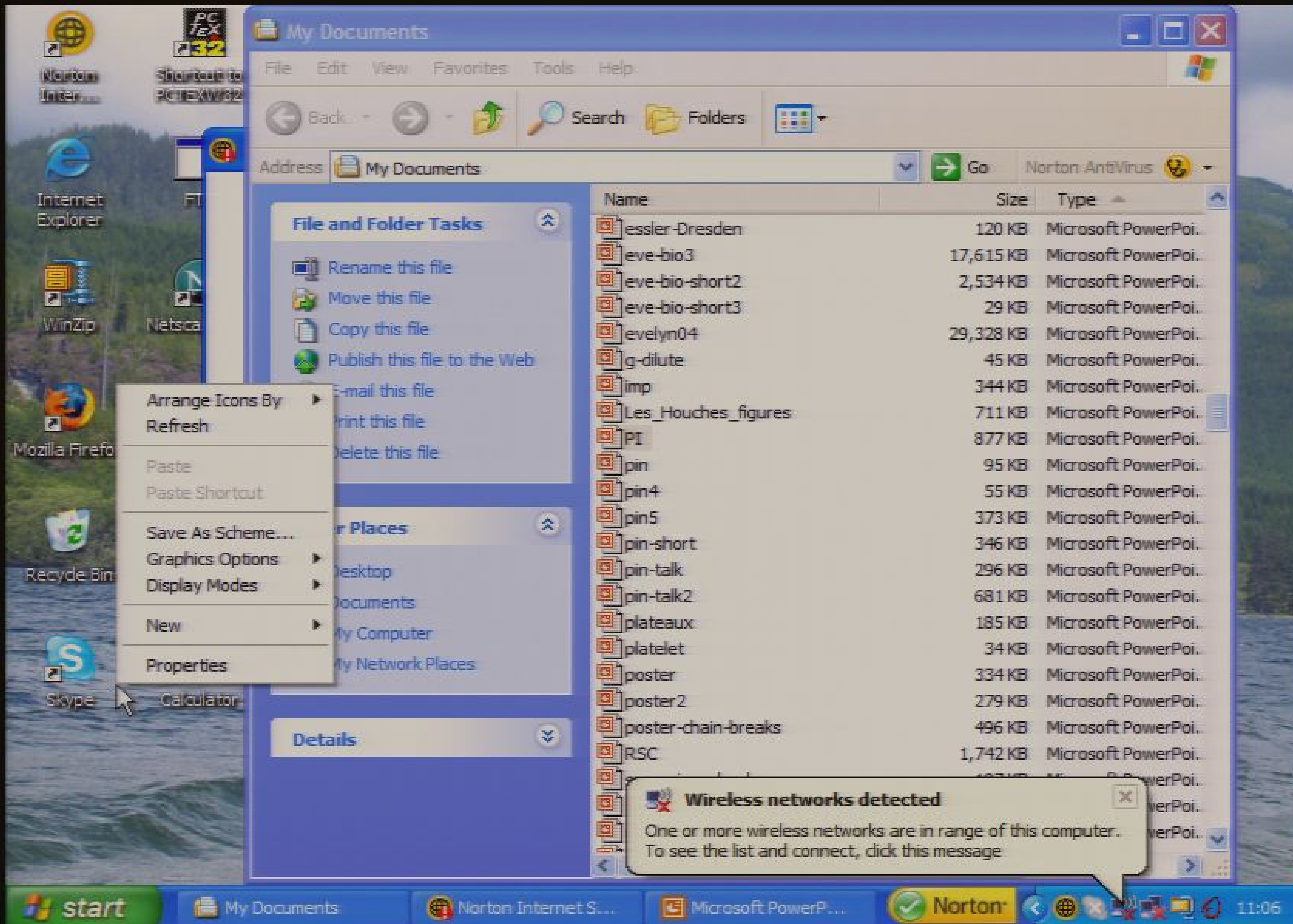
My Documents
File Edit View Favorites Tools Help
Back
Search
Folders
Address
My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
Norton Inter...
Shortcut to PCTEXW32
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

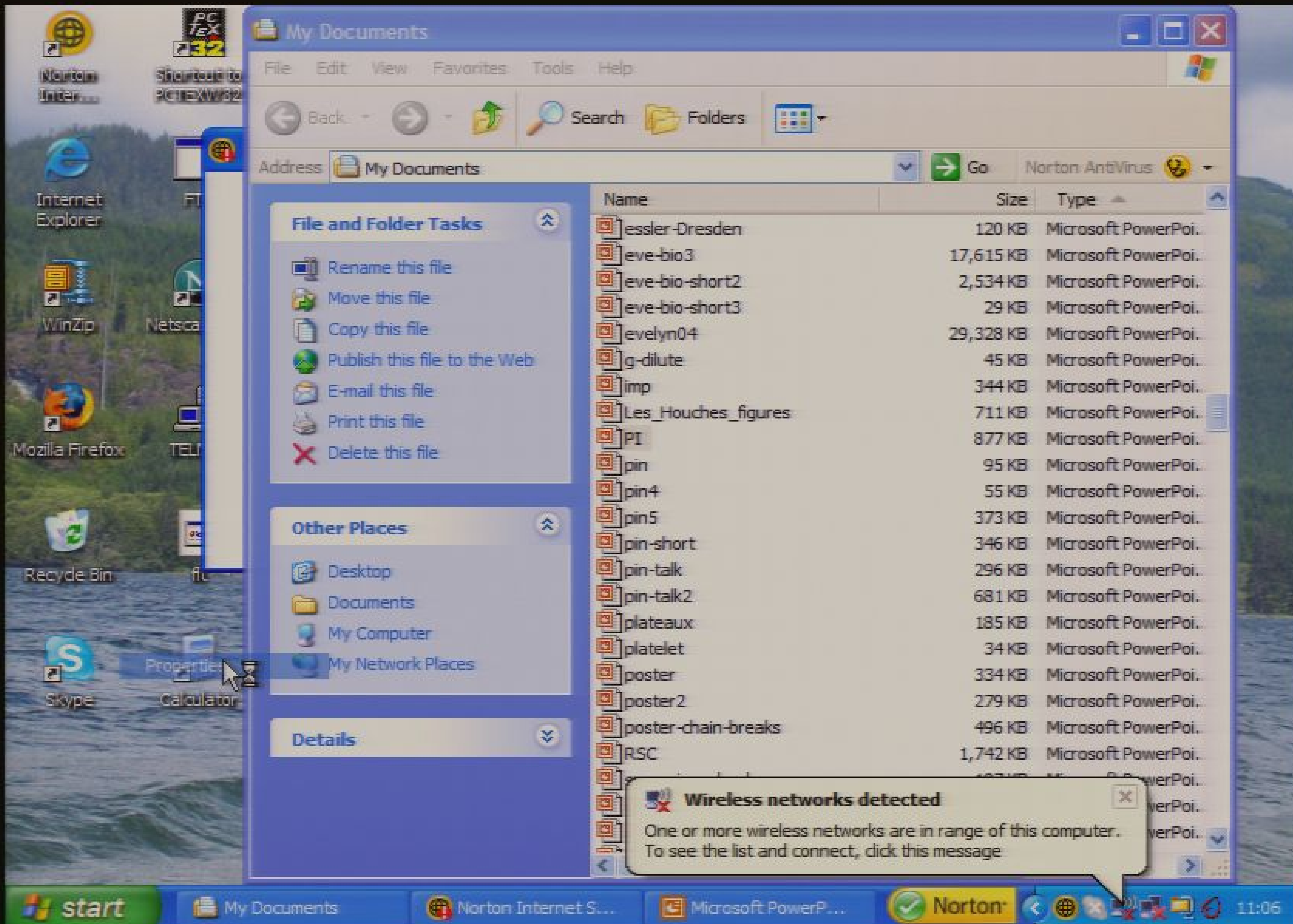

Control Panel
File Edit View Favorites Tools Help
Back
Search
Folders
Address
Control Panel
Go
Norton AntiVirus
Control Panel
Switch to Category View
See Also
Windows Update
Help and Support
Accessibility Options
Add Hardware
Add or Remov...
Administrative Tools
Automatic Updates
Date and Time
Dell Modem-on-...
Display
Folder Options
Fonts
Game Controllers
Intel(R) Extre...
Internet Options
Java
Keyboard
Mail
Mouse
Network Connections
Network Setup Wizard
Phone and Modem ...
Portable Media Devices
Power Options
Printers and Faxes
Regional and Language ...
Scanners and Cameras
Scheduled Tasks
Security Center
Sounds and Audio Devices
Speech
Symantec LiveUpdate
System
Taskbar and Start Menu
User Accounts
Windows Firewall
Wireless Network Set...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
start
2 Windows Expl...
Norton Internet S...
Microsoft PowerP...
Norton
11:06

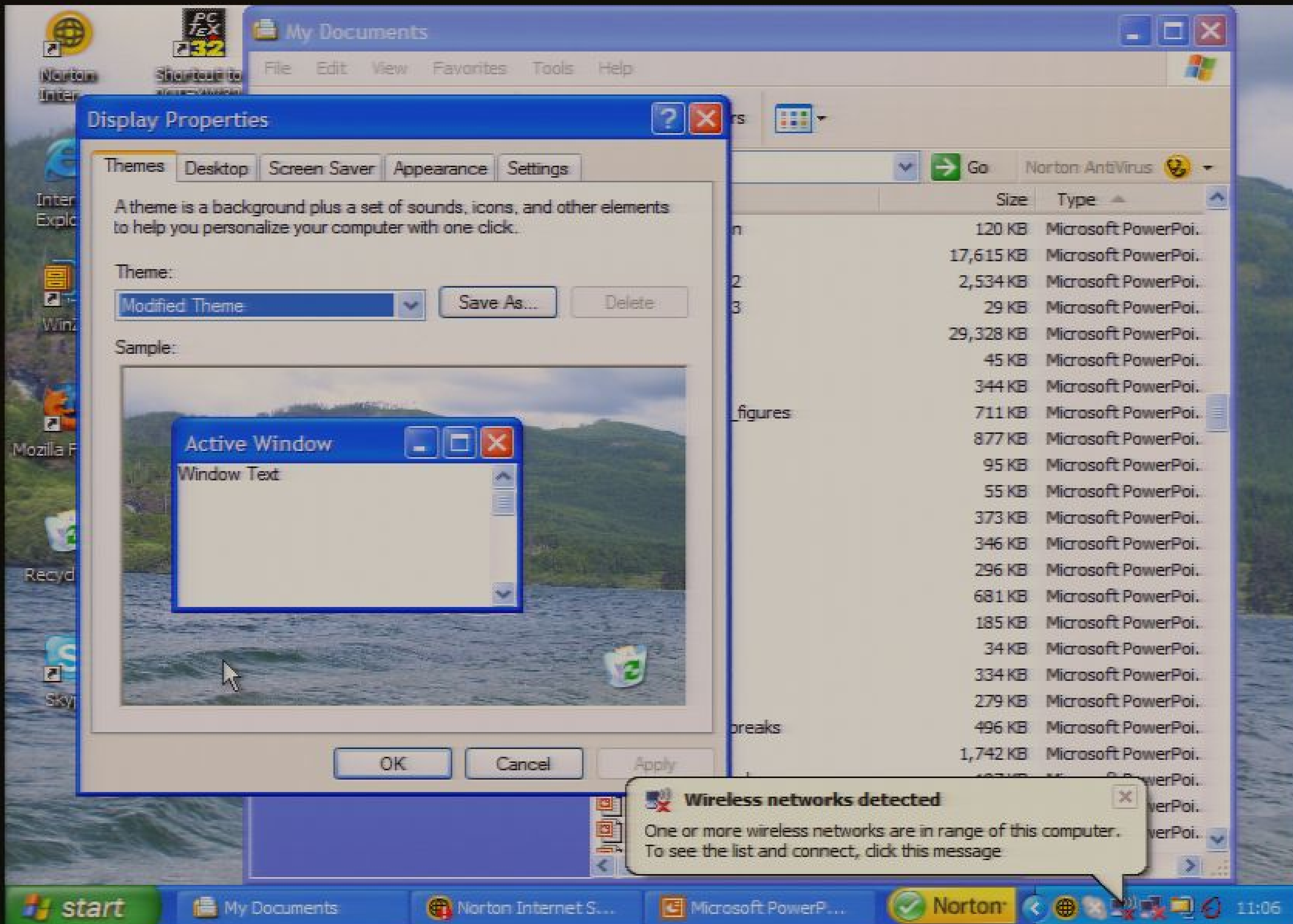


My Documents
File
Edit
View
Favorites
Tools
Help
Back
Search
Folders
Address
My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

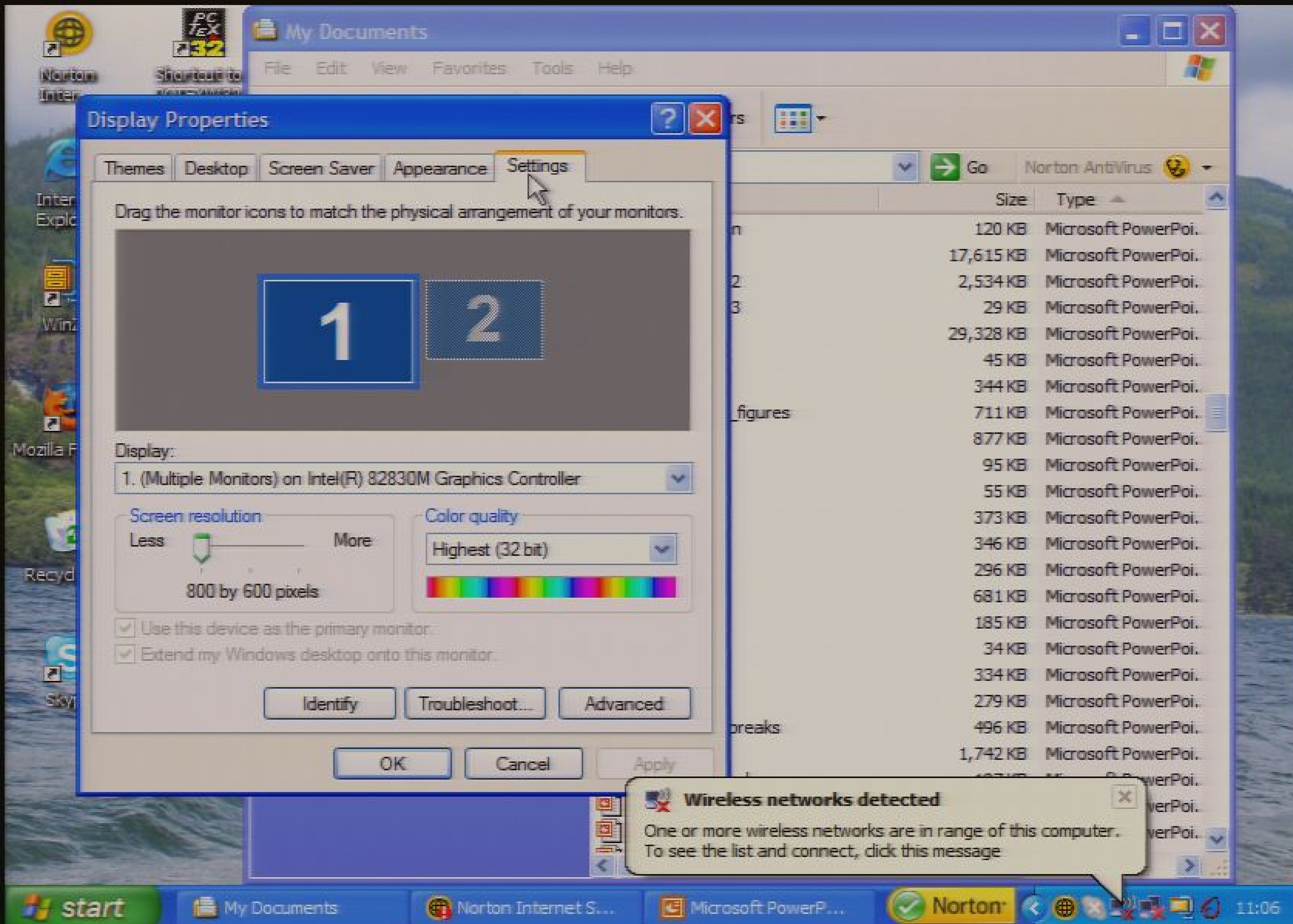

My Documents
File Edit View Favorites Tools Help
Back
Search
Folders
Address
My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name
Size
Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
Norton Inter...
Shortcut to PCTEXW32
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

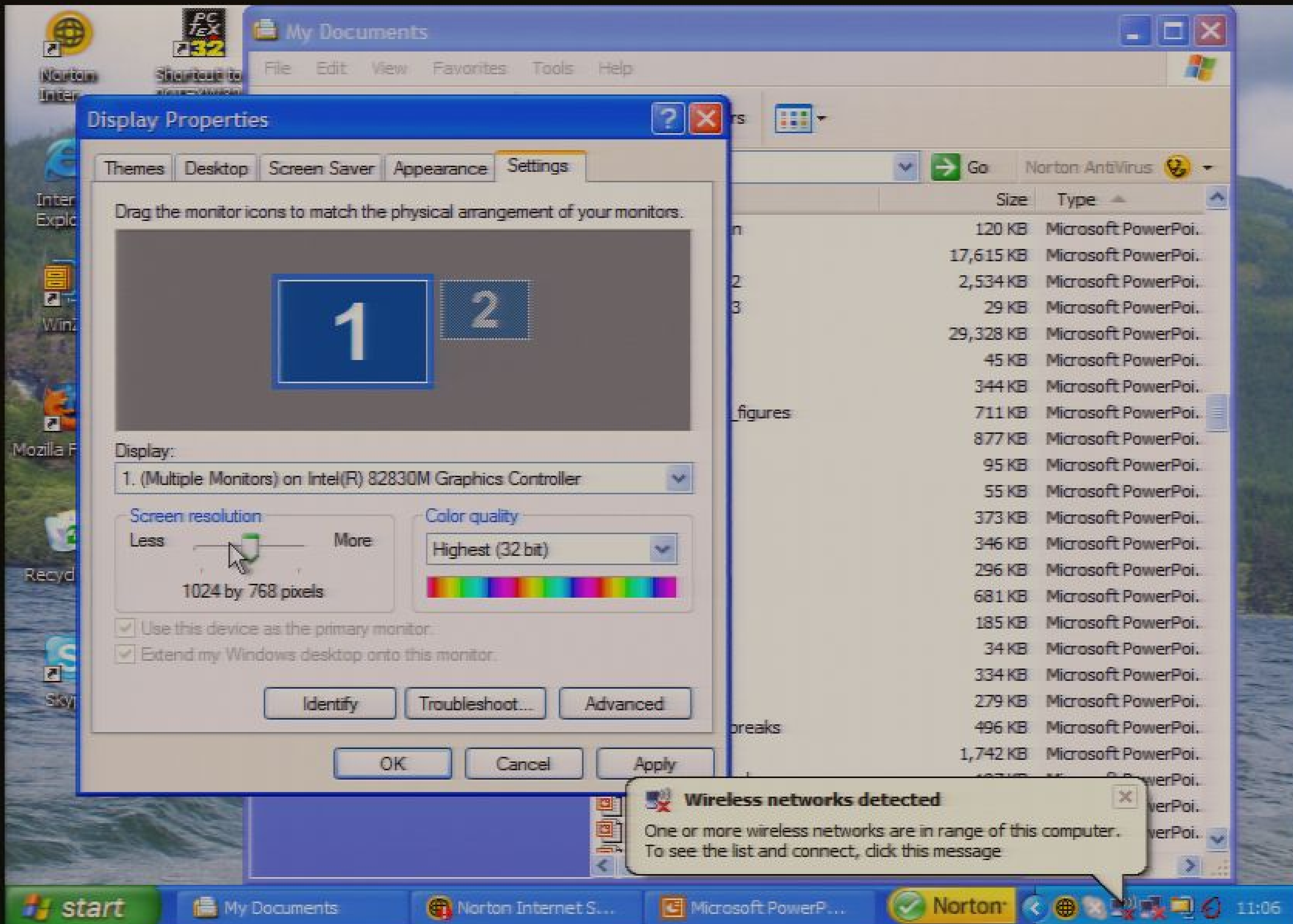

My Documents
File Edit View Favorites Tools Help
Back
Search
Folders
Address
My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Places
Desktop
Documents
My Computer
My Network Places
Details
Name Size Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Arrange Icons By
Refresh
Paste
Paste Shortcut
Save As Scheme...
Graphics Options
Display Modes
New
Properties
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
Norton Inter...
Shortcut to PCTEXW32
Internet Explorer
WinZip
Mozilla Firefo
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

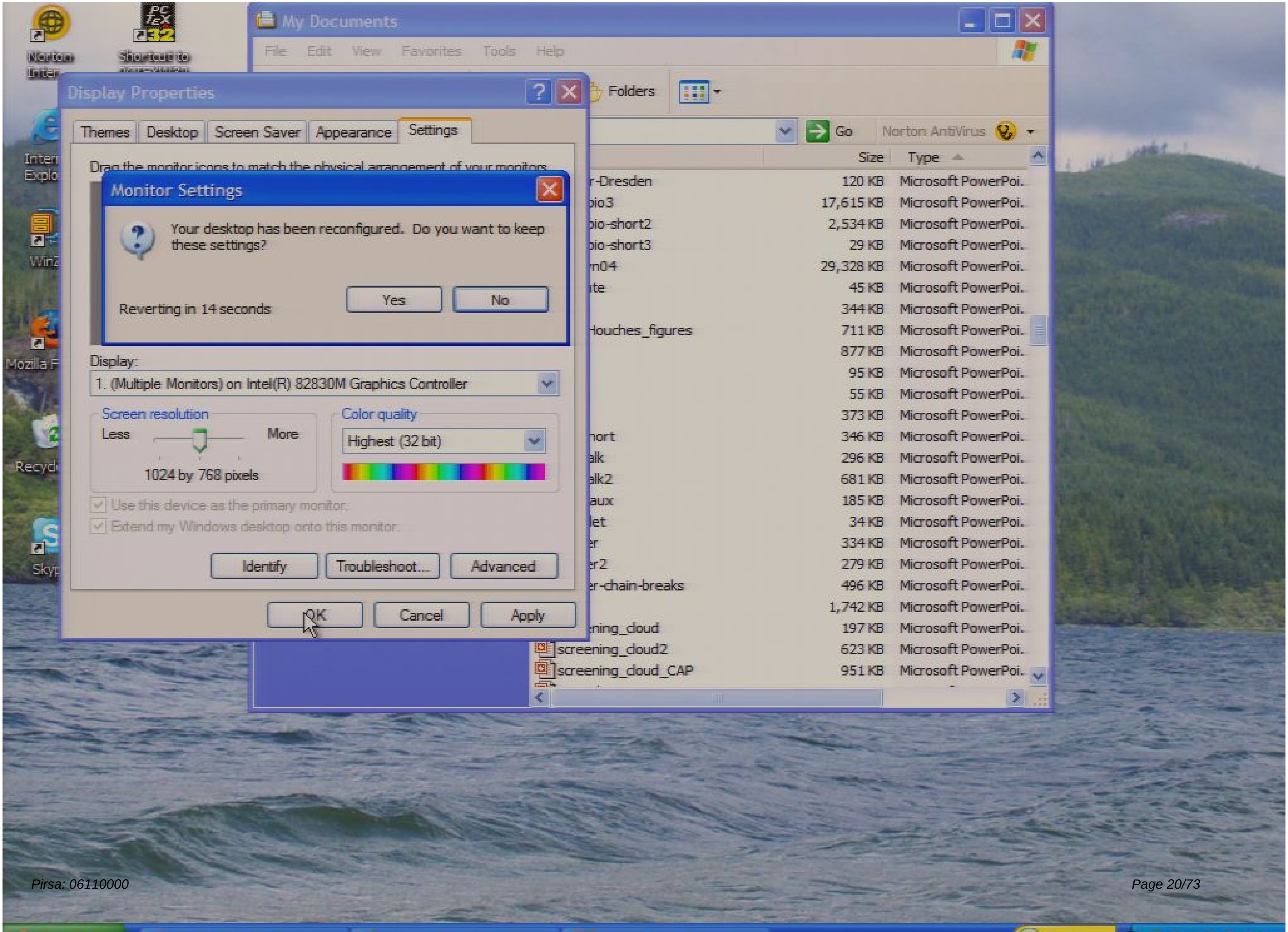

My Documents
File Edit View Favorites Tools Help
Back
Search
Folders
Address My Documents
Go
Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name Size Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
pin4 55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
Norton Inter...
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
Properties
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

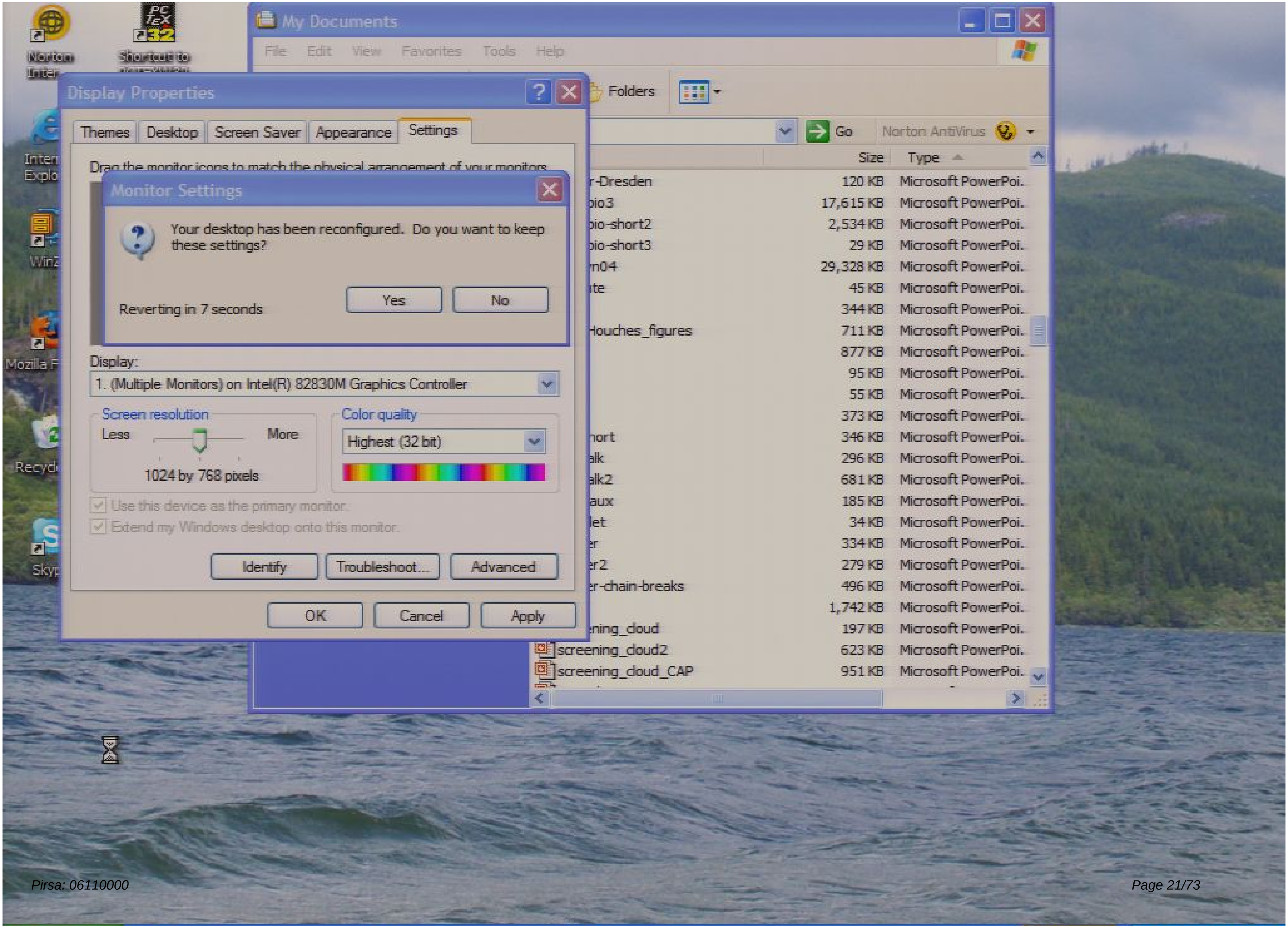


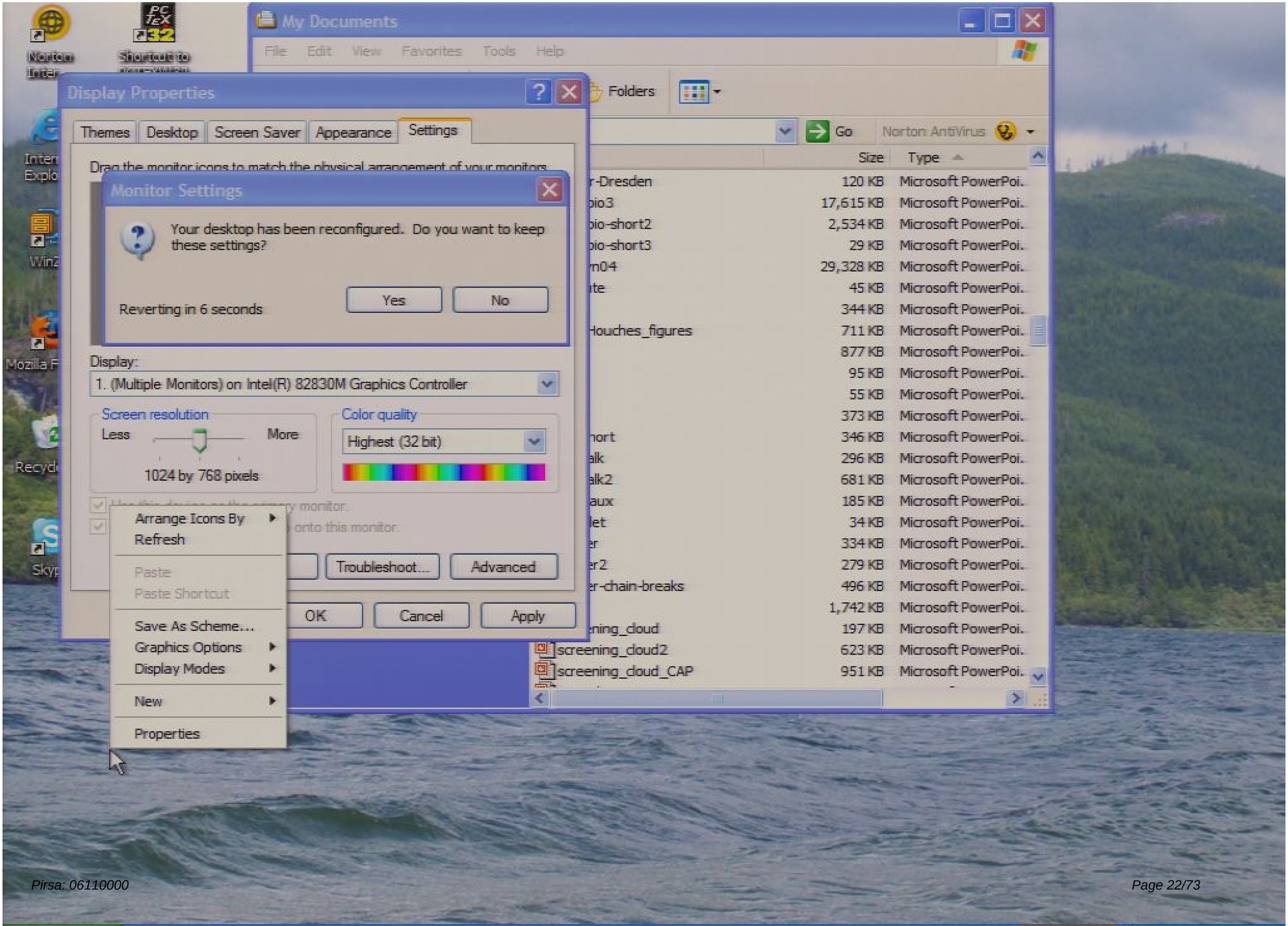
My Documents
File Edit View Favorites Tools Help
Display Properties
Themes Desktop Screen Saver Appearance Settings
A theme is a background plus a set of sounds, icons, and other elements to help you personalize your computer with one click.
Theme:
Modified Theme
Save As...
Delete
Sample:
Active Window
Window Text
OK
Cancel
Apply
Go
Norton AntiVirus
Size
Type
Wireless networks detected
One or more wireless networks are in range of this computer. To see the list and connect, click this message
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

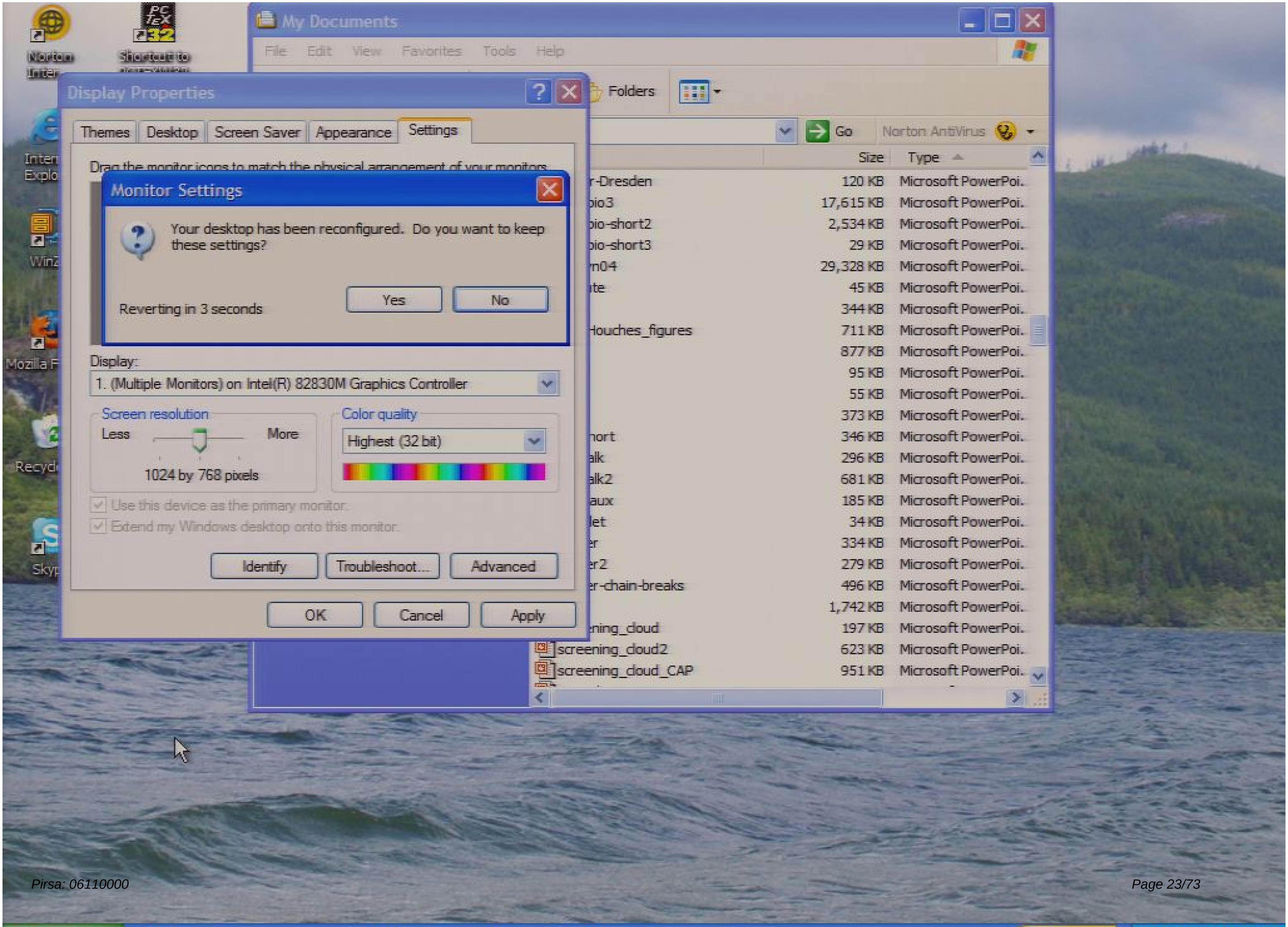

My Documents
File Edit View Favorites Tools Help
Display Properties
Themes Desktop Screen Saver Appearance Settings
Drag the monitor icons to match the physical arrangement of your monitors.
1
2
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
800 by 600 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply
Go
Norton AntiVirus
Size
Type
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

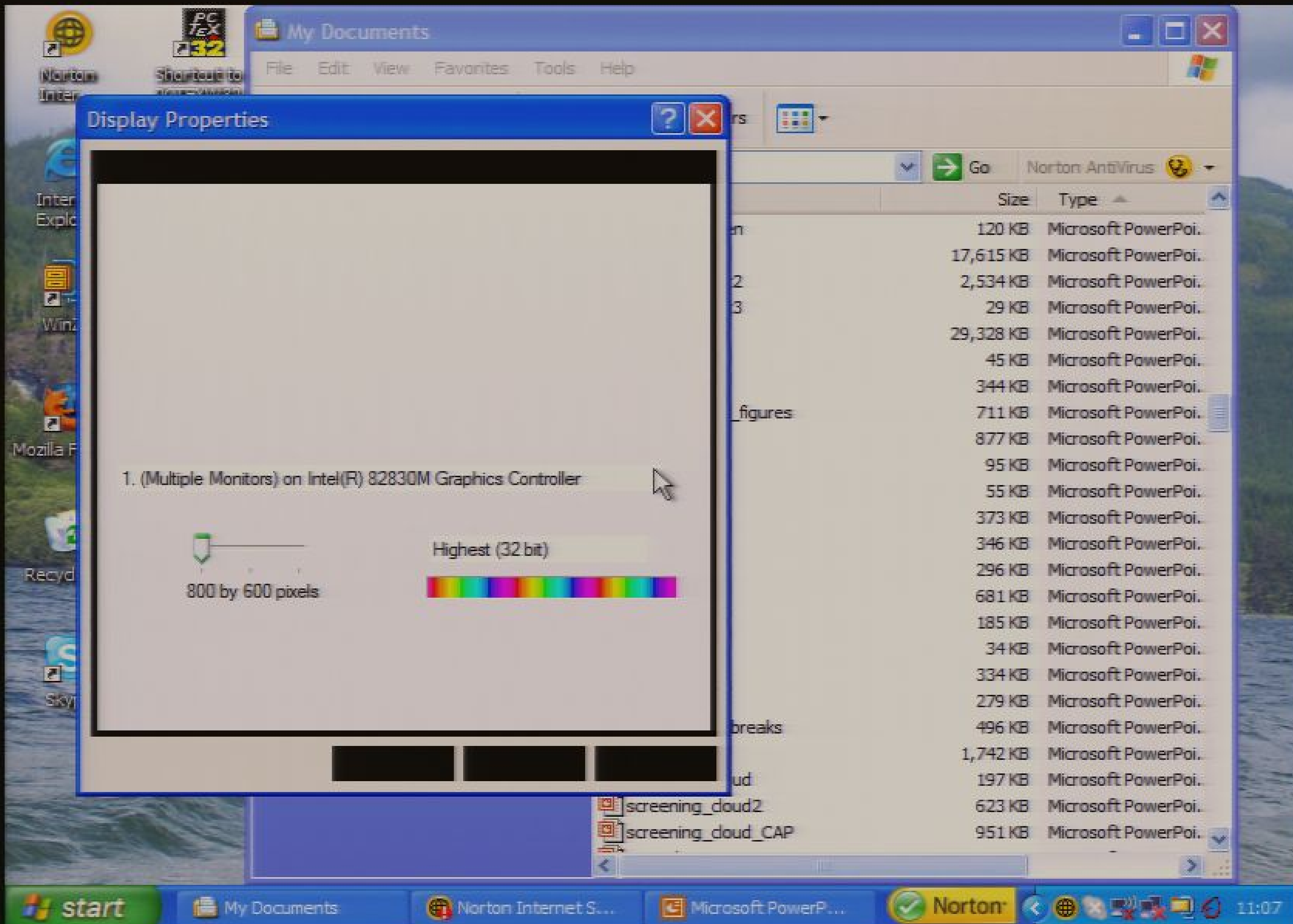

My Documents
File Edit View Favorites Tools Help
Display Properties
Themes Desktop Screen Saver Appearance Settings
Drag the monitor icons to match the physical arrangement of your monitors.
1
2
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
1024 by 768 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply
Go
Norton AntiVirus
Size
Type
Wireless networks detected
One or more wireless networks are in range of this computer.
To see the list and connect, click this message
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:06

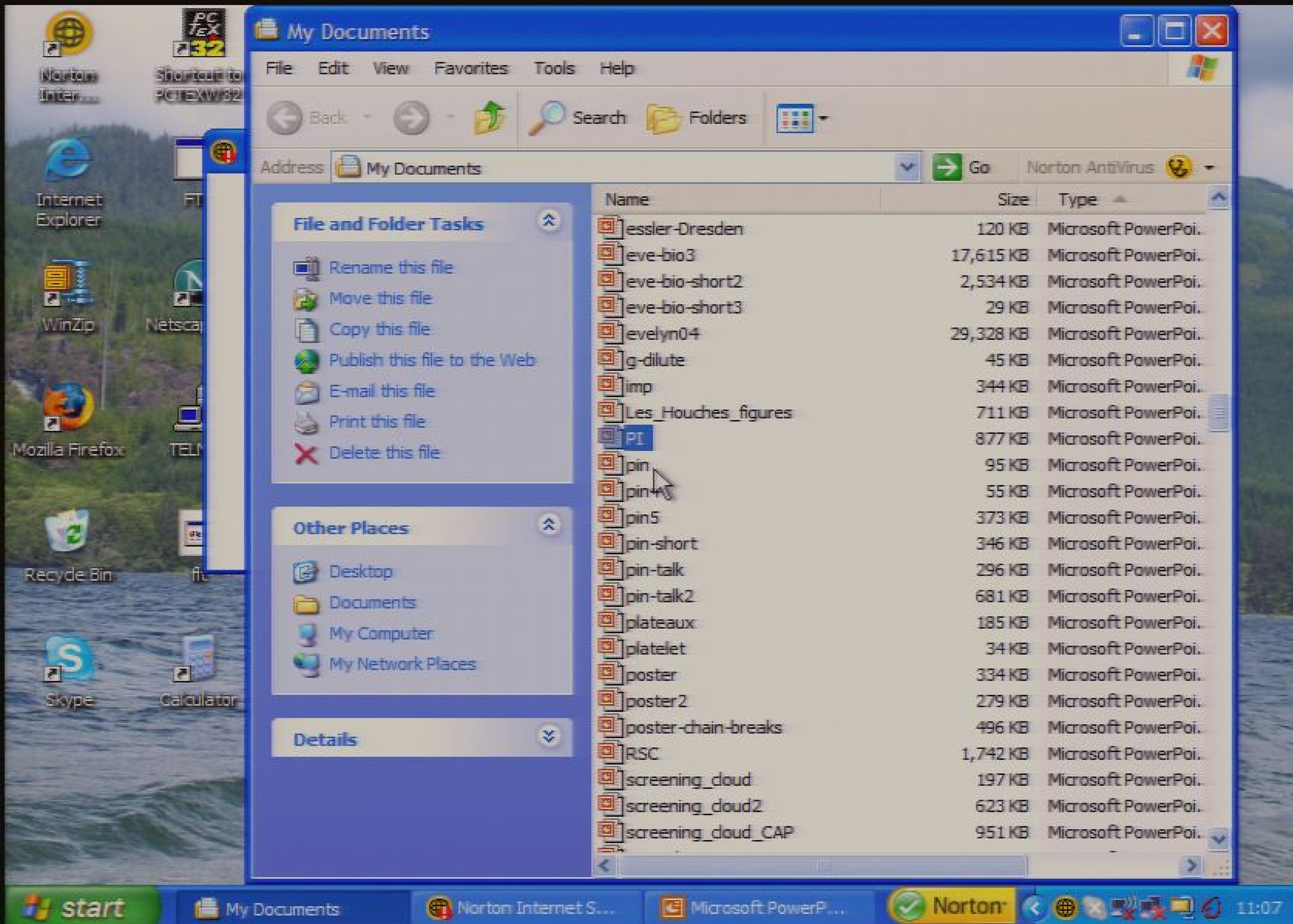

My Documents
File
Edit
View
Favorites
Tools
Help
Folders
Go
Norton AntiVirus
Size
Type
Display Properties
Themes
Desktop
Screen Saver
Appearance
Settings
Monitor Settings
Your desktop has been reconfigured. Do you want to keep these settings?
Reverting in 14 seconds
Yes
No
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
1024 by 768 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply
screening_cloud2
screening_cloud_CAP

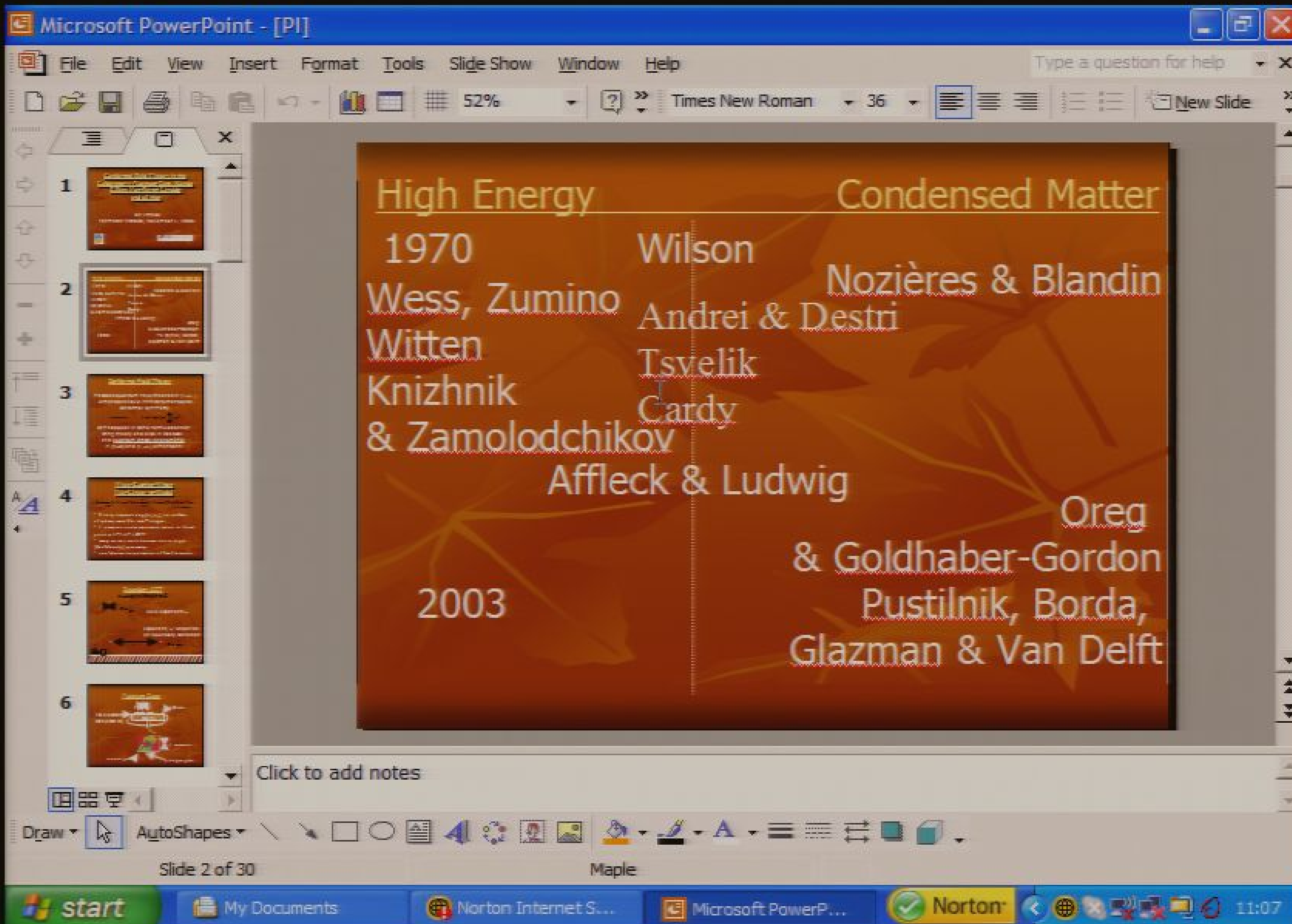

My Documents
File
Edit
View
Favorites
Tools
Help
Folders
Go
Norton AntiVirus
Size
Type
Display Properties
Themes
Desktop
Screen Saver
Appearance
Settings
Monitor Settings
Your desktop has been reconfigured. Do you want to keep these settings?
Reverting in 7 seconds
Yes
No
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
1024 by 768 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply
screening_cloud2
screening_cloud_CAP

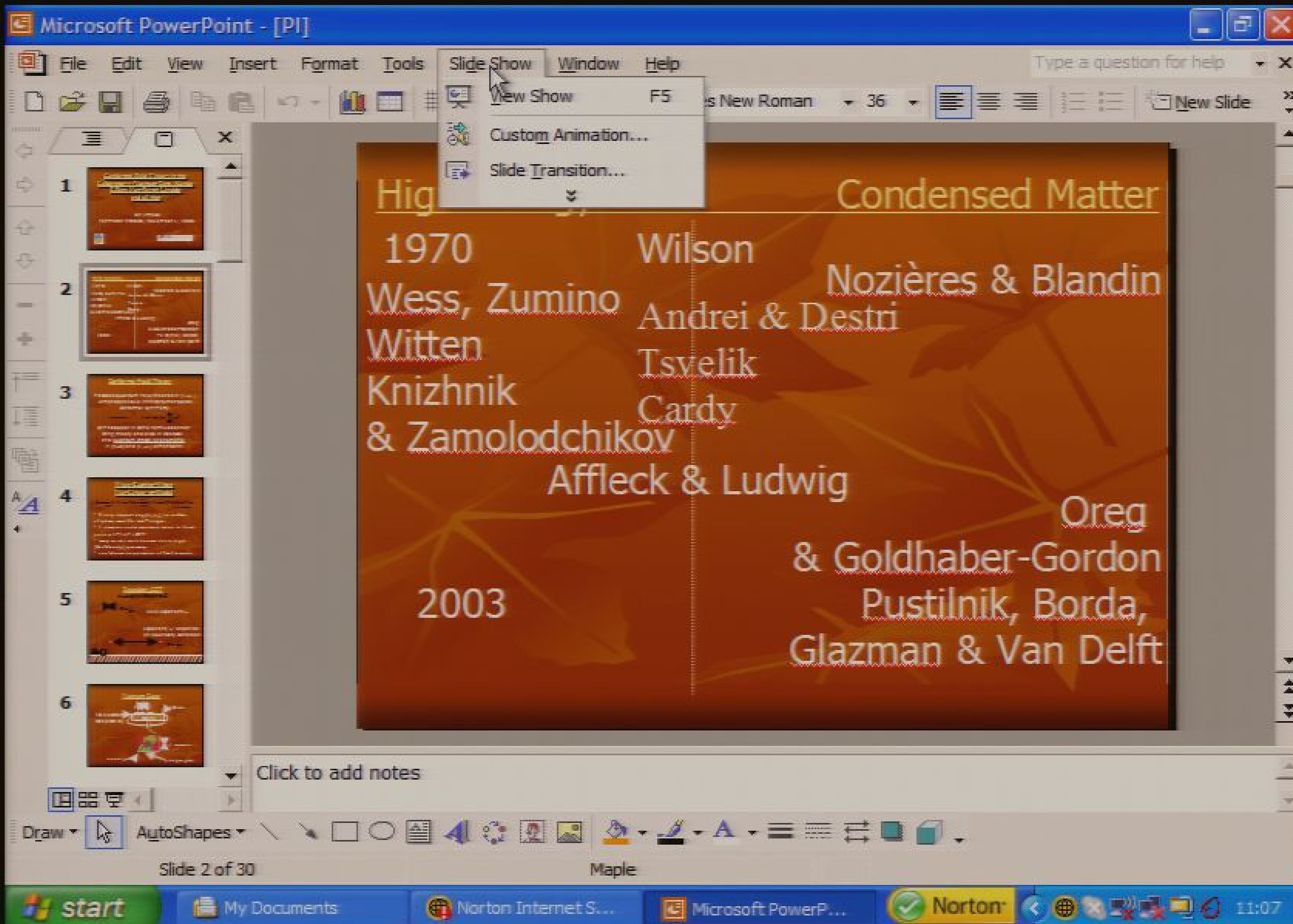

My Documents
File
Edit
View
Favorites
Tools
Help
Folders
Go
Norton AntiVirus
Size
Type
Display Properties
Themes
Desktop
Screen Saver
Appearance
Settings
Monitor Settings
Your desktop has been reconfigured. Do you want to keep these settings?
Reverting in 6 seconds
Yes
No
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
1024 by 768 pixels
Color quality
Highest (32 bit)
Troubleshoot...
Advanced
OK
Cancel
Apply
Arrange Icons By
Refresh
Paste
Paste Shortcut
Save As Scheme...
Graphics Options
Display Modes
New
Properties
screening_cloud2
screening_cloud_CAP

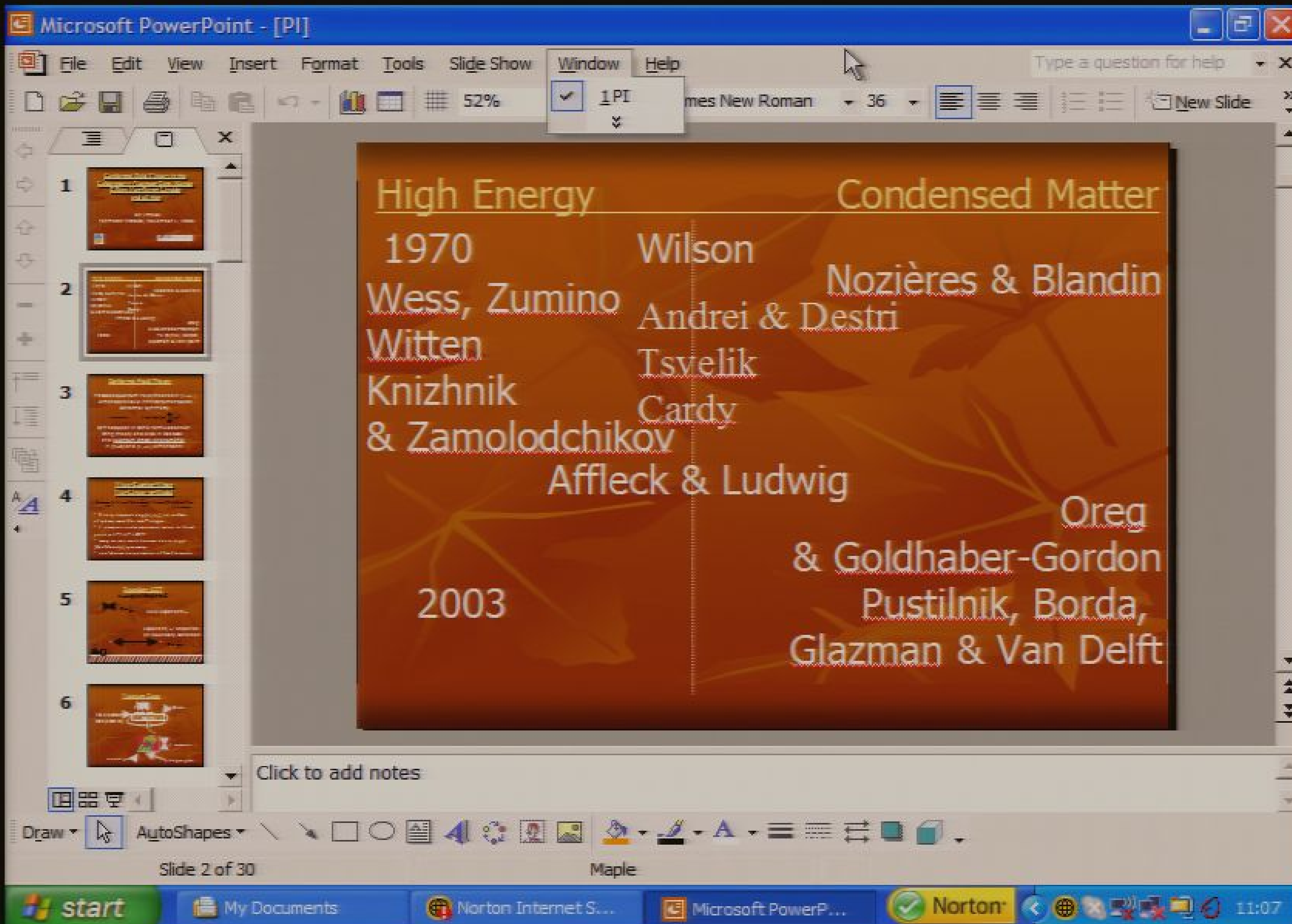

My Documents
File Edit View Favorites Tools Help
Folders
Go
Norton AntiVirus
Size Type
Display Properties
Themes Desktop Screen Saver Appearance Settings
Monitor Settings
Your desktop has been reconfigured. Do you want to keep these settings?
Reverting in 3 seconds
Yes
No
Display:
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
Screen resolution
Less
More
1024 by 768 pixels
Color quality
Highest (32 bit)
Use this device as the primary monitor.
Extend my Windows desktop onto this monitor.
Identify
Troubleshoot...
Advanced
OK
Cancel
Apply
120 KB Microsoft PowerPoi..
17,615 KB Microsoft PowerPoi..
2,534 KB Microsoft PowerPoi..
29 KB Microsoft PowerPoi..
29,328 KB Microsoft PowerPoi..
45 KB Microsoft PowerPoi..
344 KB Microsoft PowerPoi..
711 KB Microsoft PowerPoi..
877 KB Microsoft PowerPoi..
95 KB Microsoft PowerPoi..
55 KB Microsoft PowerPoi..
373 KB Microsoft PowerPoi..
346 KB Microsoft PowerPoi..
296 KB Microsoft PowerPoi..
681 KB Microsoft PowerPoi..
185 KB Microsoft PowerPoi..
34 KB Microsoft PowerPoi..
334 KB Microsoft PowerPoi..
279 KB Microsoft PowerPoi..
496 KB Microsoft PowerPoi..
1,742 KB Microsoft PowerPoi..
197 KB Microsoft PowerPoi..
screening_cloud2 623 KB Microsoft PowerPoi..
screening_cloud_CAP 951 KB Microsoft PowerPoi..

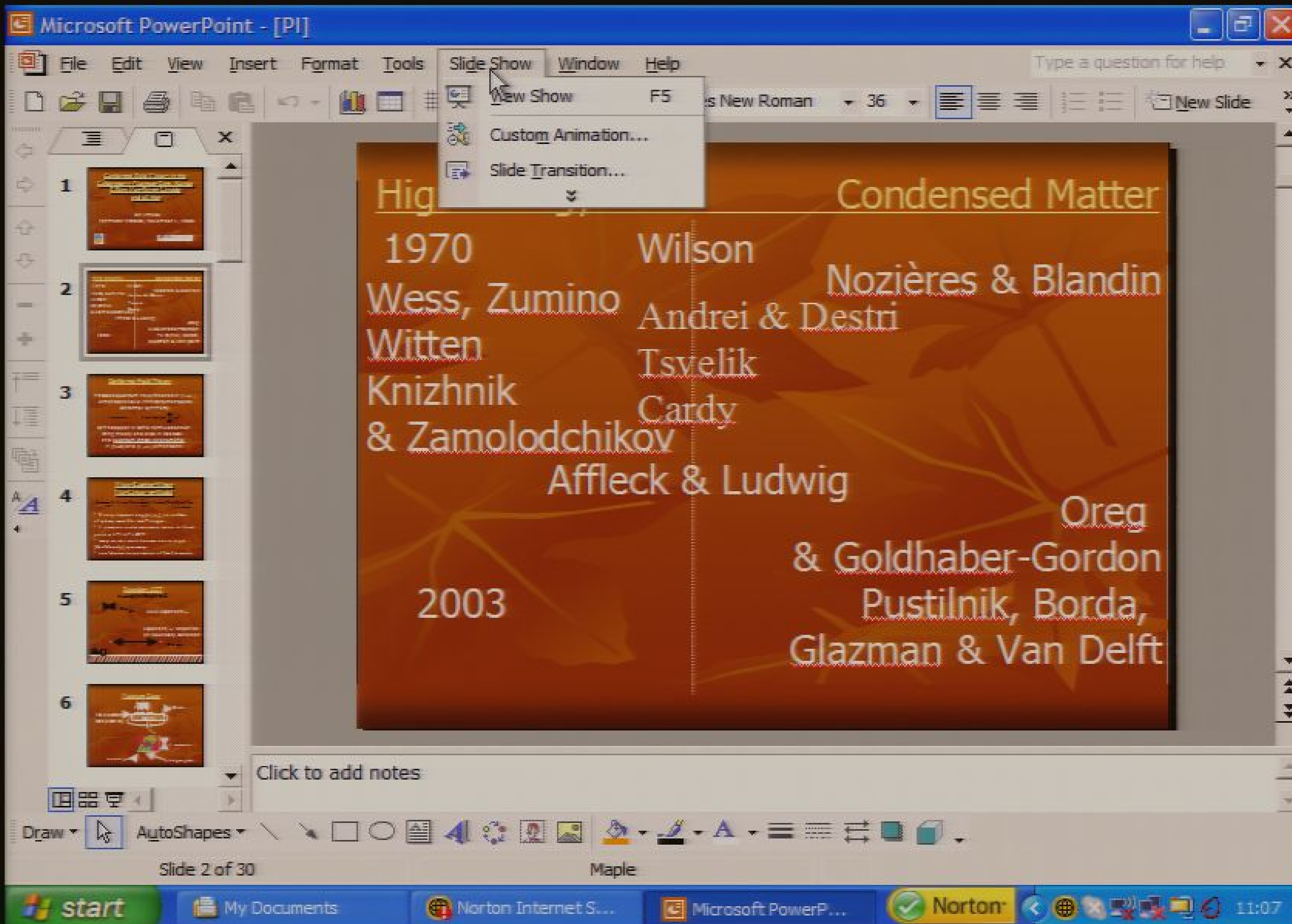

Norton Inter
My Documents
File Edit View Favorites Tools Help
Display Properties
1. (Multiple Monitors) on Intel(R) 82830M Graphics Controller
800 by 600 pixels
Highest (32 bit)
Go
Norton AntiVirus
Size
Type
120 KB Microsoft PowerPoi.
17,615 KB Microsoft PowerPoi.
2,534 KB Microsoft PowerPoi.
29 KB Microsoft PowerPoi.
29,328 KB Microsoft PowerPoi.
45 KB Microsoft PowerPoi.
344 KB Microsoft PowerPoi.
_figures 711 KB Microsoft PowerPoi.
877 KB Microsoft PowerPoi.
95 KB Microsoft PowerPoi.
55 KB Microsoft PowerPoi.
373 KB Microsoft PowerPoi.
346 KB Microsoft PowerPoi.
296 KB Microsoft PowerPoi.
681 KB Microsoft PowerPoi.
185 KB Microsoft PowerPoi.
34 KB Microsoft PowerPoi.
334 KB Microsoft PowerPoi.
279 KB Microsoft PowerPoi.
breaks 496 KB Microsoft PowerPoi.
1,742 KB Microsoft PowerPoi.
197 KB Microsoft PowerPoi.
screening_cloud2 623 KB Microsoft PowerPoi.
screening_cloud_CAP 951 KB Microsoft PowerPoi.
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:07


My Documents
File Edit View Favorites Tools Help
Back Search Folders
Address My Documents Go Norton AntiVirus
File and Folder Tasks
Rename this file
Move this file
Copy this file
Publish this file to the Web
E-mail this file
Print this file
Delete this file
Other Places
Desktop
Documents
My Computer
My Network Places
Details
Name Size Type
essler-Dresden 120 KB Microsoft PowerPoi...
eve-bio3 17,615 KB Microsoft PowerPoi...
eve-bio-short2 2,534 KB Microsoft PowerPoi...
eve-bio-short3 29 KB Microsoft PowerPoi...
evelyn04 29,328 KB Microsoft PowerPoi...
g-dilute 45 KB Microsoft PowerPoi...
imp 344 KB Microsoft PowerPoi...
Les_Houches_figures 711 KB Microsoft PowerPoi...
PI 877 KB Microsoft PowerPoi...
pin 95 KB Microsoft PowerPoi...
55 KB Microsoft PowerPoi...
pin5 373 KB Microsoft PowerPoi...
pin-short 346 KB Microsoft PowerPoi...
pin-talk 296 KB Microsoft PowerPoi...
pin-talk2 681 KB Microsoft PowerPoi...
plateaux 185 KB Microsoft PowerPoi...
platelet 34 KB Microsoft PowerPoi...
poster 334 KB Microsoft PowerPoi...
poster2 279 KB Microsoft PowerPoi...
poster-chain-breaks 496 KB Microsoft PowerPoi...
RSC 1,742 KB Microsoft PowerPoi...
screening_cloud 197 KB Microsoft PowerPoi...
screening_cloud2 623 KB Microsoft PowerPoi...
screening_cloud_CAP 951 KB Microsoft PowerPoi...
Internet Explorer
WinZip
Mozilla Firefox
Recycle Bin
Skype
Calculator
start
My Documents
Norton Internet S...
Microsoft PowerP...
Norton
11:07


Microsoft PowerPoint - [PI]
High Energy
Condensed Matter
1970
Wilson
Nozières & Blandin
Wess, Zumino
Andrei & Destri
Witten
Tsvelik
Knizhnik
Cardy
& Zamolodchikov
Affleck & Ludwig
Oreg
& Goldhaber-Gordon
2003
Pustilnik, Borda,
Glazman & Van Delft
Click to add notes
Slide 2 of 30
Maple


Microsoft PowerPoint - [PI]
Condensed Matter
1970
Wilson
Nozières & Blandin
Wess, Zumino
Andrei & Destri
Witten
Tsvelik
Knizhnik
Cardy
& Zamolodchikov
Affleck & Ludwig
Oreg
& Goldhaber-Gordon
2003
Pustilnik, Borda,
Glazman & Van Delft
Click to add notes
Slide 2 of 30
Maple


Microsoft PowerPoint - [PI]
High Energy
Condensed Matter
1970
Wilson
Nozières & Blandin
Wess, Zumino
Andrei & Destri
Witten
Tsvelik
Knizhnik
Cardy
& Zamolodchikov
Affleck & Ludwig
Oreg
& Goldhaber-Gordon
2003
Pustilnik, Borda,
Glazman & Van Delft
Click to add notes
Slide 2 of 30
Maple


Microsoft PowerPoint - [PI]
File Edit View Insert Format Tools Slide Show Window Help
View Show F5
Custom Animation...
Slide Transition...
Condensed Matter
1970
Wilson
Nozières & Blandin
Wess, Zumino
Andrei & Destri
Witten
Tsvelik
Knizhnik
Cardy
& Zamolodchikov
Affleck & Ludwig
Oreg
& Goldhaber-Gordon
2003
Pustilnik, Borda,
Glazman & Van Delft
Click to add notes
Slide 2 of 30
Maple

Conformal Field Theory in the Laboratory: Quantum Dots, Kondo Effect, Non-Fermi Liquids and all that

Ian Affleck
Perimeter Institute, November 1, 2006

CIAR The Canadian Institute for Advanced Research

Conformal Field Theory in the Laboratory: Quantum Dots, Kondo Effect, Non-Fermi Liquids and all that

Ian Affleck

Perimeter Institute, November 1, 2006

UBC

CIAR The Canadian Institute for Advanced Research

High Energy | Condensed Matte

1970

Wilson

Nozières & Bland

Wess, Zumino

Andrei & Destri

Witten

Tsvelik

Knizhnik & Zamolodchikov

Cardy

Affleck & Ludwig

Oreg

& Goldhaber-Gordo

2003

Pustilnik, Borda

Glazman & Van Del

Conformal Field Theory

massless quantum field theories in (1+1) dimensions have infinite-dimensional conformal symmetry

$$z \equiv \tau + ix \qquad z \to w(z) = \sum_{n=0}^{\infty} a_n z^n$$

CFT's appear in some formulations of string theory and also in classical and quantum critical phenomena in (2+0) and (1+1) dimensions

Wess-Zumino-Witten Non-Linear σ-Model

$$S_{WZW}^{k} = \frac{1}{8\pi\lambda}\int d^2x \,\mathrm{tr}\, \partial_\mu g^{+} \partial_\mu g + \frac{k}{12\pi}\int d^3x\, \varepsilon_{\mu\nu\rho} \mathrm{tr}\, g^{+}\partial_\mu g g^{+}\partial_\nu g g^{+}\partial_\rho g$$

$$g \in SU(2)$$

- S only depends on $g(x_1,x_2)$, on surface of sphere, mod $2\pi i \Rightarrow k$=integer
- λ increases under renormalization to fixed point at λ=1/k – a CFT
- many exact results known due to high (Kac-Moody) symmetry
- non-abelian bosonization of free fermions

Boundary CFT

$$z \to w(z) \text{ with } w(\tau) \in R$$

r

$$G \propto \frac{1}{r^{\eta}}$$

bulk exponent η

exponent, η′ depends
on boundary conditio

r

$$G \propto \frac{1}{r^{\eta'}}$$

x

τ

Quantum Dots

- when dot is small and tunneling on/off dot is weak, dot contains a well-defined number of electrons, due to charging energy
- this number is controlled in single steps by plunger gate
- when number is odd, dot has spin-1/2
- at low energies, spin of quantum dot is its only active degree of freedom
- interaction of this spin with conduction electrons in 2DEG lead to interesting physics

Kondo Effect

$$S = \int d^2x d\tau \left[\psi^+ \left(\partial_\tau - \frac{1}{2m} \nabla^2 \right) \psi + J\delta^2(\vec{x}) \psi^+ \frac{\vec{\sigma}}{2} \psi \cdot \vec{S} \right]$$

- fermions (with spin) & S=1/2 impurity spin
- although interactions only occur at origin, this model exhibits non-trivial many body effects!
- Kondo coupling, J, grows large under renormalization at low energies (for J>0)
- first (1965) example of asymptotic freedom

effective coupling becomes large at energy scale T_K: $T_K = De^{-(1/J\rho)}$

where ρ is density of states, D is band width (ultra-violet cut-off)

- T_K is like Λ_{QCD} in high energy physics
- strong coupling physics is very simple:

-one electron forms a singlet with impurity spin (remember it has S=1/2)

-other electrons must “stay away” or go into orthogonal wave-functions due to Pauli principle

•screening electron is from s-wave channel

•strong coupling fixed point described by a $\pi/2$ s-wave phase shift, corresponding to an infinite short-range repulsion at origin

•this is clear if we introduce a lattice: electrons live on lattice sites only and hop between sites with amplitude t

•if J>>t we solve single site problem first

•1 electron sits at the origin and forms single

•other electrons avoid origin, otherwise free for small T_K, we may linearize the dispersion relation: $\vec{k}^2/2m - \varepsilon_F \approx v_F(k - k_F)$

and use a quantum field theory which Is Lorentz invariant when J=0:

$$S = \int d\tau \int_0^\infty dx \left[\psi_L^{\,+}(\partial_\tau - i\partial_x)\psi_L + \psi_R^{\,+}(\partial_\tau + i\partial_x)\psi_R\right]$$

$$+J\int d\tau\, \psi_L^+(\tau,0)\frac{\vec{\sigma}}{2}\psi_L(\tau,0)\cdot\vec{S}, \qquad \psi_L(\tau,0) = -\psi_R(\tau,0)$$

strong coupling fixed point corresponds to:

$$\psi_L(\tau,0) = +\psi_R(\tau,0)$$

•this is a simple example of how interactions with a quantum impurity renormalize to a fixed point corresponding to a conformally invariant boundary condition

• we can use non-abelian bosonization to replace free fermions (with spin) by a

•(k=1) WZW model for spin degrees of freedom and a free boson model for charge degrees of freedom

for small T_K, we may linearize the dispersion relation: $\vec{k}^2/2m-\varepsilon_F \approx v_F(k-k_F)$

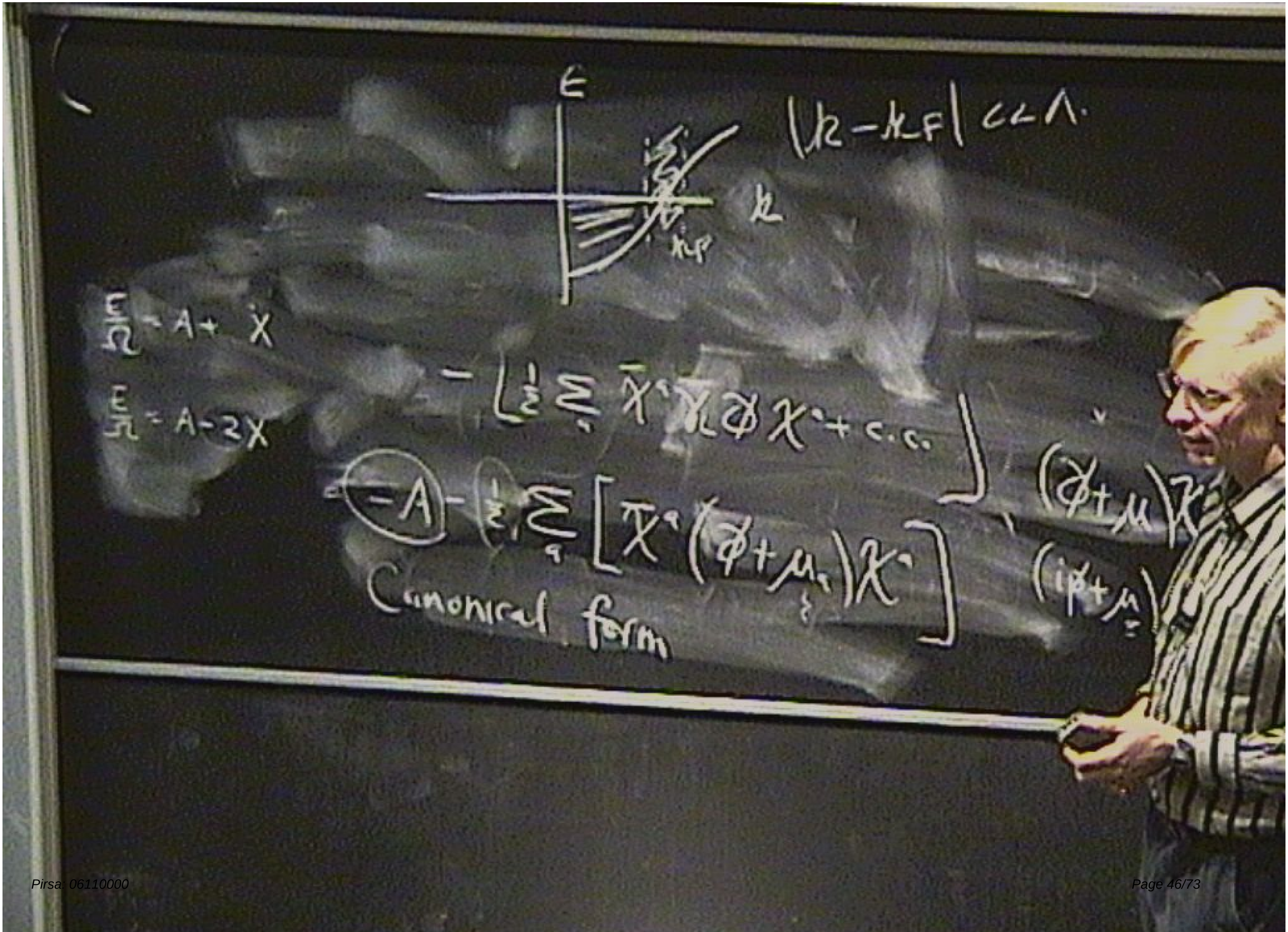
and use a quantum field theory which Is Lorentz invariant when J=0:

$$S=\int d\tau \int_0^\infty dx \left[\psi_L^{\ +}(\partial_\tau - i\partial_x)\psi_L + \psi_R^{\ +}(\partial_\tau + i\partial_x)\psi_R\right]$$

$$+J\int d\tau\, \psi_L^+(\tau,0)\frac{\vec{\sigma}}{2}\psi_L(\tau,0)\cdot\vec{S}, \qquad \psi_L(\tau,0)=-\psi_R(\tau,0)$$

strong coupling fixed point corresponds to:

$$\psi_L(\tau,0)=+\psi_R(\tau,0)$$


E
|k − k_F| << Λ
k
k_F
E/Ω = A + X
E/Ω = A − 2X
+ c.c.
Canonical form

for small T_K, we may linearize the dispersion relation: $\vec{k}^2/2m - \varepsilon_F \approx \mathrm{v_F}(k - k_F)$ and use a quantum field theory which Is Lorentz invariant when J=0:

$$S = \int d\tau \int_0^\infty dx \left[\psi_L^{\ +}(\partial_\tau - i\partial_x)\psi_L + \psi_R^{\ +}(\partial_\tau + i\partial_x)\psi_R\right]$$

$$+J\int d\tau\, \psi_L^+(\tau,0)\frac{\vec{\sigma}}{2}\psi_L(\tau,0)\cdot\vec{S}, \qquad \psi_L(\tau,0) = -\psi_R(\tau,0)$$

strong coupling fixed point corresponds to:

$$\psi_L(\tau,0) = +\psi_R(\tau,0)$$

•this is a simple example of how interactions with a quantum impurity renormalize to a fixed point corresponding to a conformally invariant boundary condition

• we can use non-abelian bosonization to replace free fermions (with spin) by a

•(k=1) WZW model for spin degrees of freedom and a free boson model for charge degrees of freedom

•this is a simple example of how interactions with a quantum impurity renormalize to a fixed point corresponding to a conformally invariant boundary condition

• we can use non-abelian bosonization to replace free fermions (with spin) by a

•(k=1) WZW model for spin degrees of freedom and a free boson model for charge degrees of freedom

$$S = S_0(\varphi) + S_{WZW}^{k=1}(g) + \lambda \int d\tau \, \vec{J}_L(\tau,0) \cdot \vec{S}(\tau), \qquad \vec{J}_L = \mathrm{tr}\, g^{+} \partial_{-} g \vec{\sigma}, \ \lambda \prec J$$

apart from modified boundary condition, strong coupling fixed point is also characterized by a leading irrelevant interaction: $S_{\mathrm{int}} = S_{WZW}^{k=1}(g) - \frac{1}{T_K} \int d\tau \left[\vec{J}_L(\tau,0)\right]^2$

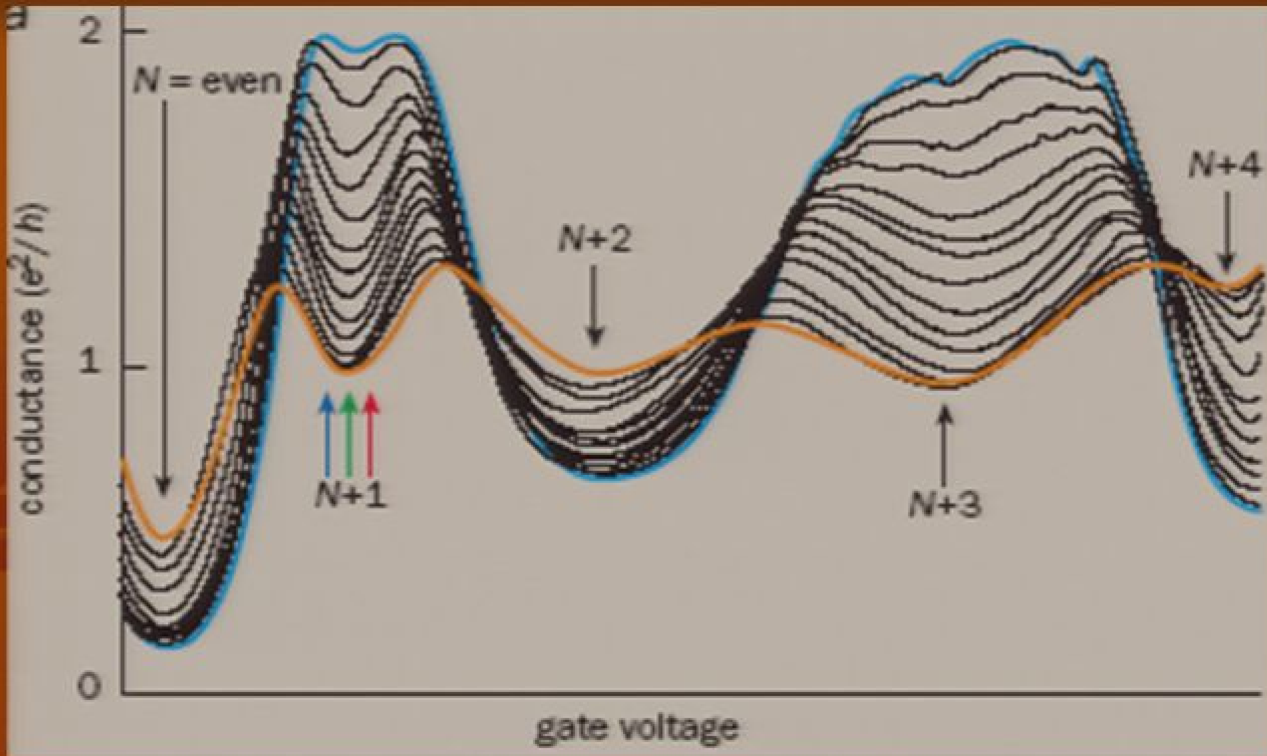
- N.B. screened impurity spin doesn't appear
- single power of $1/T_K$ follows from fact that operator has dimension 2
- at low temperature, $T \ll T_K$, we can do perturbation theory in T/T_K

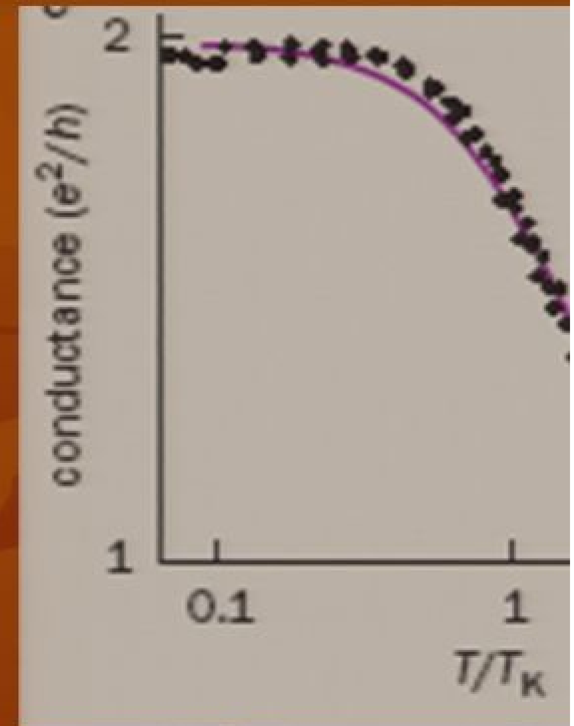
Kondo interaction between spin of quantum dot (when number of electrons is odd) and conduction electrons in 2DEG:

$$S = S_{0,1} + S_{0,2} + J[\psi^{\dagger 1}(0_-) + \psi^{\dagger 2}(0_+)]\vec{\sigma}[\psi^1(0_-) + \psi^2(0_+)] \cdot \vec{S}$$

Kondo interaction transmits electrons across Quantum dot

•conductance gets *enhanced at* low temperatur
by growth of effective Kondo coupling
•electrons are transported thru quantum dot
in p-wave channel with no resistance at $T \rightarrow 0$
•$I = G(T)\,\Delta V$
•$G = 2e^2/h$ for a dot which conducts perfectly
in 1 channel (only) – Landauer formula
•for a small quantum dot, conductance is
very small except at $T \ll T_K$ where:
$G \rightarrow 2e^2/h[1 - c(T/T_K)^2]$
(2^{nd} order in perturbation theory in $1/T_K$)





Coulomb blockade suppresses conductance except for transition gate voltages where 2 electron numbers on dot have same energy an on plateaus where N is odd, at $T<<T_K$

•this is a simple example of a much more general, and interesting, phenomena (IA, AL)

•very general interactions with various types of quantum impurities lead to low energy behaviour which is characterized by generalized conformally invariant "boundary conditions"

•in general, these boundary conditions are *not* free particle like – they encode interactions at the boundary

- non-interacting boundary conditions correspond to "Fermi liquid" behaviour in usual condensed matter terminology
- interacting boundary conditions give "non-Fermi liquid" behaviour
- models can be solved by Cardy's "boundary state" formalism

$$Z_{AB} = \mathrm{tr}\exp[-\beta \mathrm{H}_{\mathrm{AB}}^{\mathrm{L}}] = < A | \exp[-L H_P^{\beta}] | B >$$

finite temperature, T=1/β, finite size, L, partition function with boundary conditions A,B is equivalent to propagation for time L between initial and final *boundary states* |A> and |B> with Hamiltonian with periodic b.c. on circle of circumference β one of simplest physical examples is provided by 2-channel Kondo model

$$S=\int d^2x d\tau\left[\psi^{a+}\left(i\partial_\tau-\frac{1}{2m}\nabla^2\right)\psi_a+J\delta^2(\vec{x})\psi^{a+}\frac{\vec{\sigma}}{2}\psi_a\cdot\vec{S}\right]$$

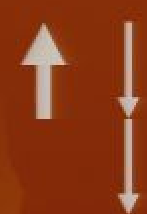
•here channel index, a, is summed over 2 valu
as is spin index (not written)

•J renormalizes towards strong coupling at low energies, as before

•but now strong coupling fixed point is unstable!

easily seen from lattice model:

- if we assume J>>t and solve single site model, impurity is overscreened
- i.e. 1 electron from each channel sits at origin in a symmetric S=1configuration
- ground state of electron-spin system has S=1/2



•now low energy effective Hamiltonian still contains an effective S=1/2 impurity, and therefore a Kondo interaction: J' ~1/J^2

•J' gets stronger under renormalization implying that a very large J gets weaker

•intermediate coupling stable fixed point is described by a non-trivial conformally invariant boundary condition

•we can again map low energy effective action into a Lorentz invariant model

•interacting part is same as before except now we get WZW model with topolgical coupling constant k=2

$$S = S_{WZW}^{k=2}(g) + \lambda \int \vec{J}_L(\tau,0) \cdot \vec{S}(\tau)$$

we identified stable fixed point with a particular non-trivial boundary condition by a phenomenological argument and checked our conjecture against numerical and Bethe ansatz results

•important consequence of our solution is that leading irrelevant operator has dimension 3/2 (1^{st} descendent of s=1 primary)

$$S_{\text{int}} = S_{WZW}^{k=2}(g) + \frac{1}{\sqrt{T_K}} \int d\tau \, \vec{J}_{-1} \cdot \vec{\phi}_{s=1}(\tau,0)$$

•now perturbation theory gives a series in $(T/T_K)^{1/2}$, rather than T/T_K

•again we can calculate 1^{st} order terms although calculations are rather different and more complicated

Experimental Realization

- a variety of different experiments have been interpreted in terms of 2 channel Kondo model
- have all remained controversial until recent (unpublished) quantum dot experiments by D. Goldhaber-Gordon's group at Stanford

•non-Fermi liquid fixed point is unstable against channel anisotropy:

$$S = \int d^2x d\tau \left[\psi^{a+} \left(i\partial_\tau - \frac{1}{2m}\nabla^2 \right) \psi_a + \sum_a J_a \delta^2(\vec{x}) \psi^{a+} \frac{\vec{\sigma}}{2} \psi_a \cdot \vec{S} \right]$$

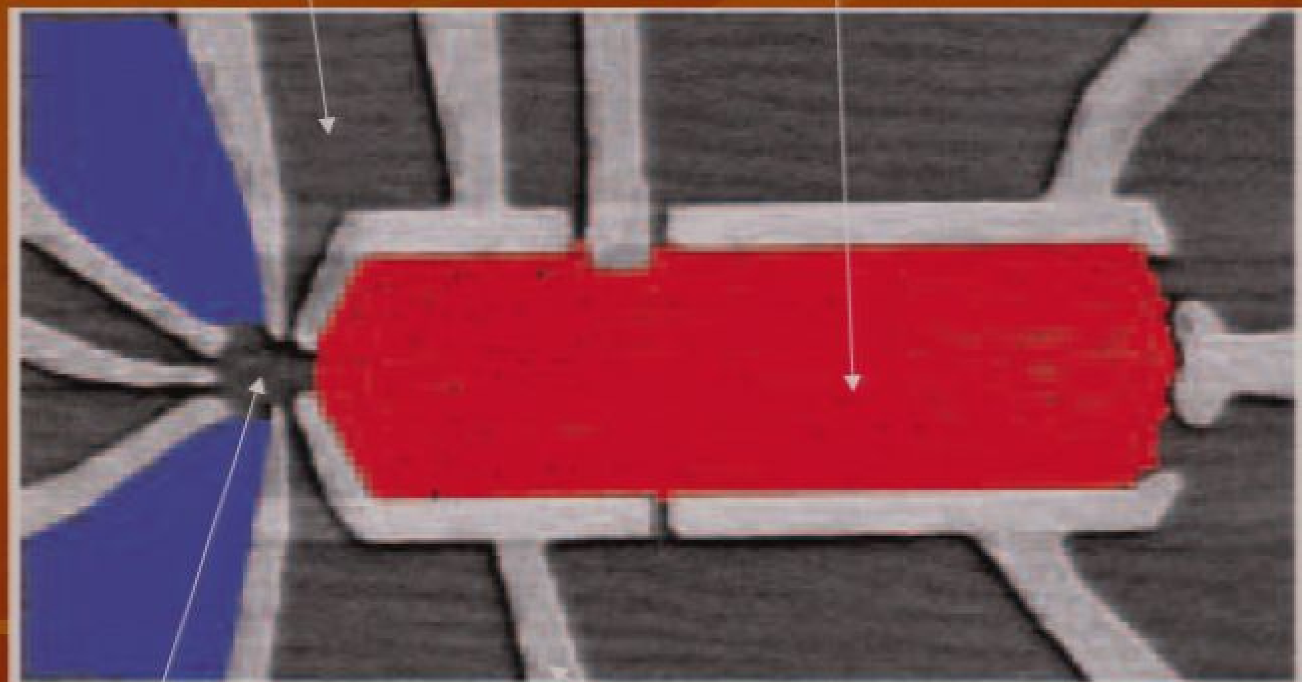
if $J_1 > J_2$ then channel 1 screens spin and channel 2 decouples at low energies yielding a Fermi liquid fixed point:

$$\psi_{L1}(\tau,0) = +\psi_{R1}(\tau,0), \quad \psi_{L2}(\tau,0) = -\psi_{R2}(\tau,0)$$

•very difficult to make $J_1 = J_2$, while avoiding magnetic fields and other destructive effects

1st channel

2nd channel



quantum dot

V_c controls J_2

- complicated device has many knobs
- can tune to non-Fermi liquid fixed point

•lowest order perturbation theory in irrelevant interaction now gives a conductance:

$G=(1/2)G_0\,[1-(T/T_K)^{1/2}]$

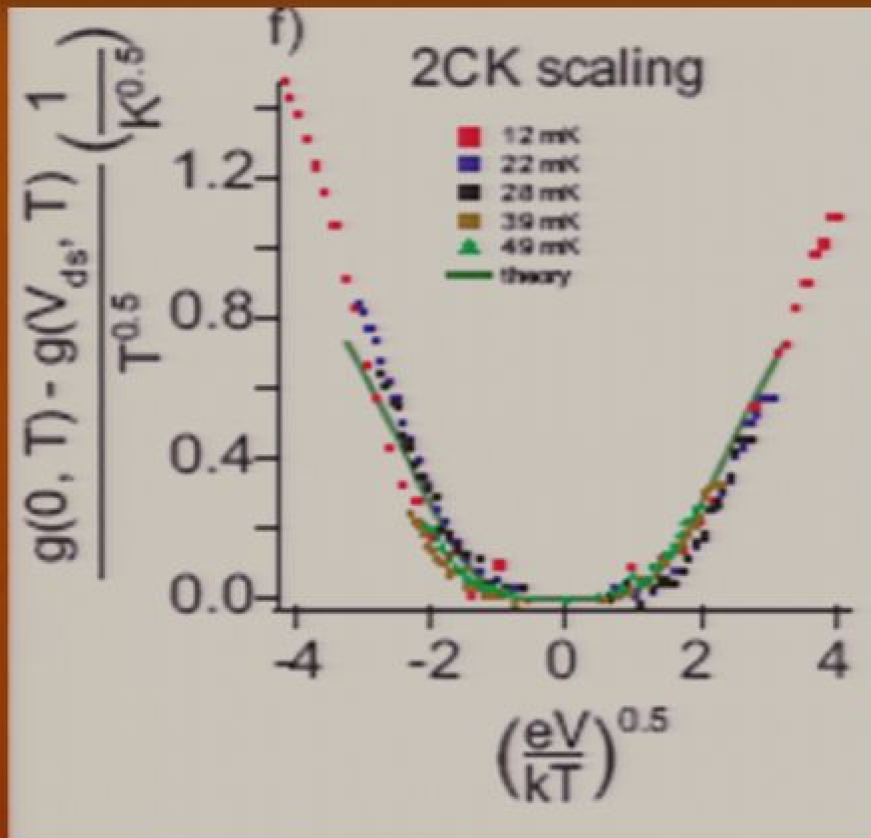
•T=0 value is ½ as big as for 1-channel case and T-dependence has exponent ½ instead of 2

for finite bias voltage:

$dI/dV = G_0[1-(T/TK)^2 f(eV/T)]$ (for FL)

$dI/dV = (1/2)G_0[1-(T/T_K)^{1/2}\,h(eV/T)]$ (NFL)

•scaling functions f(x) and h(x) are known in certain limits



•conductance measurement, versus T and bias voltage, V, with all parameters tuned to non-Fermi liquid fixed point exhibits expected scaling (note $T^{0.5}$)

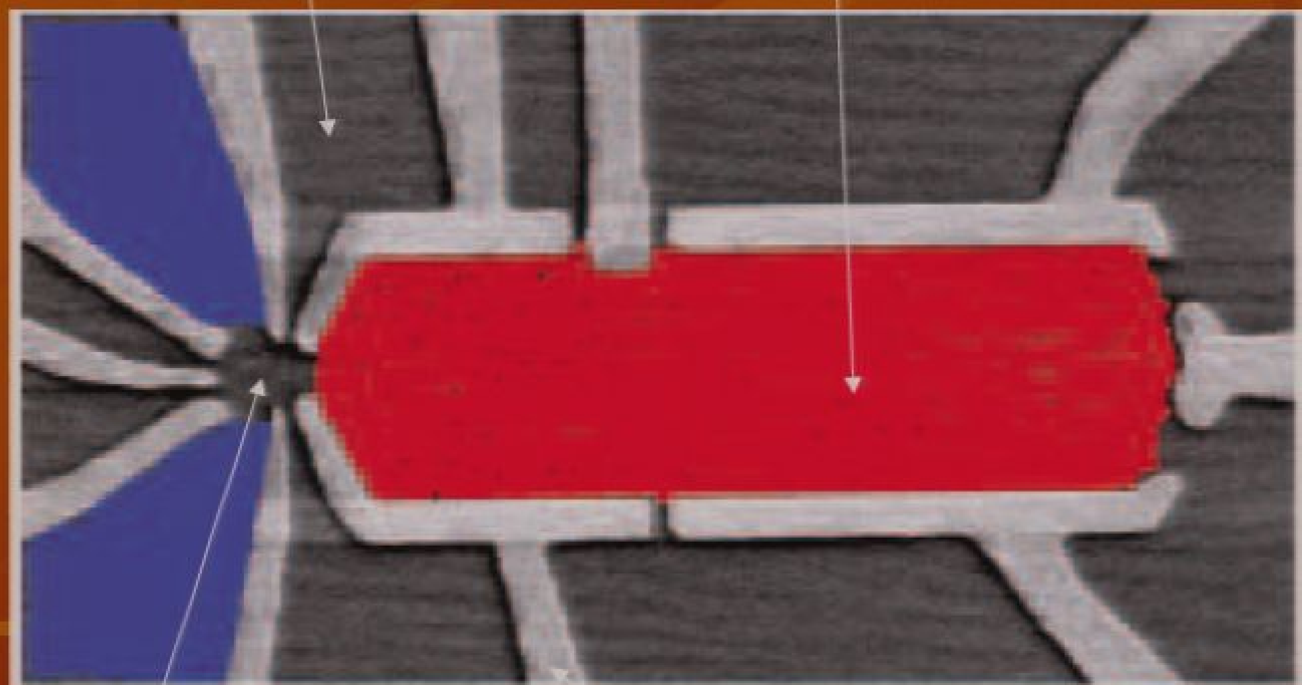
Conclusions

•boundary CFT describes quantum impurity models of condensed matter physics

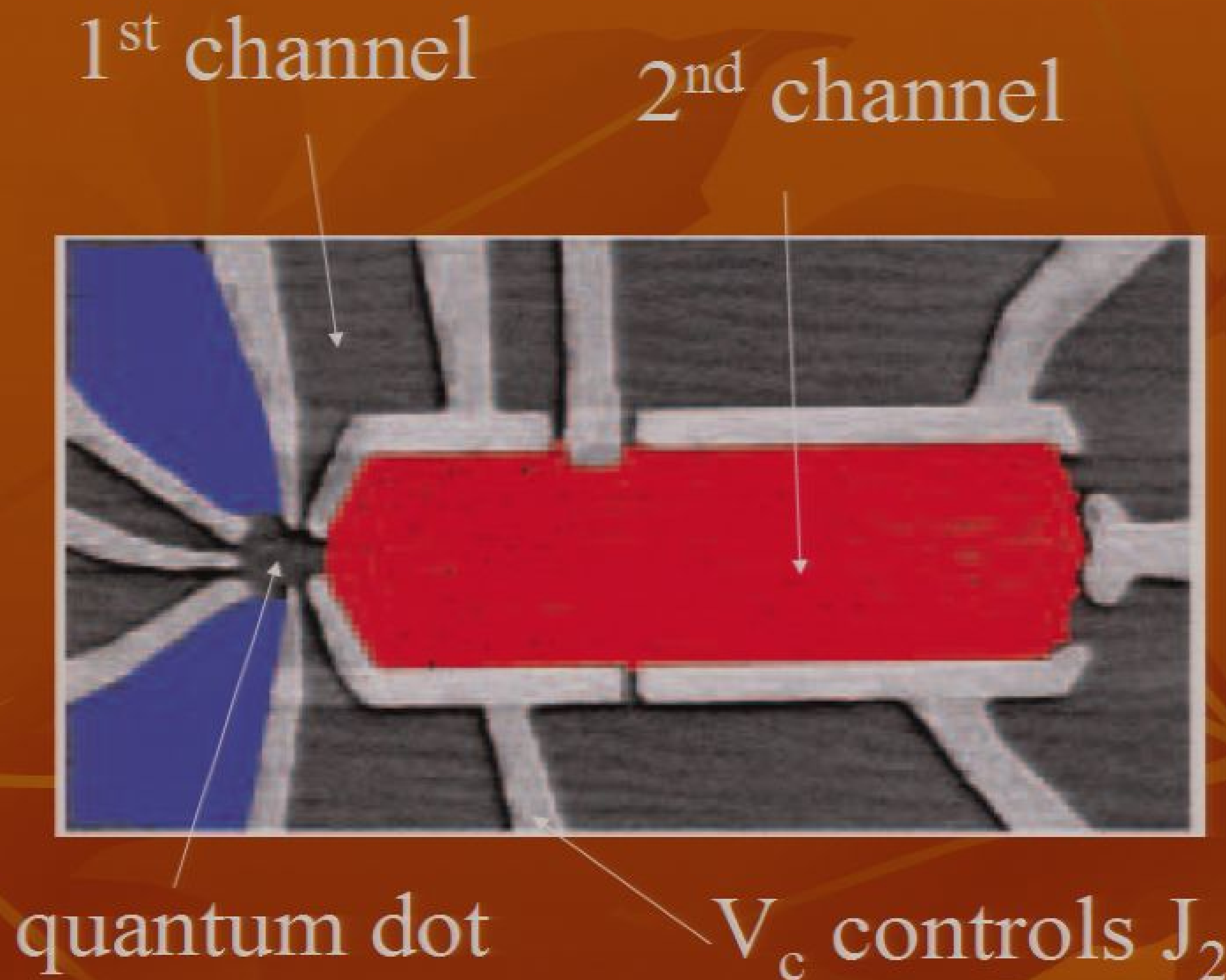
•2-channel Kondo, k=2 WZW, model has a non Fermi liquid boundary condition

•solution of this model by CFT methods leads to predictions verified by quantum dot experiments

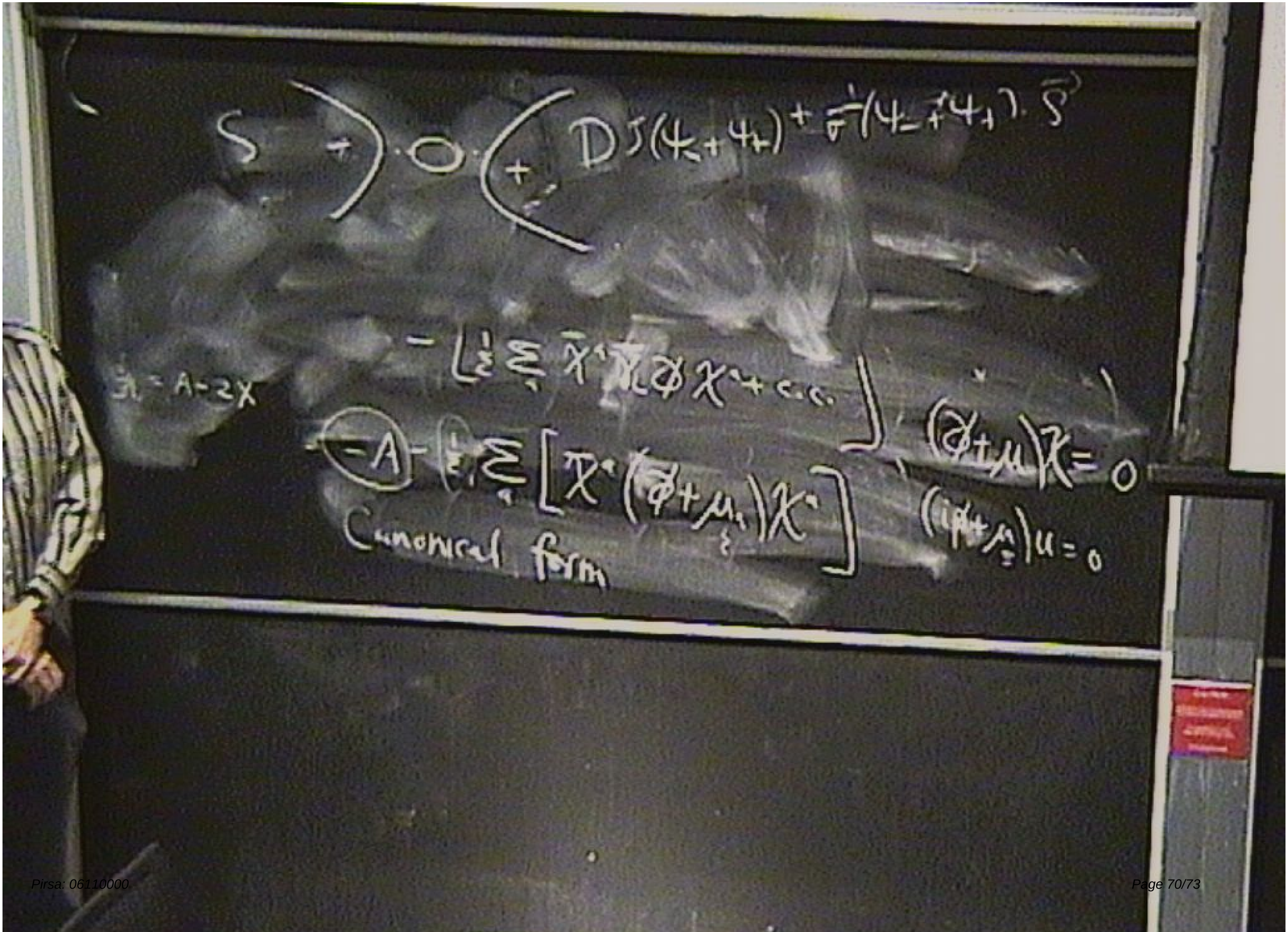
•CFT may or may not be part of a “theory of everything” but we now know it is definitely a theory of something ☺

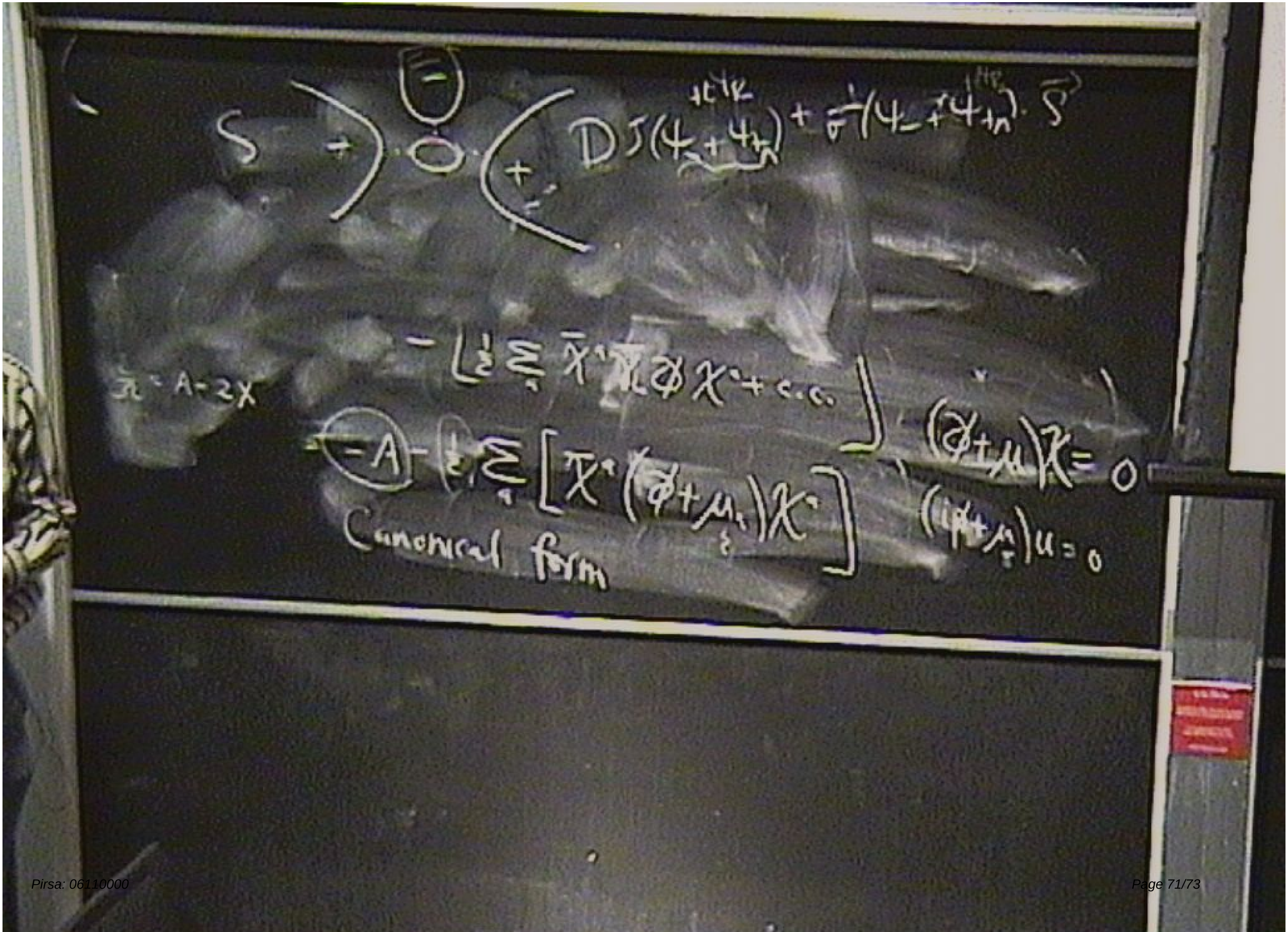


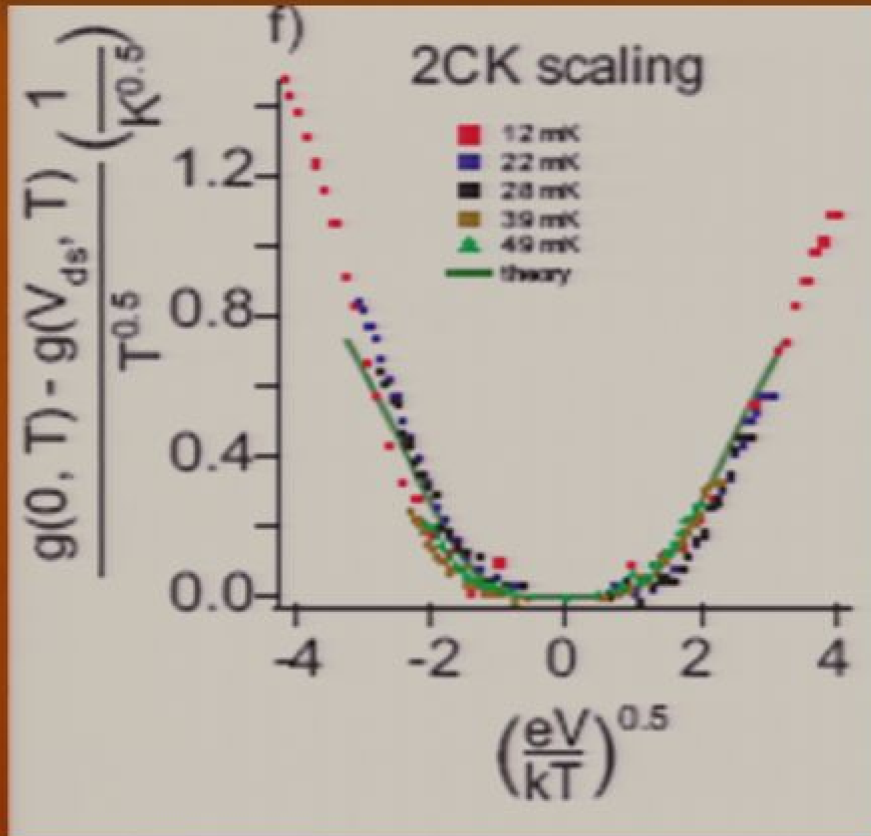
- complicated device has many knobs
- can tune to non-Fermi liquid fixed point



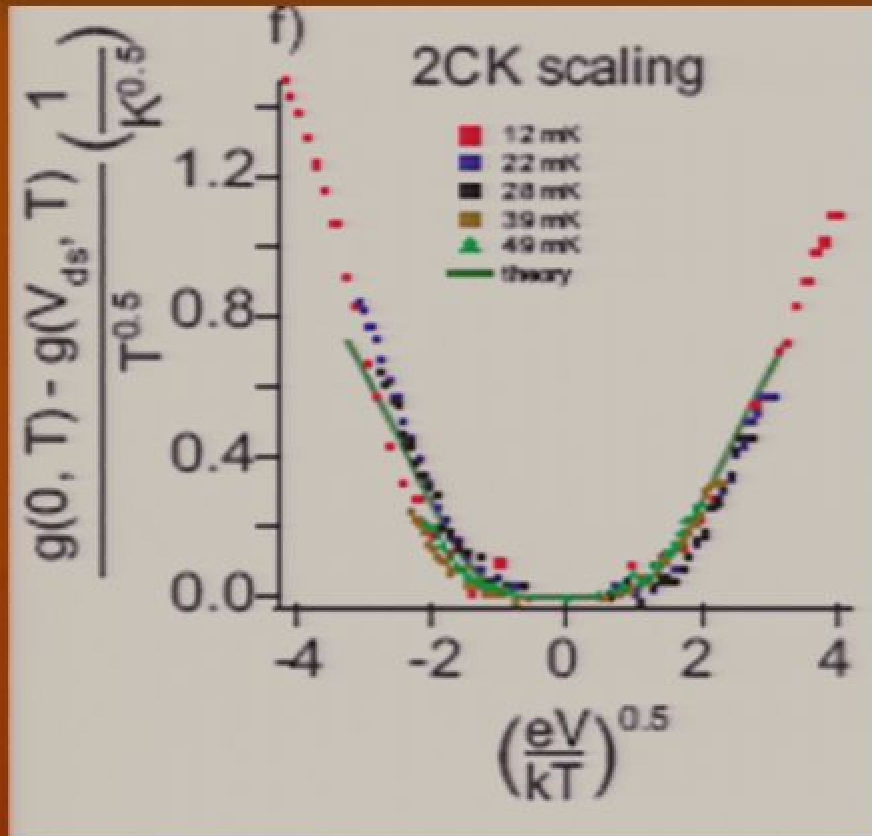
- complicated device has many knobs
- can tune to non-Fermi liquid fixed point


Canonical form


Canonical form



•conductance measurement, versus T and bias voltage, V, with all parameters tuned to non-Fermi liquid fixed point exhibits expected scaling (note $T^{0.5}$)



•conductance measurement, versus T and bias voltage, V, with all parameters tuned to non-Fermi liquid fixed point exhibits expected scaling (note $T^{0.5}$)