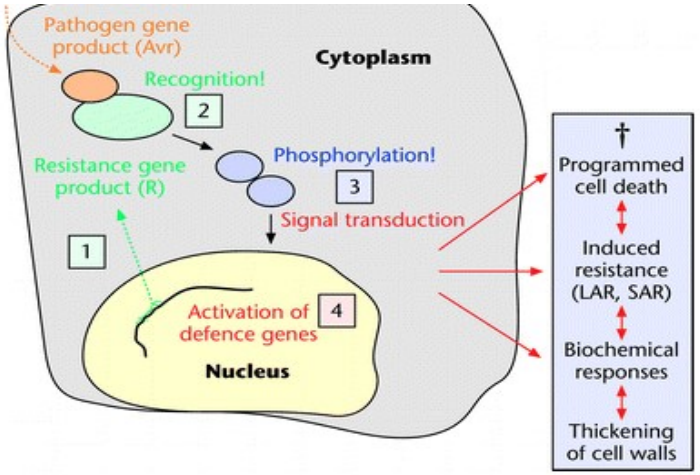
Host Resistance to Plant Viruses



"Science, unlike theology, never leads to insanity." L. Burbank

Objectives:

1. Be able to recognize the different types of resistance to plant viruses
2. Understand the differences among the types of resistances
3. Know what elicitors are required for the different types of resistances
4. Understand the appropriate uses of different types of resistances to plant viruses

Types of Virus-Plant Interactions

1. Plant is immune, no or limited viral replication occurs, no cell-to-cell movement.

Non-host Resistance

2. Virus replicates and moves through out the plant without obvious symptoms evident – latent (tolerance)

3. Virus replicates and causes symptoms in new leaves but with time and further plant growth symptoms disappear - recovery

4. Virus replicates but the plant responds with hypersensitivity - cell death (may not always be noticed; necrosis, local lesions).

Types of Host Resistance

5. Virus replicates and moves through out the plant with obvious symptoms

No obvious Resistance

The type of interaction is dependent upon the combination of host and virus

Table 1. Susceptibility types to *Tobacco mosaic virus* (TMV) and *Tobacco etch virus* (TEV) in 310 plant species tested.

Plant response		Inoculation with TMV No. of species	Inoculation with TEV No. of species
No symptoms No recovered virus	Immunity	111	227
No symptoms Virus in inoculated leaves only	??	100	15
Local symptoms Virus in inoculated leaves only	Hypersensitivity	27	7
No symptoms Virus in upper leaves	Latent	15	8
Systemic symptoms Virus in inoculated leaves	Susceptible	57	53

P. Palukaitis and J.P. Carr (2008) Journal of Plant Pathology 90:153-171

Mechanisms of Resistance

A. Immunity

B. Genetic Host Resistance

C. Systemic Acquired Resistance

D. Post-transcriptional Gene Silencing

E. Transgenic Resistance

Broad Types of Resistance to Viruses:

A. Immunity:

- All the genotypes within a species are resistant
- Very under-studied, potential area for new resistance
- Most common type of resistance

B. Host Resistance:

- Genotypes within a species vary in their resistance to the pathogen
- Most research is with this type of resistance (because its genetically accessible)
- Most commercial development uses this type of resistance

Broad Types of Resistance to Viruses:

C. Systemic Acquired Resistance:

- Active response by host in response to infection by diverse pathogens that cause necrotic cell death, resulting in diminished susceptibility to later pathogen attack.

D. Post-transcriptional Gene Silencing:

- Active cellular response by the host induced by infection with a virus
- Can interfere with virus replication at diverse parts of the replication cycle

E. Transgenic Resistance:

- Engineered resistance and tolerance to plant viruses
- Uses transgenes derived from a wide range of organisms including plant-derived natural R genes, pathogen-derived transgenes, and even non-plant and non-pathogen-derived transgenes

Mechanisms of Resistance

1. **Immunity**
2. Genetic Host Resistance
3. Systemic Acquired Resistance
4. Post-transcriptional Gene Silencing
5. Transgenic Resistance

A. Immunity:

Resistance is against all biotypes of a pathogen and in all cultivars or accessions of a particular plant species = **Non-Host Resistance**

Immunity is usually characterized by the prevention of virus replication. This is assessed in isolated, single cells (protoplasts), or multiple leaf cells co-infected by agroinfiltration of DNA expressing viral genomes to exclude the possibility of resistance due to cell-to-cell or systemic movement.

Lecture Outline:

1. Non-host Resistance
2. **Host Resistance**
3. Systemic Acquired Resistance
4. Post-transcriptional Gene Silencing
5. Transgenic Resistance

B. Host Resistance

- One of a several approaches used to protect crops from virus infection
- Resistant varieties, where available and if durable, are still considered the most cost-effective and reliable approach to virus management
- Considerable time and cost are required to develop cultivars with the appropriate array of resistances

B. Host Resistance

- Plant genotypes within a species are resistant to a given virus due to a constitutive mechanism (always produced by the cells under all physiological conditions) or an active (induced) mechanism.
- Genes that confer this type of resistance are known as R genes
- Over 200 R genes that confer resistance to viruses have been identified in crops and their wild relatives
- The mechanism of very few R genes have been elucidated (20 as of 2007)

B. Host Resistance

- More than 80% of reported viral resistance is monogenically controlled; the remainder shows oligogenic or polygenic control.

- About half of all monogenic resistance traits is recessive. This is different from fungal or bacterial resistance where most reported resistance is dominant.

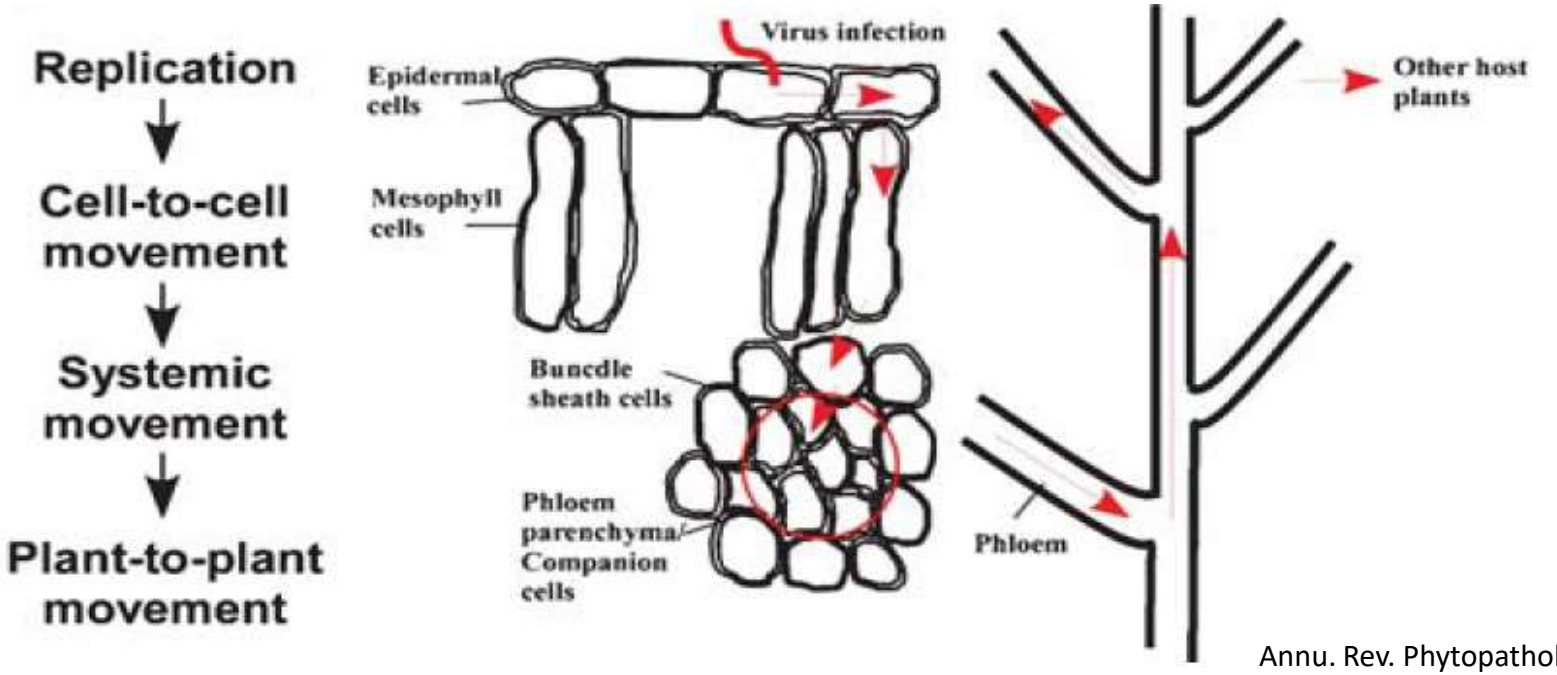
B. Host Resistance

Mechanisms of R genes:

- R gene may be an active response to a viral protein
- R gene may be the absence of a host factor necessary for replication or transport
- R gene may be the gene for the host factor that contains a mutation that prevents completion of the viral infection cycle

Cellular resistance to virus:

- Replication is prevented or suppressed OR
- Plant cell responds actively to infection with an necrotic reaction
- Cell-to-cell movement is prevented or suppressed
- Long distance movement is prevented or suppressed



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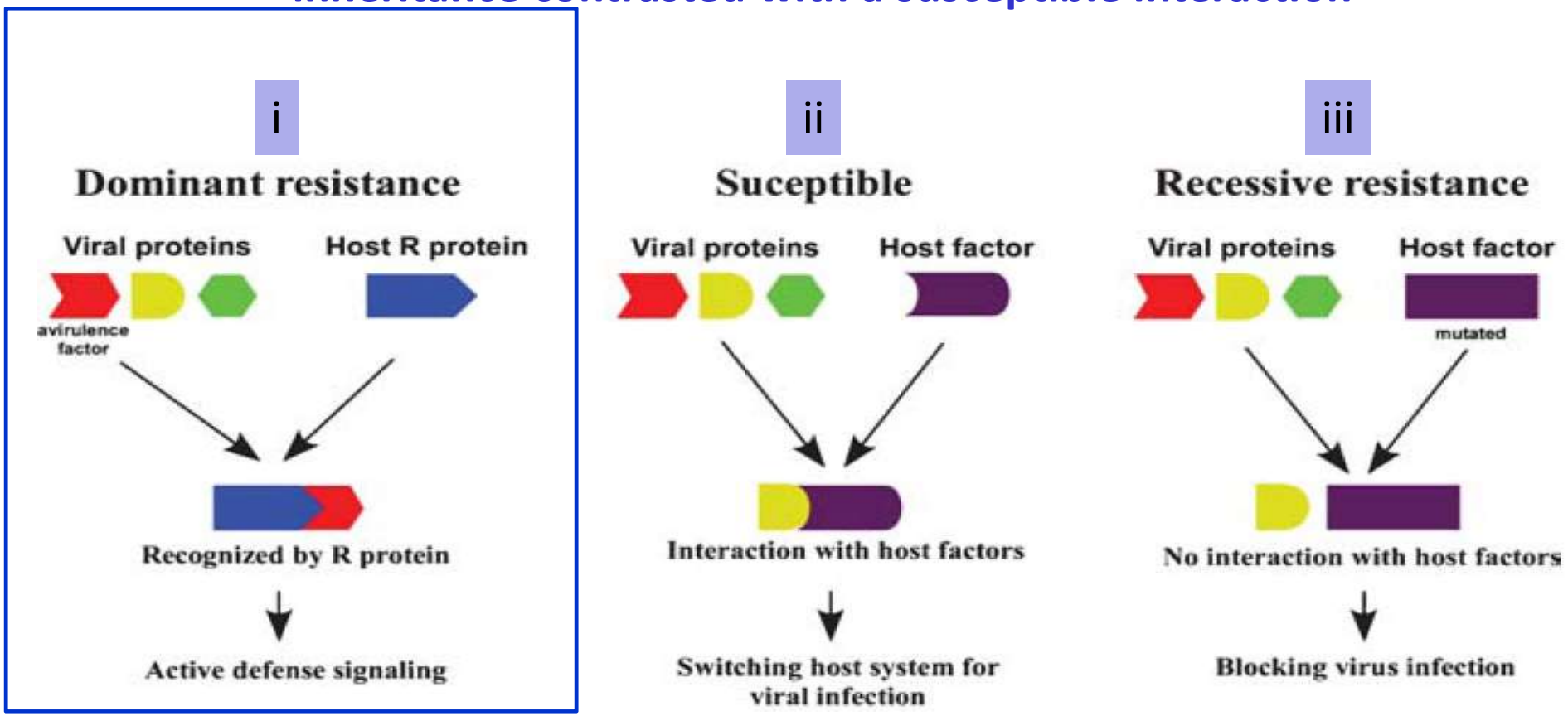
B. Host Resistance

Genetics of Host Resistance can be divided into 3 categories:

- `i` Dominant resistance
- `ii` Susceptible
- `iii` Recessive resistance

Possible virus resistance mechanisms showing dominant or recessive inheritance contrasted with a susceptible interaction



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i Dominant Resistance

(aka) Positive resistance mechanism:

- Resistant plants contain some property that **actively or directly inhibit some phase of the viral replicative cycle**

- Most dominant R genes interfere with replication or movement

- These mechanisms may be **Constitutive:**
  The plant produces **an inhibitor which interferes with some stage of the virus replicative cycle**

- or **Induced: (by a signal transduction pathway)**
  Plant contains a factor which **recognizes some virus-coded molecule** (often a viral protein) and switches on a resistance response (HR).

Naturally occurring plant virus resistance genes for which nucleotide sequences are known

	Gene	Plant	Virus[a]	Resistance mechanism
Dominant	*N*	*N. tabacum*	TMV	Cell-to-cell movement (HR)
	Rx1	*S. tuberosum*	PVX	Replication
	Rx2	*S. tuberosum*	PVX	Replication
	Sw5	*S. esculentum*	TSWV	Cell-to-cell movement (HR)
	HRT	*A. thaliana*	TCV	Cell-to-cell movement (HR)
	RTM1	*A. thaliana*	TEV	Systemic movement
	RTM2	*A. thaliana*	TEV	Systemic movement
	RCY1	*A. thaliana*	CMV	Cell-to-cell movement (HR)
	$Tm2^2$	*S. lycopersicum*	ToMV	Cell-to-cell movement (HR)
Recessive	*pvr1*, $pvr1^2$	*C. annuum*	PVY	Replication
	$pvr1^1$			Cell-to-cell movement
	$mo1^1$	*L. sativa*	LMV	Replication
	$mo1^2$			Tolerance
	sbm1	*P. sativum*	PSbMV	Replication

Only some R gene/virus combinations produce a visible HR

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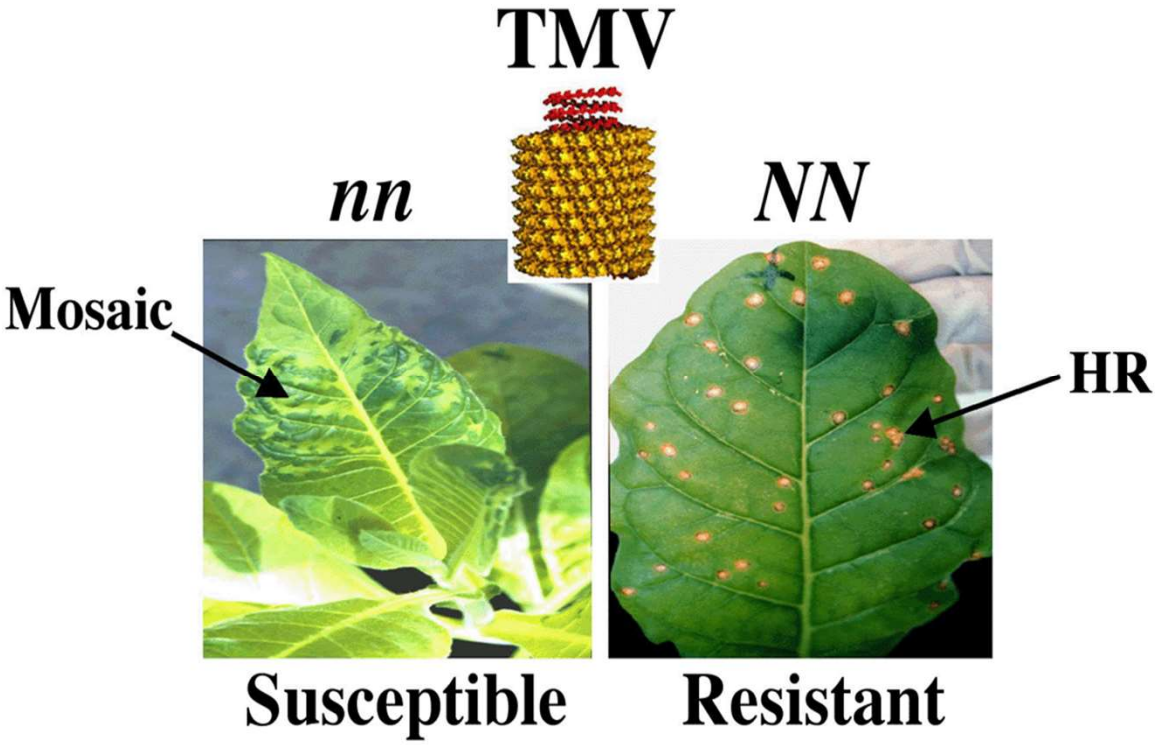
Example: Naturally occurring R gene responsible for HR

TMV infected *Nicotiana glutinosa*
(N. glutinosa – source of the *N* gene)



- Most R genes for virus resistance occur in gene clusters with R genes for resistance to other pathogens
- There are recognizable gene families of R genes for resistance to pathogens including viruses
- Examples of dominant resistance (R) genes against viruses and other pathogens

R Gene	Plant	Pathogen	R Gene Family
Prf	Tomato	*P. syringae*	LZ-NB-LRR
Mi	Tomato	*Meloidogyne incognita*	LZ-NB-LRR
Rx	Potato	PVX	LZ-NB-LRR
HRT	Arabidopsis	TCV	LZ-NB-LRR
Sw-5	Tomato	TSWV	LZ-NB-LRR
12c	Tomato	*Fusarium oxysporum*	NB-LRR
Bs2	Pepper	*Xanthomonas campestris*	NB-LRR
Mla 1	Barley	*Blumeria graminis*	CC-NB-LRR
N	Tobacco	TMV	TIR-NB-LRR
RPS4	Arabidopsis	*P. syringae*	TIR-NB-LRR

Breadth of Resistance of R Genes:

- There are a number of examples of dominant and recessive genes that appear to control a relatively wide range of viral genotypes that span multiple viral species.

- The most dramatic examples appear to involve members of the *Potyviridae.*

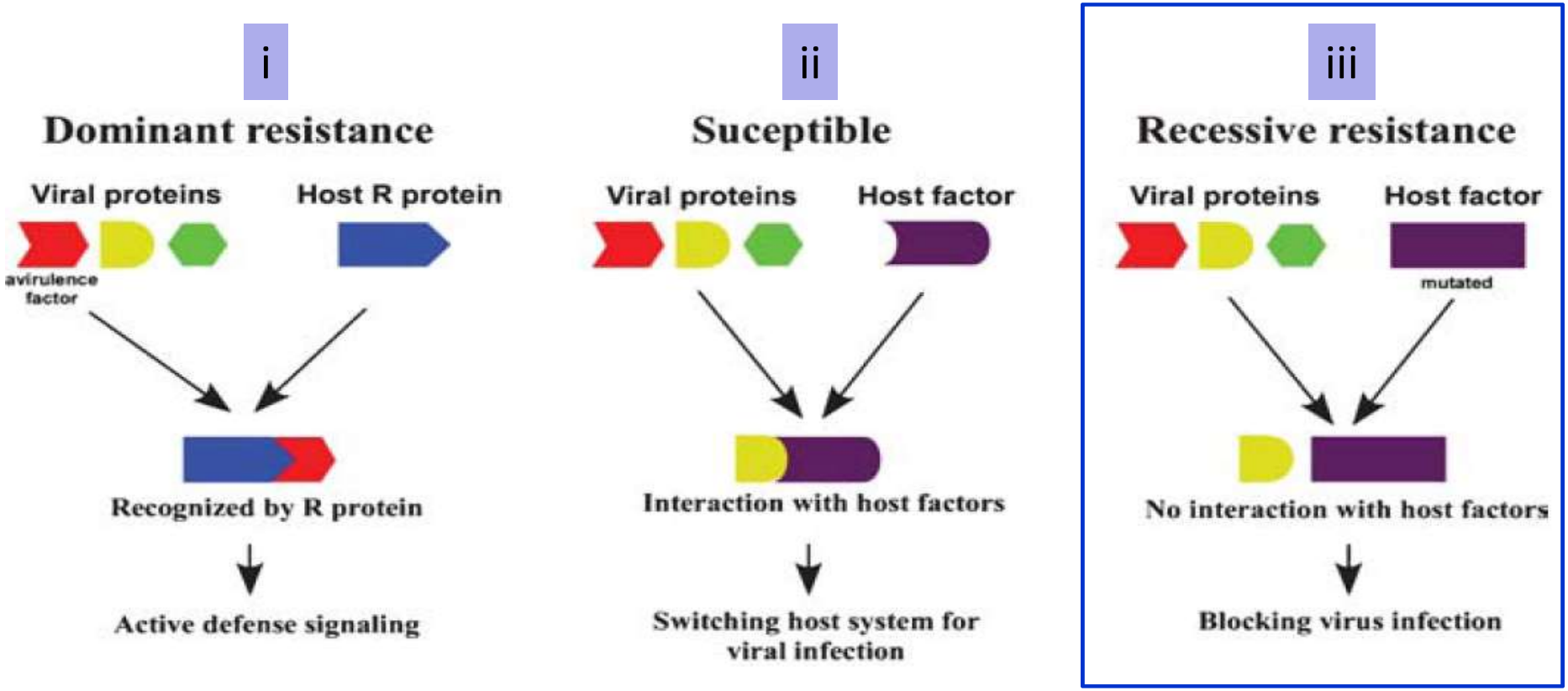
Ex. the I gene of *Phaseolus vulgaris*:

- I gene provides dominant resistance or a dominant necrotic response to ten different but related viruses in the *Potyviridae*

    - This locus plays a role in producing a necrotic response to *Bean severe mosaic virus* (*Comoviridae*)

    - Detailed physical mapping of the I locus has established that it occurs in a large cluster of TIR-NBS-LRR sequences

Possible virus resistance mechanisms showing dominant or recessive inheritance contrasted with a susceptible interaction



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iii Recessive Resistance:

- **Negative (passive) (recessive) resistance mechanisms:**

- These types of resistance mechanisms are usually constitutive (not induced) and controlled by recessive alleles (recessive inheritance).

- Plants are resistant because they **lack the specific host helper functions required by the virus**, or possess them in a mutated form that prevents them from operating in the virus replicative cycle.

Examples of R genes that confer resistance to viruses:

	Gene	Plant	Virus[a]	Resistance mechanism
Dominant	*N*	*N. tabacum*	TMV	Cell-to-cell movement (HR)
	Rx1	*S. tuberosum*	PVX	Replication
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	$mo1^2$			Tolerance
	sbm1	*P. sativum*	PSbMV	Replication

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Example: *ty5* locus, recessive resistance in TY-172, a TYLCV-resistant tomato line

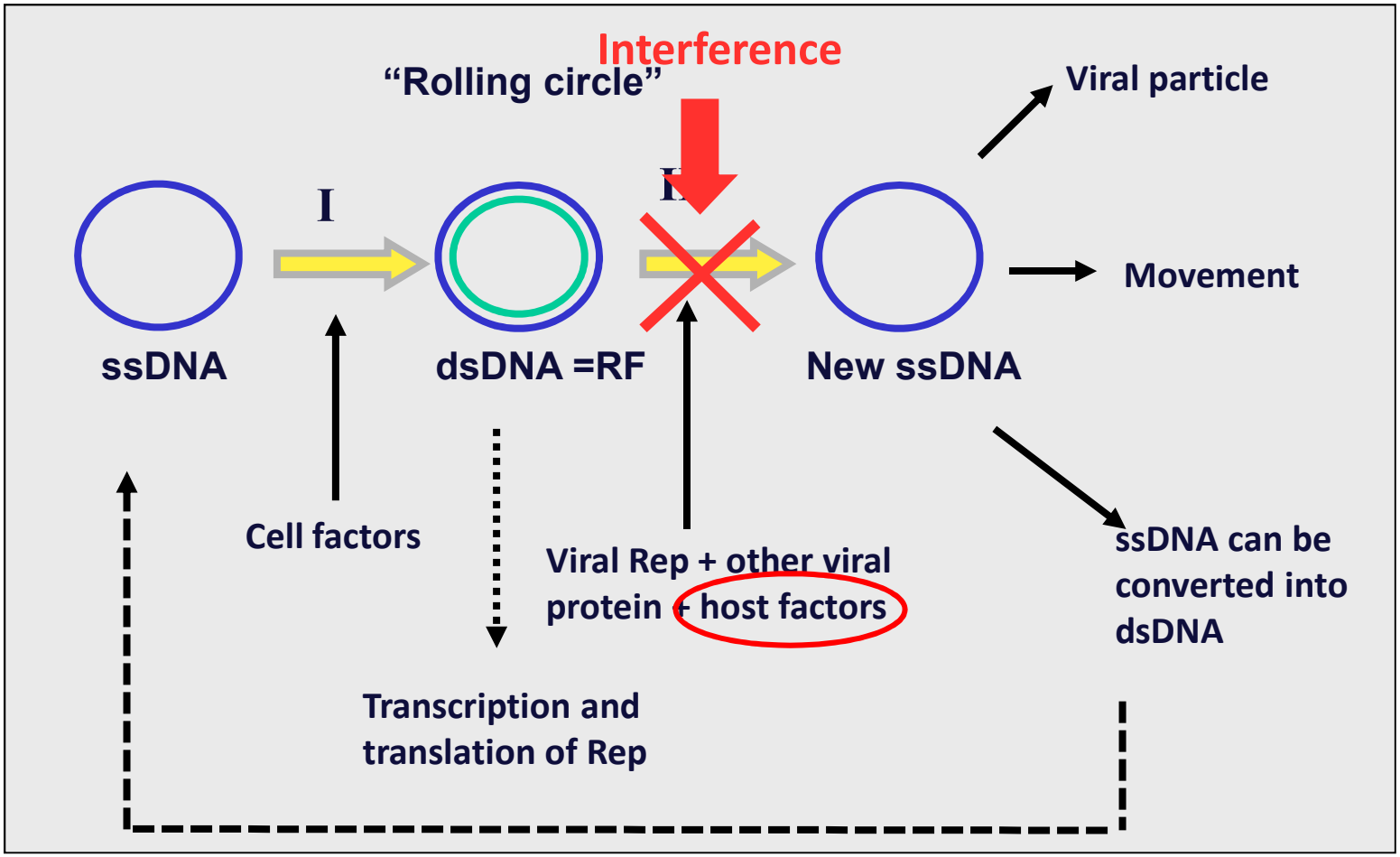
The resistance in TY-172 was obtained by crossing different TYLCV-resistant accessions of *Solanum peruvianum* and *S. arcanum* with *S. lycopersicon*.

Resistance is recessive, and controlled by the *ty5* locus, plus four additional minor QTLs)

Following inoculation with TYLCV:

- TY-172 shows no symptoms
- Low amounts of TYLCV DNA are detected

TYLCV DNA Replication and *ty5* resistance



Example: *ty5* mediated resistance to TYLCV (from genotype TY172)

The mutated gene codes for a protein that probably promotes resistance through the ribosome recycling phase of protein synthesis, rather than to initiation of protein synthesis. So this mutation infers with the ability of the virus to produce all the proteins it needs to complete replication of progeny genomes.

[[Resistance associated with *ty5* was localized to a mutation(s) in a 425 bp region of a gene that encodes the tomato homolog of the messenger RNA surveillance factor Pelota (*Pelo*). A transversion (substitution of a (two ring) purine (A or G) for a (one ring) pyrimidine (C or T) (or vice versa) in the first exon of *Pelo* results in resistance to TYLCV.]]

Lapidot et al (2015) A Novel Route Controlling Begomovirus Resistance by the Messenger RNA Surveillance Factor Pelota. PLOS Genetics DOI: 10.1371/journal.pgen.1005538

Lecture Outline:

1. Non-host Resistance
2. Host Resistance
3. **Systemic Acquired Resistance**
4. Post-transcriptional Gene Silencing
5. Transgenic Resistance

Systemic Acquired Resistance

- Term coined by Frank Ross to describe the observation that prior infection of tobacco plants by TMV enhanced resistance in the systemic tissue to subsequent challenge by TMV or other pathogens. (AF Ross 1961. Systemic acquired resistance induced by localized virus infections in plants. Virology. 1961;14:340–358).

- Not specific for viruses

- Plants are often exposed to injuries (herbivorous insects, pathogens: fungi, bacteria, viruses, phytoplasmas, chemical compounds, mechanical wounding) and so they evolved sophisticated defense responses to minimize damage from these attacks.

- Plants respond by producing protective compounds, at the **site of the attack** which can protect distant and as-yet unchallenged tissues.

Systemic Acquired Resistance:

- This is an induced response
- The response depends on the presence of an early warning **signal** which is then followed by the activation of specific defense response genes.
- Regardless of the origin of the attack (virus, bacteria wound, etc..), plants activate a limited number of **common defense mechanisms** in response to a wide variety of attacks.
- It has been shown that **microorganisms** and **chemicals** (produced naturally by the plant or introduced as an amendment) can turn on these defense responses.
- Most of these chemicals have been demonstrated to turn on defense responses to bacteria and fungi, but fewer have been evaluated for their effect on viruses.

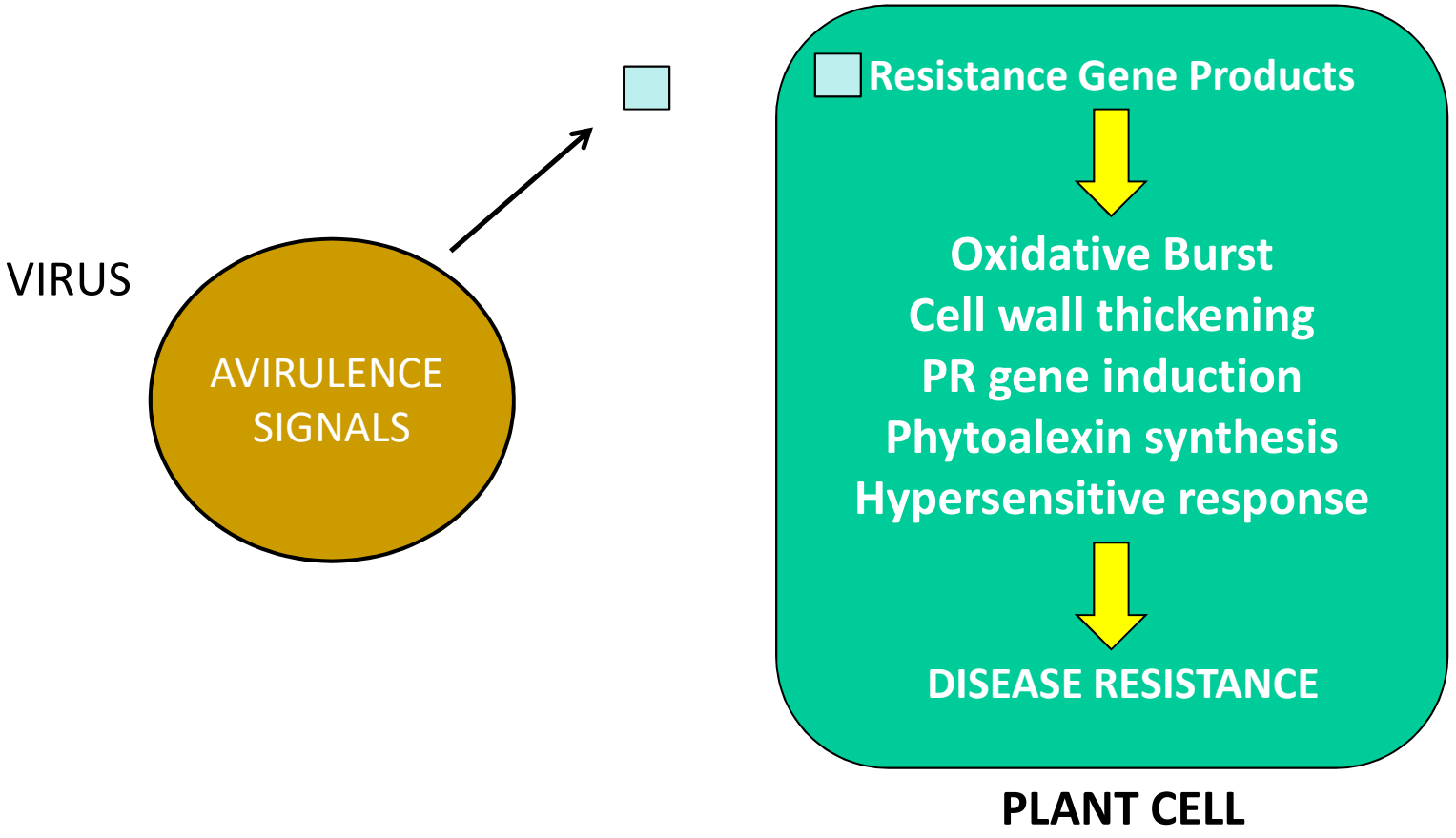
Systemic Acquired (Induced) Resistance:

Two well known Induced Host Defense Pathways:

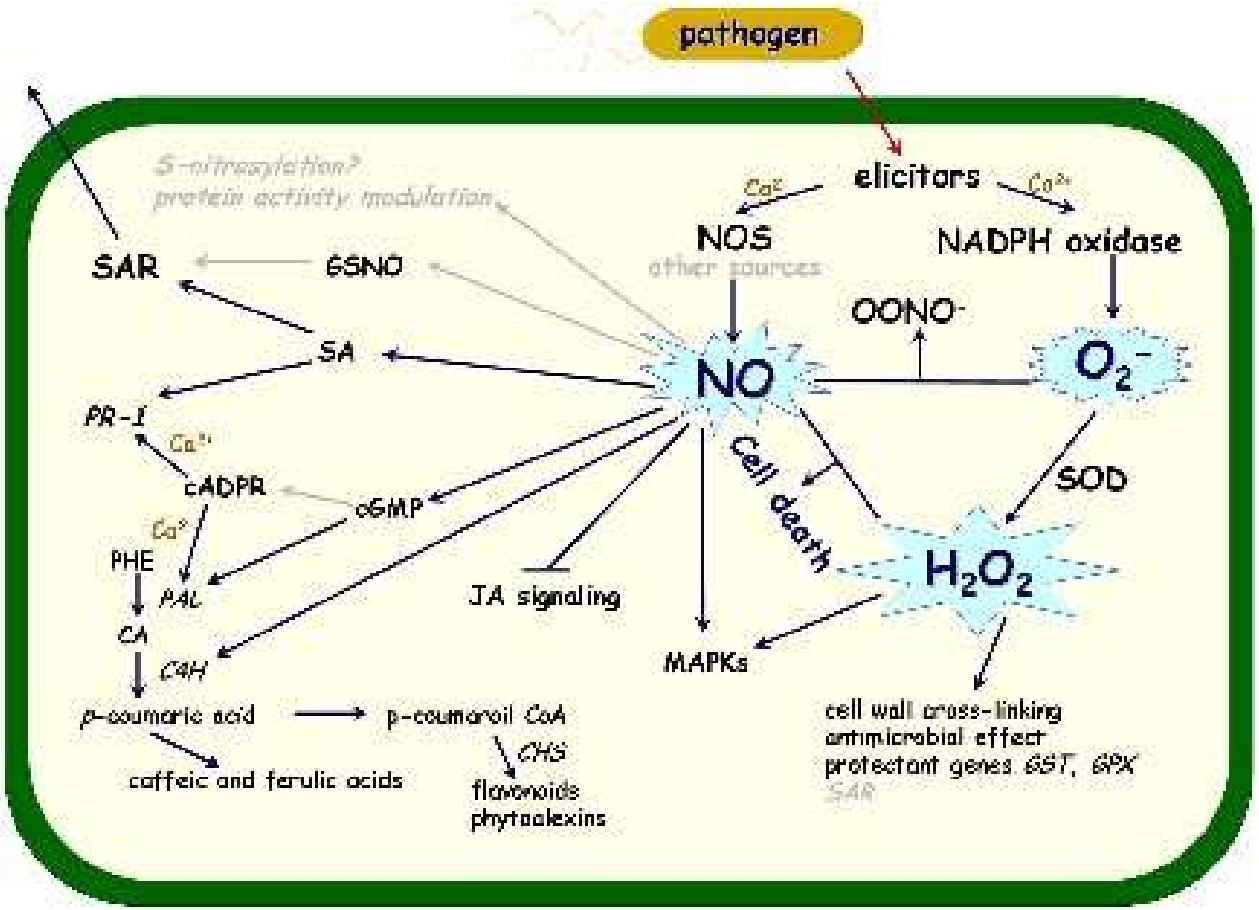
- **Salicylic Acid Pathway** – Induces SAR (systemic acquired resistance), a natural biological defense response to pathogen attack (and some insects)

- **Jasmonic Acid Pathway** - Induces the production of disease and insect defense compounds (and some viruses)

Systemic Acquired Resistance: a “Shot gun” Host Response



Systemic Acquired Resistance: a "Shot gun" Host Defense Response

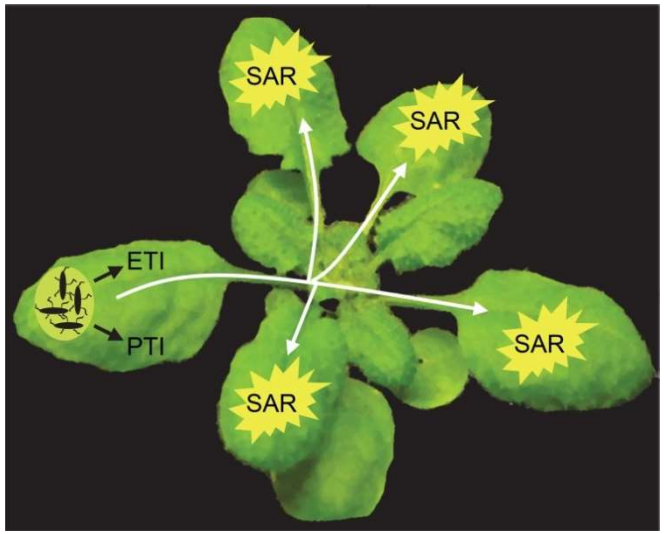


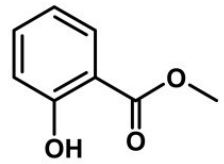
A cascade of many host proteins are turned on either at the site of inoculation or distant from the site, that result in defense genes being turned on

Many questions remain unanswered to the exact details of the signaling of SAR

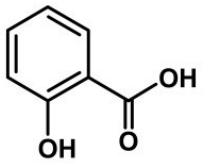
SAR is an induced systemic response

- Signaling uses the vascular system
- Signaling is a complex system with cross talk with other defense pathways
- Multiple metabolites are involved in the long distance signaling:

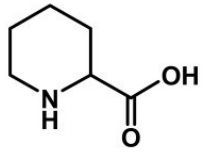




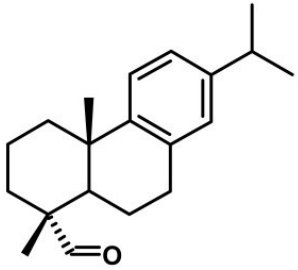
methyl salicylate



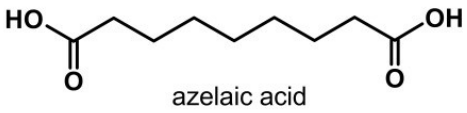
salicylic acid



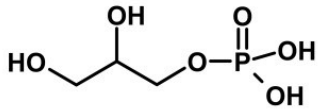
pipecolic acid



dehydroabietinal

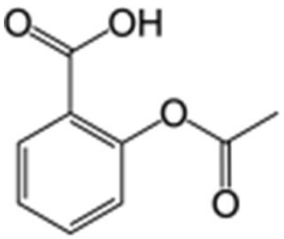


azelaic acid



glycerol-3-phosphate

ASPIRIN acetylsalicylic acid (ASA)



Dempsey and Klessig *BMC Biology* (2017) 15:23
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BMC Biology

QUESTION AND ANSWER Open Access

How does the multifaceted plant hormone salicylic acid combat disease in plants and are similar mechanisms utilized in humans?

D'Maris Amick Dempsey and Daniel F. Klessig*

Salicylic acid (SA) is an important plant hormone that regulates many aspects of plant growth and development, as well as resistance to abiotic and biotic stresses. SA binds to and alters the activity of multiple plant proteins (this is a shift from the paradigm that hormones mediate their functions via one or a few receptors). SA and its derivatives also have multiple targets in animals; some of these proteins, like their plant counterparts, are associated with pathological processes. These findings suggest that SA exerts its defense-associated effects in both kingdoms via a large number of targets.

Salicylic Acid Pathway

Characterized by:

- Production of active oxygen (hydrogen peroxide, peroxidase)
  (peroxidases have been associated with fungal cell wall degradation and pathogen defense signaling)

- Thickening of the plant cell wall
  - Increasing lignification
  - Production of phenolic esters that strengthen cross linking

- Systemic and local accumulation of Pathogenesis Related Proteins (PR-Proteins)

- Systemic accumulation of anti-microbial compounds called phytoalexins.

Jasmonic Acid Pathway:

- Farmer and Ryan (1990) discovered that jasmonic acid volatilized from sagebrush could trigger defense gene expression in adjacent tomatoes.

- Jasmonic acid volatiles act as attractants for beneficial insects

- Jasmonic acid induces the production of disease and insect defense compounds:
  - Defense Proteins
  - Phytochemicals

Systemic Acquired (Induced) Resistance:

- Where resistance to a pathogen is associated with a localized necrotic lesion, the plant will subsequently be systemically "**immunized**" so that further infection will either exhibit increased resistance or reduced disease symptoms.

- This "**systemic acquired resistance**" (**SAR**) is a response that occurs some distance from the challenged leaf and implies the **systemic movement of a signal** that alters gene expression in as yet un-challenged plant parts.

- SAR is associated with the systemic expression of a subset of defense genes, e.g. the acidic forms of pathogenesis-related proteins (PR proteins).

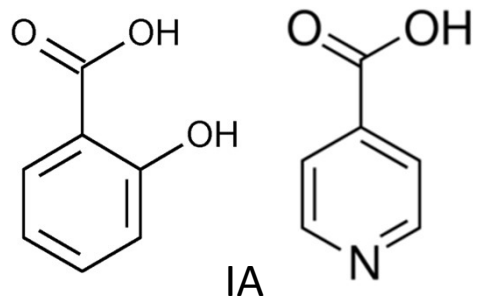
Systemic Acquired (Induced) Resistance:

- Salicylic acid (SA) is synthesized to high levels around the necrotic lesion, before being (possibly) mobilized through the phloem to accumulate, at much lower levels, systemically
- Exogenous applications of SA can induce both PR proteins and resistance to pathogen attack
- SA appears to be involved somehow in the signaling process but other molecules (lipids) may play a bigger role

Plant Activators (Elicitors) of SAR:

- In contrast to conventional pesticides, plant activators have no direct effect on pathogens. Plant activators induce plants to produce natural disease-fighting compounds.

- Acibenzolar (Actigard)
- Harpin (Messenger)
- Biological control organisms
- Salicylic acid
- Benzothadiazone (BTH)
- Brassinolide (BL) a brassinosteroid,
- Probenazole (PBZ, the active ingredient in Oryzemate, a fungicide used in rice)
- Pyraclostrobin (strobilurin fungicide),
- Isonicotinic acid,
- 2,6-dichloroisonicotinic acid (breakdown prod. of the insecticide Imidacloprod)
- *N*-cyanomethy-2-chloroisonicotinamide (NCI)



SA IA IA

Benzene or Pyridine rings

Examples of Activators That Can Induce Virus Resistance:

Activator (Inducer)	Virus Affected
Acibenzolar (Actigard)	*Tomato spotted wilt virus (Tospovirus)* *Tomato yellow leaf curl virus (Begomovirus)*
2,6 - dichloroisonicotinic acid	*Tobacco mosaic virus* (Tobamovirus) *Turnip vein-clearing virus* (Tobamovirus)
2 PGPRs (plant growth promoting rhizobacteria)	*Tomato mottle virus (Begomovirus)*

Acquired or induced resistance may be elicited by a chemical treatment

Ex. Applications of cadmium ions block systemic spread of a tobamovirus (TVCV)

The systemic movement of a tobamovirus is inhibited by a cadmium-ion-induced glycine-rich protein

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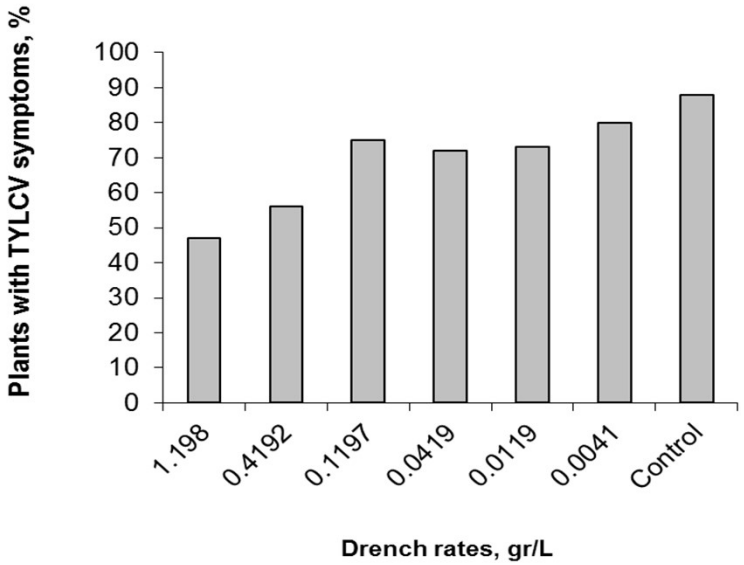
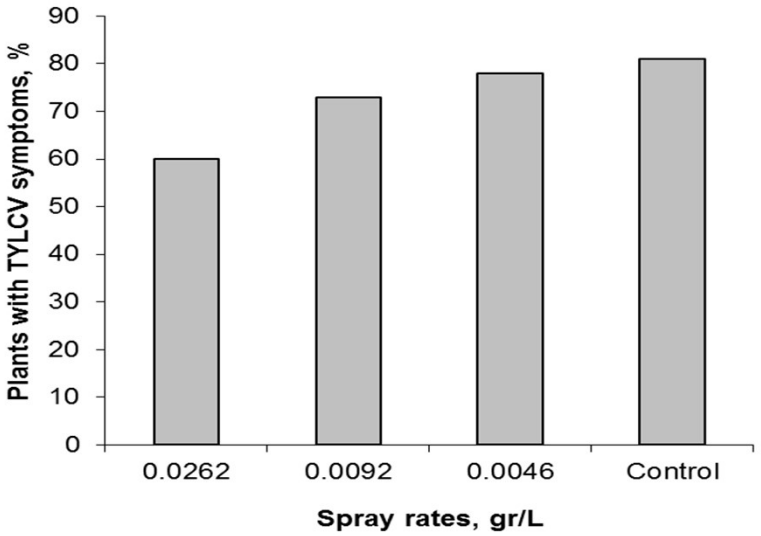
Systemic movement is central to plant viral infection. Exposure of tobacco plants to low levels of cadmium ions blocks the systemic spread of turnip vein-clearing tobamovirus (TVCV). We identified a tobacco glycine-rich protein, cdiGRP, specifically induced by low concentrations of cadmium and expressed in the cell walls of plant vascular tissues. Constitutive cdiGRP expression inhibited systemic transport of TVCV, whereas suppression of cdiGRP production allowed TVCV movement in the presence of cadmium. cdiGRP exerted its inhibitory effect on TVCV transport by enhancing callose deposits in the vasculature. So cdiGRP may function to control plant viral systemic movement.

Evaluation of Actigard (Acibenzolar) for its ability to induce resistance to TYLCV:

% TYLCV-symptomatic plants





- Actigard reduced % plants with visible symptoms of TYLCV

Disclaimers –

1. Mechanisms of many resistances are not known

2. On the surface, one mechanism may look like another

Example 1:

HR may occur at a cellular level so may not be visible and therefore the plant might be classified as immune.

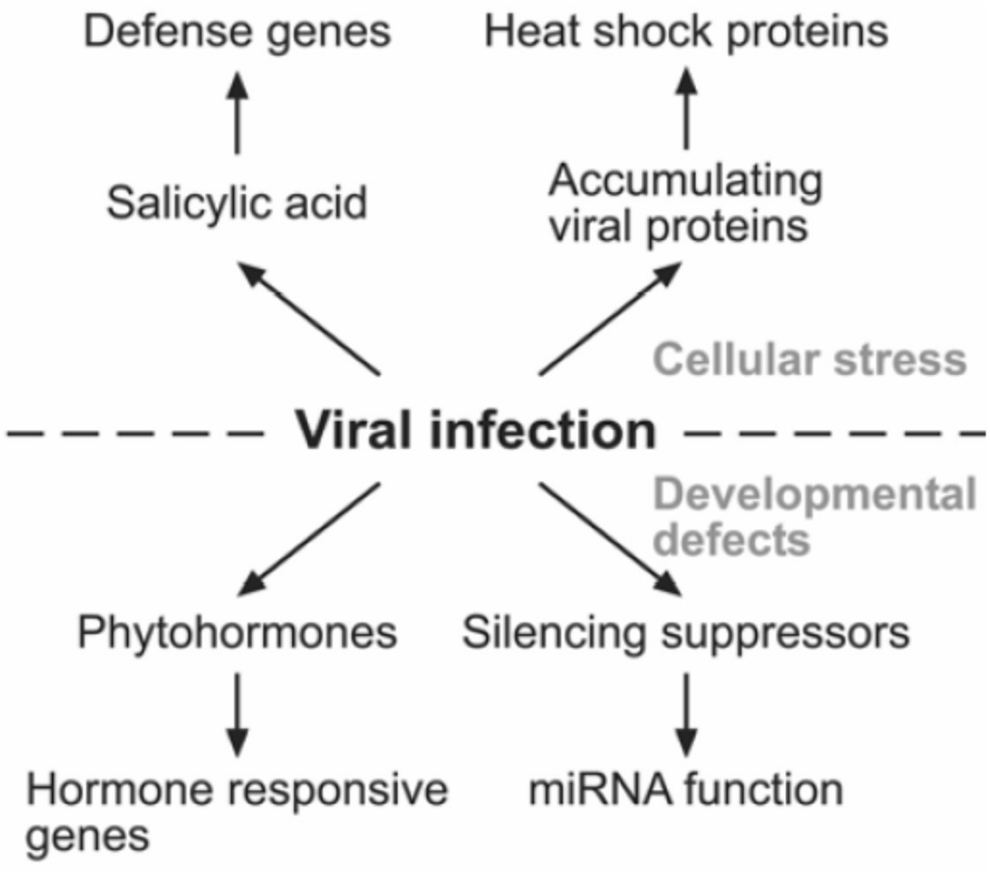
Example 2:

HR occurs in both R gene and SAR-mediated resistances (so 2 different mechanisms can produce the same symptom)

Example 3.

Once some R genes have been turned on, the plant is more resistant to infection at sites distant from the site of inoculation (is that R genes or SAR? or both? or?)

Compatible interactions: Host responses and altered gene expression



The expression of these genes is controlled by signaling pathways in the plants associated with initiation of **defense responses** and by other **cellular stress response** pathways.

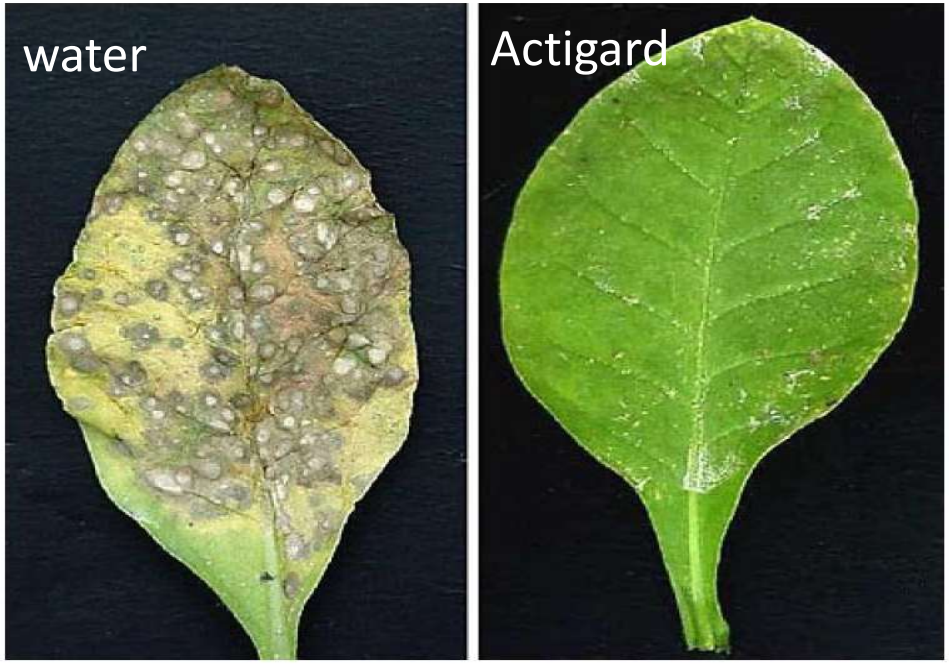
Viral infections can also disrupt the functions of regulatory small RNAs, such as micro RNAs, and phytohormone signaling or biosynthesis leading to developmental defects.

There can be interactions of different defense pathways

Effect of acibenzolar-S-methyl on R gene resistance (HR) to TSWV

Leaves treated with water or acibenzolar-S-methyl prior to mechanical inoculation with TSWV

So SAR interfered with R-gene mediated HR response to TSWV in tobacco



Normal response

“There’s no such thing as a free lunch”

Yield penalties of disease resistance in crops

James KM Brown

Recently, there have been rapid developments in understanding the costs of disease and pest resistance in model plants and their ecological relevance in wild plants. In crop plants, however, much (although not all) of our current understanding of costs of resistance must be inferred from research on model species. To determine the true costs of resistance in crops and the likely benefit of resistance genes in new cultivars, however, other aspects of the plant's phenotype must be studied alongside resistance.

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deciding whether or not to market a cultivar. If resistance has a substantial cost, therefore, it has commercial significance because it may hinder the more important objective of increasing yield.

Two useful, general reviews on costs of resistance have been written by Purrington [3], who focuses on the mechanisms of costs, and Bergelsen and Purrington [1], who comprehensively review research published before 1995 on costs of resistance to pathogens, herbivores and herbicides. Bergelsen and Purrington [1] emphasise studies in which the genetic background was controlled so that the effects of resistance (*R*) genes could be distinguished from those of other genes. They include meta-analyses of the influence of several factors on the

Types of Virus-Plant Interactions

	Mechanism
1. Plant is immune, no or limited viral replication occurs, no cell-to-cell movement.	Non-host Resistance, PTGS
2. Virus replicates and moves through out the plant without obvious symptoms evident – latent (tolerance)	R Gene
3. Virus replicates and causes symptoms in new leaves but with time and further plant growth symptoms disappear - recovery	PTGS, SAR (for a short time)
4. Virus replicates but the plant responds with hypersensitivity - cell death (may not always be noticed; necrosis, local lesions).	R Gene, SAR
5. Virus replicates and moves through out the plant with obvious symptoms	Susceptible